Master's degree thesis

LOG950 Logistics

Warehouse operations: Case study of a manufacturing warehouse at Brunvoll AS

Kristen Moland

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This master's degree thesis is the final task that completes the Master of Science in Logistics degree at Molde University College. The research has been carried out during winter and spring 2014.

In order to be able to do this research I will foremost thank Brunvoll AS, with Hartwig Banzer, head of material management, as my main contact person. This thesis would not have been commenced without his permission. The research would never have been carried out without his interest in making it happen, and his willingness to dedicate time to the project.

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Molde, 26.05.2014

Kristen Moland

Abstract

This research is based on a real life manufacturing warehouse with several entry and exit points for stock keeping units. It uses a practical approach to solve the objective of reducing warehouse operating costs and increase capacity utilization. The method suggested in this thesis is to change the storage policy from a dedicated storage to class based storage in order to increase storage utilization, and still be able to reduce travel distance compared to the current situation.

Two mathematical models are suggested in order to optimize the storage assignment. By using optimization software (AMPL) to solve the models several times with different input data, it is shown possible options for how to assign storage locations for products heading to the different exit points. In addition ABC-analysis' is done for products heading to each exit point, and for the stock keeping units heading to assembly it is shown optimized storage locations for each storage class. There are also mentioned other factors that might influence the capacity utilization and warehouse operating costs.

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1.0 Introduction

This chapter contains the history and a description of Brunvoll AS, along with the research problem and its corresponding research questions.

1.1 Company background

Brunvoll AS was founded in 1912 as a company building engines and pitchable propellers for the fishing fleet. In 1965 they started making thrusters for all kind of vessels, and in the latter years they have also started making azimuth positioning and propulsion solutions.

Propellers are most efficient when used in the direction they are designed for, when reversing them they will be less efficient due to the way the pitch of the propeller is designed. While thrusters are fixed propulsion that only can push water in two directions, by running them in forward and reverse mode (clockwise and counter-clockwise).
The azimuths are mounted on a top-swivel that makes the whole gearbox and propeller to rotate 360 degrees and in that way be able to push water more efficiently, as the propeller is always running in the most efficient direction. This makes them usable as both a thruster and a forward/reverse propulsion unit. Some of the azimuths Brunvoll make are also retractable for easier inspection/maintenance and less drag in the water when the vessel is in transit. Examples of the different propulsion systems Brunvoll offers are shown In Figure 1.

Figure 1. Picture of different thruster systems Brunvoll makes (Brunvoll).

In the last decade Brunvoll have had a significant increase in incoming orders. This increase has filled the main warehouse, which stores raw materials, components and fabricated goods ready for assembly, close to the capacity limit. In addition it contains many articles for obsolete positioning systems in case they are needed for service and maintenance. This leads to ineffective picking of goods, since the workers have to temporarily store goods on the floor, in front of the aisles, which often cause them to later move these goods out of the way to get access to the articles they need to pick. Also it makes it problematic to store incoming goods in the dedicated storage location as it might already be full, sometimes causing extra time usage to find these articles when needed as they are stored in another location.

Due to external factors the business has strict restrictions on expanding the buildings. This means that it is impossible to expand the warehouse area and height with its current location. One has to work with the current area and utilize/organize it in a better way, given the space and current organizing of shelves. And since the firm has a policy that spare parts for expired earlier produced products should be available in the warehouse, some of the capacity is occupied by these products.

The fact that the overall average inventory turnover rate for articles is approximately 3 turns p.a. tells us that there might be several factors to why the warehouse is running on high capacity. This turnover include inactive products for service, the turnover for active production parts is about 6 turns p.a. Some of the costs associated with this high inventory are shown in the company's financial accounting, where they had a revenue of 980 mill NOK and an inventory balance of 246 mill NOK at the end of the year 2012.
The main warehouse has an area of 3664 m^2 for parts to be processed and about 1200m^2 for finished products ready for shipping. It has 54 pallet racks with room for about 3700 euro-pallets, as well as 2 vertical rotary racks with 152 shelves. They also have a remote inventory for some of the parts for expired positioning systems which have a capacity of 270 euro-pallets. On the 26 of November 2013 Brunvoll had about 10500 active articles in their inventory.

Brunvoll engineer products to order, with very few exceptions. The finished products are highly specialized towards customer demands and are constructed by a large amount of parts where many of them are fabricated by the firm itself. The specialization is mainly done in the final assembly stages, so the articles stored in the warehouse are standard for most projects. But since the product portfolio consists of 8 thruster types and 3 azimuth types the combined number of articles stored are about 12000. This number will most likely increase in the future as they start offering new models, and change some parts in the existing models.

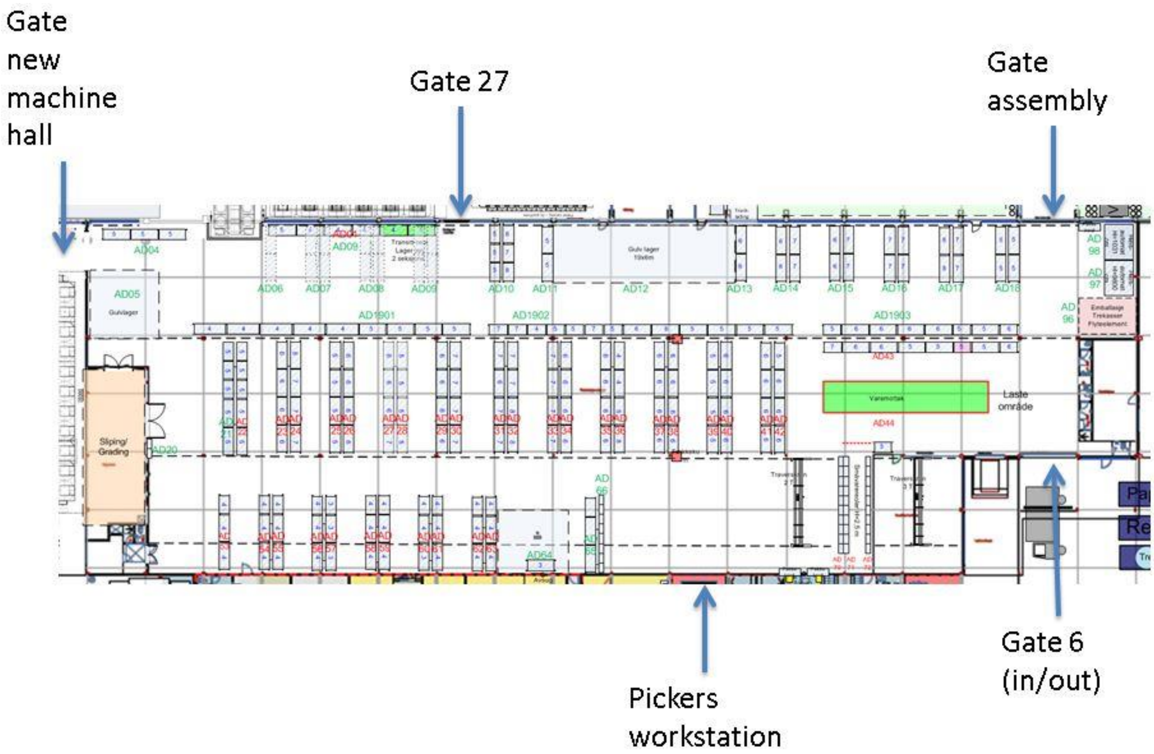

Figure 2. Layout of Brunvoll's main warehouse, enlarged version is shown in Appendix E

1.2 Research problem

During the summer of 2013 I had a temporary job as a warehouse worker at Brunvoll. During this time I observed firsthand how the warehouse was operated and how the products flow in the company.

In the end of my working period I asked Hartwig Banzer, head of material management, if there was any research problem related to my master thesis in logistics he wanted me to have a look at. After some time he replied with an offer to do a research of the warehouse operations in order to reduce time spent on replenishing and retrieving goods in the warehouse, and if possible increase storage utilization and reduce turnover times for stored products. I chose to take a look at the time used to handle the products in the warehouse as my main research problem, and to increase utilization of the storage as a sub-problem.

To reduce turnover times would be a research on purchasing policies and routines, and are therefore mentioned as a possible further research. This also have an impact on the storage capacity, since purchased quantity will affect storage locations needed.
This leads to the following research question:

Which factors affect the efficiency in a manual picker-to-part warehouse?

This in turn leads to more case specific sub-questions which have to be answered in order to find possible solutions for Brunvoll:

How can Brunvoll reduce their warehouse operating time?
And:
How can Brunvoll increase their storage utilization?

2.0 Literature review

In this chapter I will go through the literature used to answer the research questions.

2.1 Warehouse operations

Tompkins et al. (2010) states that it is old fashioned to think of warehousing as a non-value added activity. Further, they claim that; traditionally warehousing has been perceived as a cost-adding burden to the supply chain, and has not gone through the same type of quantitative scrutiny as other functions. Warehousing provides the utility of time and place that is needed to satisfy customers, by having the right product in the right place at the right time.

2.1.1 Order picking policies

Order picking, the activity by which a number of goods are retrieved from a warehousing system to satisfy a number of customer orders, is an essential link in the supply chain and is the major cost component of warehousing (Petersen II 1999). In this case the customers are both internal (fabrication, machines and assembly) and external.

According to de Koster et al. (2007) order picking has long been identified as the most labor-intensive and costly activity for almost every warehouse; the cost of order picking is estimated to be as much as 55% of the total warehouse operating expense, while Coyle et al. (1996) point out that up to 65% of the operating costs of a warehouse can be attributed to order picking.

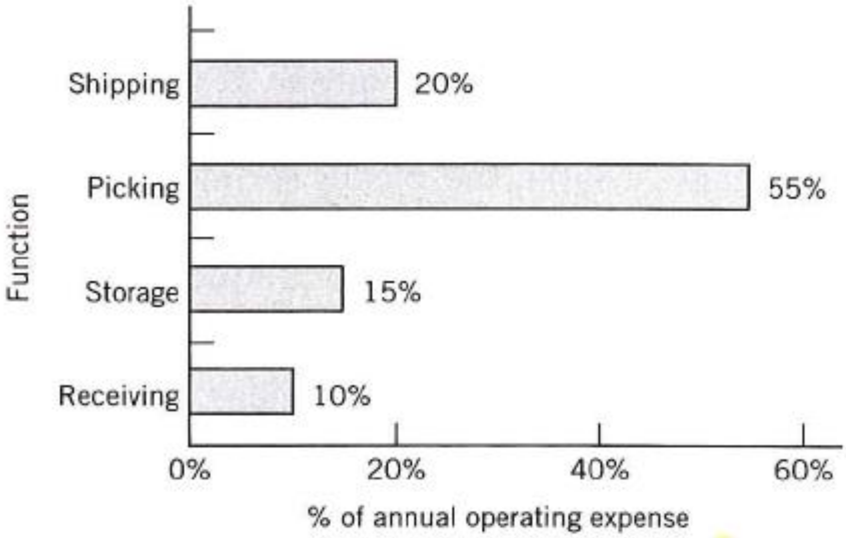

Figure 3. Typical distribution of warehouse operating expenses (Tompkins et al. 2010).

Further, research shows that most of the picker's time is spent on travel. In Tompkins et al. (2010) it is estimated that a pickers typically use 50% of their time on travel. Hence, there are often opportunities to reduce the time spent on travel in order to reduce total warehouse expenses.

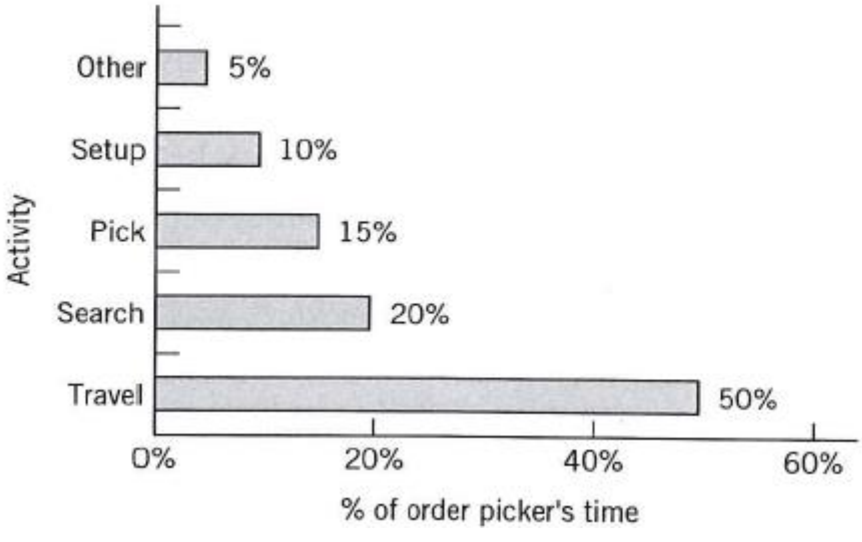

Figure 4. Typical distribution of an pickers time (Tompkins et al. 2010).

This paper will only consider manual picker-to-part system since this is the only one used in the case business. This means that the picker has to travel to the parts in order to retrieve fulfill the picking-order.

Travel time is an increasing function of travel distance for manual picker-to-part systems. This means that travel distance often is the primary objective when designing and optimizing warehouses. There are mainly two types of travel distances used in the literature; average length per pick tour, and total travel distance. When given a set of orders, minimizing average tour length is equivalent to minimizing the total travel distance (de Koster et al. 2007).

2.1.2 Storage policies

Storage assignment policy is the policy that determine where to locate the stored products in the warehouse (Chan and Chan 2011).

There are mainly five different types of storage assignment policies in use; Random storage, closest open location storage, dedicated storage, full turnover storage, and class-based storage (CBS) (Roodbergen 2001, Hausman et al. 1976).

Random storage is widely used as storage assignment policy in many warehouses since it is easy to use. It works in the way that incoming goods are assigned to an empty storage location in the warehouse randomly and with equal probability (Petersen II 1997). It has a very high capacity utilization, but at an expense of increased travel distance (Choe and Sharp 1991).

For manually controlled warehouses where the order pickers freely can choose amongst the empty locations, a closest open location storage policy would be natural. With this policy the order picker will locate the incoming goods in the first available location closest to the incoming depot. This will typically lead to a warehouse where the racks are full close to the depot and gradually emptier further away from the depot (Roodbergen 2001).

Another possibility is to store each product at a fixed location, this is called dedicated storage. A disadvantage of dedicated storage is that a location is reserved even for products that are out of stock. Moreover, for every product sufficient space has to be reserved such that the maximum inventory level can be stored. Thus the space utilization is lowest among all storage policies. An advantage is that order pickers become familiar with product locations (de Koster et al. 2007).

When using full turnover storage one locates the products according to their turnover. The products that are most often picked are stored closest to the depot, and slow moving products further in the back of the warehouse. This leads to short picking tours for the pickers, but the disadvantage is that the demand for products constantly vary and one have to change locations for products frequently (Roodbergen 2001).

Class-based storage policy combines some of the methods above. This policy divides every product into a number of classes. Each class is then assigned to a dedicated area of the warehouse; storage within the area is random. The classes are usually determined by some measure of demand frequency of the products. Products that have a high picking frequency are grouped in A-items, less frequent products in B-items and so on. The number of classes is often restricted to three, but sometimes more classes can be lead to better results. This policy have the advantage of storing products that are frequently picked close to the depot, leading to shorter travels, while the flexibility and capacity utilization is fairly high. Also it is easier to manage as one doesn't have to decide where every product should be stored, only what class they should be in (Roodbergen 2001, Hausman et al. 1976).

Chan and Chan (2011, p.2687) says that:

> *"Random storage and dedicated storage are in fact extreme cases of the class-based storage policy. Random storage has all products in a single class and dedicated storage has each of the products assigned to a separate class. The main*

idea of class-based storage is to divide products into classes. Each class is then assigned to a dedicated area of the warehouse. Storage within an area is random. The advantage of this policy is that fast moving products can be stored close to the depot while the flexibility and high storage space utilization of random storage are applicable."

Further, CBS-systems are generally divided into two types: (1) dedicated purposes (Brynzér and Johansson 1996) and (2) ABC classification (Ashayeri et al. 2002). The dedicated purposes class is grouped into similar products or products that are most likely to be picked on the same order, while in the ABC classification the products are grouped according to how frequently they are picked.

The volume based storage policies (full turnover storage and class-based storage) are assigned location based on the expected demand volume or pick frequency in such a manner that the most popular products are closest to the pickup or delivery point. This have an advantage of reduced travel distance and time for the pickers, but can on the other hand lead to aisle congestion and unbalanced utilization of the warehouse (Petersen and Schmenner 1999).

When using the volume based storage policies there are mainly four different methods for assigning the products discussed in the literature. These are: Diagonal storage, within-aisle storage, across-aisle storage, and perimeter storage. All four methods are illustrated in Figure 5. The dark grey area represent high volume products, the gray area represent medium volume products, and the beige area represent low volume products. For all four methods there are examples of having pick-up and delivery point (P/D) in a corner or in the middle of the warehouse. The methods are briefly described below and are obtained from Petersen and Schmenner (1999).

Diagonal storage assigns the products in a diagonal pattern from the P/D point, with the highest volume products closest to the D/P point.

Within-aisle storage assign the products by storing the highest volume product in the first storage location in the first aisle, the next highest volume product in the second storage location in the first aisle, and so on until the first aisle are full. When the first aisle is full one start with the second closest aisle and fill this, and so on. This leads to having high volume products in aisles close to the P/D point and lower volume products further away. One disadvantage with this method is the possibility of congested aisles close to the P/D point.

Across-aisle storage method assigns storage locations by assigning the highest volume product in the first storage location in the first aisle. The second highest volume product in the first storage location in the second aisle, and so on until the first storage locations in all aisle are full. Then one starts assigning products to the second storage location in each aisle. This means that the high volume products are stored close to the front of each aisle, and less popular products further to the back of the aisles.

Perimeter storage method assigns the high volume products around the perimeter of the warehouse. The highest volume product is located in the first storage position in the first aisle, and then the rest of the products are located around the perimeter in a counter-clockwise direction. This means that the lower volume products are assigned to the middle of the aisles.

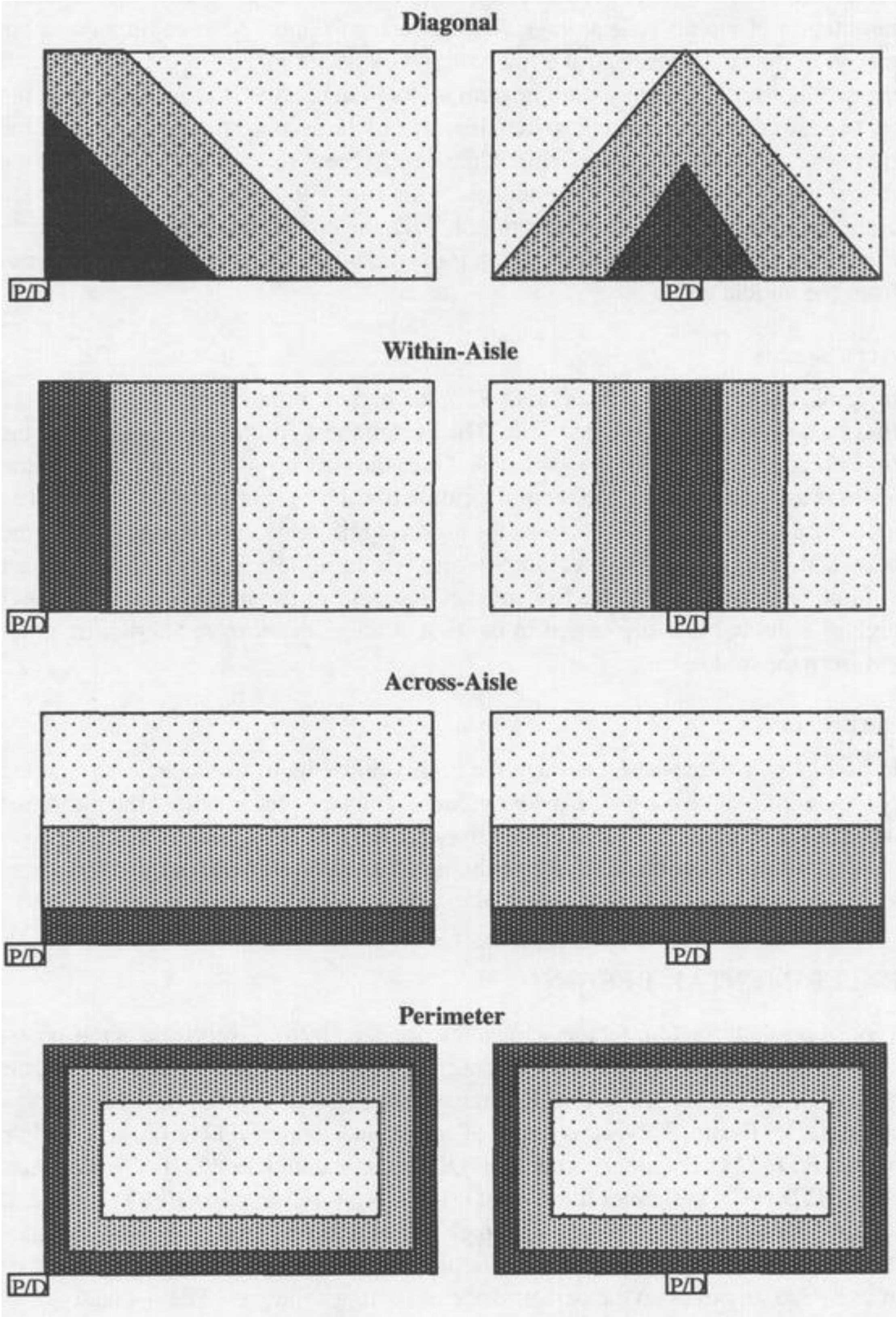

Figure 5. Volume-based storage policies (Petersen and Schmenner 1999).

Chan and Chan (2011, p.2686) claims that:

"In order to minimize the throughput time of picking an order while maximizing the use of space, equipment and labor as well as the accessibility to all items, careful design and control of the picking system is necessary."

2.1.3 ABC classification

The need to rank inventory items in terms of importance was first recognized in 1951 by H. Ford Dicky of General Electrics. He suggested classifying items according to relative sales volume, cash flow, lead time, or stock-out costs. He used what we now call ABC analysis for the classification (Coyle et al. 1996). This system assigns items to three (or more) groups according to the relative impact or value of the items that make the group. Those items that have the greatest impact, value or volume constituted the A-group while the items thought to have less importance made up the B- and C-groups respectively (Coyle et al. 1996).

The ABC analysis came from Pareto's law, which separates the "trivial many" from the "vital few". In inventory terms this suggests that a small number of SKU's account for a considerable amount of value or volume. The Pareto's law is also known as the "80-20 rule". For example one might find that 20% of a firms costumers account for 80% of its sales, a university might see that 20% of its courses generate 80% of its student credit hours (Coyle et al. 1996).

The actual demand distribution might differ somewhat from this in real situations since the demand for products changes constantly in a warehouse environment. As the SKU demand distribution become less skewed (i.e. the same amount of SKUs account for less picks), the savings for CBS and VBS over random storage diminishes. This happens because it a greater probability that a SKU with low demand will be on the pick order (Petersen et al. 2004).

The article "Designing an efficient warehouse layout to facilitate the order-filling process: an industrial distributor's experience" by Zeng et al. (2002) relies on a case study to show how some simple techniques developed in theory can be applied to a company's current practice to improve the order-filling process. It describe how one can use a short time plan, ABC analysis, to significantly reduce picking time in a company and to help store products at the right places. Further it suggests that a mathematical modeling approach can be used when there is a need for redesigning the warehouse layout, this however is a much more elaborate long term plan.

2.1.4 Routing policies

Routing policies determine the picking sequence of SKUs on the picking list. Using simple heuristics or optimal procedures, the goal is to minimize the travel distance of the picker (Petersen and Aase 2004).

There are several heuristics made for routing in a warehouse, and they mainly assume that one can enter and exit the racks in in both ends and that depot (where the picker starts and ends the tour) is the same. A summary of the most used is done below, and are obtained from Roodbergen (2001). Illustrative examples of the different ones are shown in Figure 6.

S-shape heuristic: Also called transversal heuristic. With this policy the picker traverse through the entire length of the aisle if there are any goods to pick there, he or she exits in the other end and travels to the nearest aisle where goods have to be picked, and traverse all the way through this aisle. And so on until the order is completed. Aisles with no picks are not entered.

Return heuristic: With this policy the pickers enters and exits in the same end of the aisle no matter what. This heuristic has only one main application, which is for warehouses where the only possibility for changing aisles is in the front. This happens to be the case at Brunvoll.

Midpoint heuristic: In this policy the lengths of the aisles are essentially divided into two halves. This means that picks in the front halves are accessed from the front, and picks in the back half are accessed from the back of the aisle. Only the first and the last aisle are traversed entirely.

Largest gap heuristic: Here the picker enter the first aisle and traverse through this to the back. Each subsequent aisle is entered up to the “largest gap” and left from the same side as it was entered. A gap represent the distance between any two adjacent items, or between a cross aisle and the nearest item. The last aisle is traversed entirely and the picker returns to the depot along the front entering again each aisle up to the “largest gap”. Thus the largest gap is the part of the aisle that is not traversed.

Composite heuristic: This policy is a combination of S-shape heuristic and return heuristic. This heuristic decides for each aisle individually whether it is shortest to traverse the entire aisle or to return.

Combined heuristic: This policy is a continuation of the composite heuristic. The difference is that it does not look at the aisles individually, but take into consideration whether it is shorter for the entire picking tour to return or traverse the entire aisle as one or the other could lead to a better starting point for the next aisle.

Optimal algorithm: All of the policies mentioned before restrict the possibility of creating a route. For example, the S-shaped heuristic forces the picker to traverse the whole aisle entirely. To obtain the shortest route possible, one need a routing policy that is capable of considering all possibilities for travelling in and between aisles. There are examples of algorithms that can do this in seconds on a personal computer. However, these routes tend to be confusing for pickers to follow in practical use.

Because of how the warehouse at Brunvoll is designed the only possible routing policy is the return heuristic (shown in Figure 7), this is the only one that will be considered in the remaining of the paper.

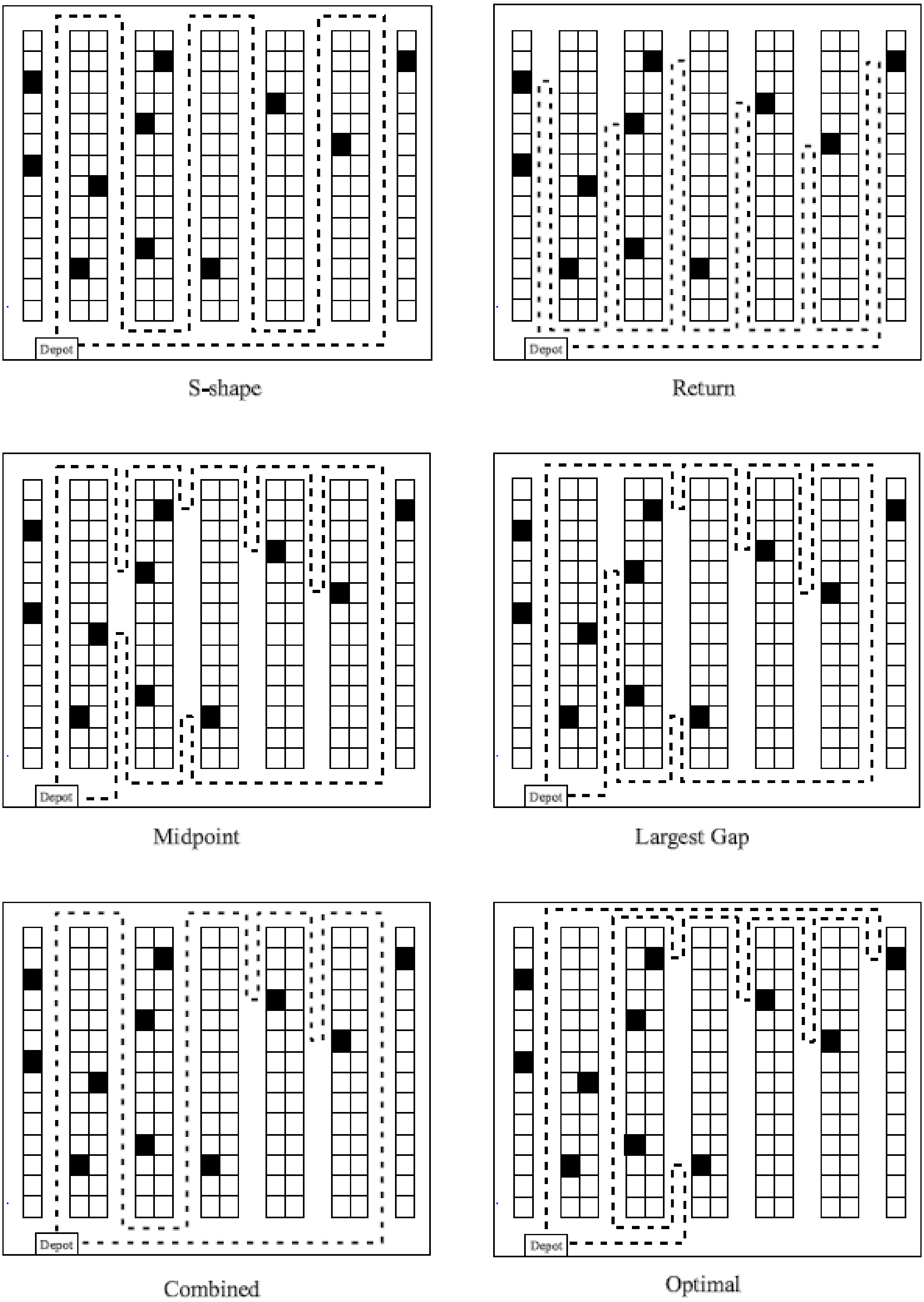

Figure 6. Examples of routing policies (Roodbergen 2001).

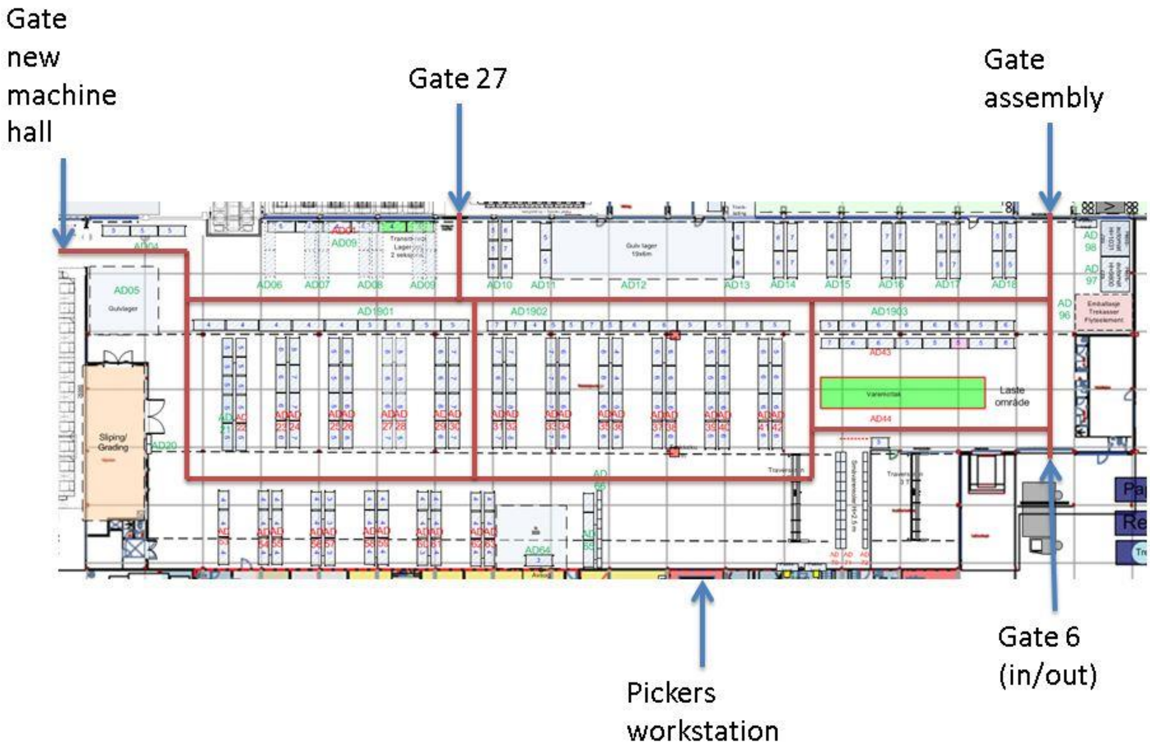

Figure 7. Possible travel routes for the pickers marked in red

de Koster et al. (2007) say that:

> *"Existing studies in picker-to-parts order-picking systems mainly focus on random storage assignments. Analytical models for optimizing dedicated and class-based storage assignment manual-pick order-picking systems are still lacking. Furthermore, storage assignment has an impact on the performance of the routing method. However, this effect seems to be largely neglected in the literature. Instead, many authors focus on random storage assignment to discuss about the performance of routing methods."*

3.0 Methodology

In this chapter I will go through the research design used to write this thesis, what data that have been used, and the quality aspect of the thesis.

3.1 Research design

Bryman and Bell (2011) discuss five different types of research designs: experimental design, cross-sectional or social survey design, longitudinal design, case study design, and comparative design.
To find out what type of design to use one need to know what the different types mean. Therefore will I do a short description of each one of them, based on the information in Bryman and Bell (2011):

Experimental design is when one compare two groups of the sample, where one of the groups have be treated and the other group act as a control.

Cross-sectional design collects quantitative data on more than one case in a single point of time and examined for connections explained by two or more variables.

Longitudinal design compares data that have been collected on at least two different time-periods of a sample.

Case study design is a detailed and intensive analysis of a single case. Also defined as: *"a study that investigates a contemporary phenomenon in depth and in its real-world context"* (Yin 2014, p. 237)

Comparative design is when one compare two or more cases in order to investigate the cases regarding to existing theory or find contrasts between the cases.

Since this research is based on a single warehouse in a company it will be considered as a case study research of a single location. Yin (2014) divide case study of a single case into one of five different categories: the critical case, the unusual case, the common case, the revelatory case, and the longitudinal case. Without discussing these categories further I can classify this case as a common case; A case that seek to explore the circumstances and conditions of an everyday situation (Yin 2014).

3.2 Data collection

Data collecting falls into one of two main categories; primary data or secondary data. Saunders et al. (2012, p. 678) defines primary data as: *"Data collected specifically for the research project being undertaken"*. Further they define secondary data as: *"Data that were originally collected for some other purpose. They can be further analyzed to provide additional or different knowledge, interpretations or conclusions"* (Saunders et al. 2012, p. 681)

3.2.1 Primary data

Yin (2014) list up six primary data sources of evidence commonly used in case studies. The six are; documentation, archival reports, interviews, direct observations, participant observation, and physical artifacts. Further he stress that none of the sources have a complete advantage over the others, and that they are highly complementary and one should rely on as many of them as possible (Yin 2014).

Saunders et al. (2012) describes four different types of participant observations. These are; complete participant, complete observer, observer-as-participant, and participant-as-observer. An illustration of how these four types are arranged and the researcher's role are shown in Figure 8.

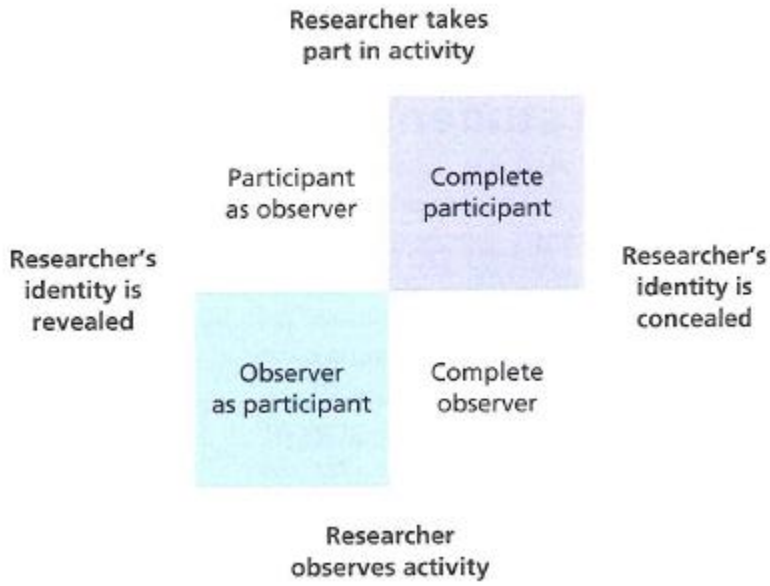

Figure 8. Typology of participant observation researcher roles (Saunders et al. 2012, p. 344)

Participant observation has its roots in social anthropology, and Saunders et al. (2012, p. 677) define it as *"Observation as which the researcher attempts to participate fully in the lives and activities of the research subjects and thus becomes a member of the subjects' group(s), organization(s) or community".*

The author happened to work temporarily in Brunvoll's main warehouse during the summer of 2013. This means that I have collected primary data through participant observation during this period.

My role in the company was as a normal warehouse worker, with the exception that I only should work there for a limited time. As I did not have any arrangements with Brunvoll to do a master thesis at the company at the time, neither me nor the other employees knew that I was observing the company based on this at the time. Hence the participant observation in this case falls under the complete participant category. This

category is defined as *"Observational role in which the researcher attempts to become a member of the group on which research is being conducted. The true purpose of the research is not revealed to the group members"* (Saunders et al. 2012, p. 667). Since I was not aware that I would write a master degree thesis with Brunvoll as an example at the time I worked there, I must stress to the other employees that this was not an undercover operation planned by me or the company in any way.
In addition, primary data has been collected by communication with the managers in Brunvoll at several occasions.

3.2.2 Secondary data

Saunders et al. (2012) classify secondary data in to three subcategories; documentary, survey, multiple source. In this thesis I have collected secondary data by asking managers at Brunvoll to do queries in M3 to extract the data needed. This falls under the documentary category, and were quantitative data. The outcome of the queries was converted from M3 to MS Excel to make editing and analyzing easier. The main query included every pick order line in 2013 in the main warehouse. For every pick order it include information about: date of the pick order, pick order number, destination, article number (SKU), storage location, article name, pick quantity, unit weight, acquiring method (whether the article is purchased from an external supplier or if it has been fabricated internally), order type (whether the product will be fabricated internally or by an external company).

3.3 Research quality

Yin (2014, p. 239) define internal validity as: *"The strength of a cause-effect link made by a case study".* And external validity as: *"The extent to which the findings from a case study can be analytically generalized to other situations that were not part of the original study"* (Yin 2014, p. 238).

In this case study I use storage assignment as a variable to reduce distance traveled for the articles and thereby reduce time and cost of warehouse operations. This would apply to warehouses other than the one in this case study; hence both the internal and external validity will be satisfied.

Yin (2014, p. 240) also mention reliability: *"the consistency and repeatability if the research procedures used in a case study"*, as one criterion for research quality. In this case I have used data that are directly given by Brunvoll's ERP system and calculations in easy to access computer software. This combined with the fact that I do not have any connections to Brunvoll, should secure the research reliability.

4.0 Analysis

In this chapter the current situation will be explained and analyzed, and possible solutions will be suggested in order to make the warehouse more efficient.

4.1 Current situation

In order to understand the analysis and remarks, it's first necessary to explain how the current situation is, and how the warehouse is operated.

The storage locations at Brunvoll are labeled in a logical way; the first letters on the label tells us in what building and where in the building to look. All SKUs in this paper are located in AD warehouse, which is Brunvoll's main warehouse. The "A" tell us that it is located at Årø, the "D" tell us to look in hall D in this building. The letters are followed by six numbers; the first two describe in which rack the items are located, the middle two explain how far into the rack the item is, and the last two tells us in what shelf number the item is located. For example storage location AD340102 tells us that the SKU is located in the main warehouse, on shelf number 2 in the first storage location in rack number 34.

There are two possible arrival-locations for incoming goods to the warehouse; firstly, all incoming goods to the warehouse arrive at gate 6 for storing. Secondly, the parts that have been machined or processed in any way get a new article number and are placed at gate 27 for the pickers to store in the warehouse before assembly.
When storing the incoming items the pickers transport the items to their workstation in order to register the items as arrived to the warehouse for completion of a purchase order or work order. The item is then assigned to a dedicated location in the warehouse, and registered in the ERP system M3. When a SKU is registered, the label printer automatically prints out a label including article number, storage location and date to be

attached to the pallet the item is stored on. In addition the label also includes a bar code that is possible to scan using a personal digital assistant (PDA).

In order to handle the goods the pickers mainly use reach-trucks, also called moving mast trucks, to pick the SKUs needed. For smaller items at the lower shelves they sometimes walk by foot to collect the item(s). Often the pick orders contains more than one SKU or the stored amount of the SKU is higher than the ordered amount, so the picker has to place the items on a new pallet before delivering it to the destination and register the pick order as completed in order for M3 to update the status.
The pick orders are created by people working at the processing machines, assembly, service department or the production planners ordering items. It is automatically printed out at the printer located at the warehouse workstation, and the pickers collect and process them as one by one.

Usually there is no batching of the pick orders before they are picked, the exception is if there happen to be several picking lists ready for picking for the same destination or the SKUs are located in the same area of the warehouse. If any batching occurs it is purely a coincidence made by the picker in that moment.

The pick orders categorize the SKUs according to storage location in ascending order, starting with the storage location with the lowest number. Thus the picking sequence is from the lowest numbered storage location to the highest. Also included in the pick orders are the article number, amount to pick, pick order number, work order number, and destination of the pick order. The pick order also includes a bar code for each SKU ordered, making it possible to scan this with a PDA in order to register the picking in the ERP system.

As mentioned the pick orders and the label on SKUs include a bar code that can be scanned by a PDA. The pickers at Brunvoll have 8 PDAs for usage when working in the warehouse. These have a user interface (UI) which is very similar to the one they are used to on their computers at the workstation. The PDAs have Microsoft Windows operating system and run M3 by WIFI. When Brunvoll first introduced the PDAs it was the intention that these units would make the work easier for the pickers, and at the same time eliminate typing errors by scanning the bar codes and by that increase unit balance quality. However, the PDAs were not that well received by the pickers. Due to the fact that they logged themselves off after only a short period of inactivity, the workers had to spend time logging on again. Also, the UI on the PDAs could be simplified by eliminate some of the more advanced options, in order to make the usage of them more efficient.

There are 4 ways a SKU can leave the warehouse; through gate 27 for machining or processing, the gate to the new machining hall for machining, the gate to assembly, or gate 6 for outgoing products.

As mentioned above, the SKUs are located using a dedicated storage model. The items are assigned so that similar items are stored close to each other. In some cases items that are to be assembled to the same finished product, are assigned close to each other. There seems to be no superior strategy of the assignment, only the pickers and the foreman's experience of where to assign locations.

Due to the overall layout of the warehouse, the only usable routing heuristic is the return heuristic, as shown earlier in Figure 7.

Brunvoll uses a manual picker-to-part system; this means that there are no automatic picking system, all SKU's are picked by manual labor. Also the "picker to part" means that the pickers have to travel, either by foot or using a forklift, to the SKU's location. The only exceptions are two elevators for smaller parts where they enter the shelf-number requested and the SKU will be transported to the front of the elevator where the picker can retrieve the article. But since the pickers still have to travel to the elevators I will consider the whole warehouse as picker-to-part.

During the process of this research, Brunvoll have done some changes to their warehouse operations in order to improve the efficiency. This study uses observations from summer 2013 and data from whole 2013 as a basis.

4.2 Case study analysis

In this chapter I will show possible solutions to how the warehouse can be operated and compare the results with the current situation in order to show differences.

Of the five storage policies mentioned, Brunvoll currently use a dedicated storage policy. This policy makes it easy for pickers to find the products needed, as they are stored in logical locations and pickers get familiar with the locations over time. However, this requires the most capacity of the ones mentioned, as one have to reserve storage locations for out of stock SKUs.

Random storage, on the other hand will utilize capacity in the most efficient way, but are very hard to implement in a manual worker environment.
This would in practice lead to a closest open location storage policy, which has good capacity performance. But with so many slow moving parts in addition to the parts for obsolete systems, one would risk storing some of these products in central locations and by that make the warehouse less efficient in handling time.

The full turnover storage policy is the most efficient in travel distances, but requires much administration as one constantly have to change storage locations according to changes in demand patterns.

For Brunvoll, where the products are transported in and out in several locations around the warehouse, a CBS policy could lead to an improvement, both for capacity utilization and handling time. As shown in the analysis later in this research, they can divide the products heading to and from the different gates into separate sub-cases and make an ABC-classification for each of these sub-cases instead of looking at the warehouse as one unit. Since this is an easy to manage policy with good overall results, it is the one used as a possible policy for Brunvoll in the analysis.

4.2.1 Data used, data processing and assumptions

I requested some data from Brunvoll in order to do the analysis. These data were listing of every pick order line going out of the main warehouse in 2013 and included: date of pick, destination, pick order number, article number, storage location, name of the article, procurement method (whether the article are coming from an external supplier of fabricated internally), unit weight, pick quantity, and order type. These data were extracted from Brunvoll's ERP system M3 and converted into Microsoft Excel format for further calculations.
In addition I requested data of SKUs with zero picks in 2013 and that had a balance of more than zero in M3, this included article number and unit balance.

Brunvoll use a system called toboks (translated to twobox) for some small items with high frequency that are stored in dedicated racks (rack 70-72). This is a variant of vendor managed inventory (VMI) where they store two boxes of the same SKU, and when one of them become empty it is placed on a pallet to be refilled by the vendor. The vendor visits every day to pick up empty boxes and deliver refilled boxes without any influence of Brunvoll's purchase department. Since these SKUs are small in size they are omitted from the data used in this thesis, as the author find the system working as intended and due to the fact that larger items can't be stored in those racks.

At this stage I ended up with a total of 14575 pick orders with a total of 48710 pick order lines and a total of 164180 items divided on 2687 SKUs picked from the main warehouse in 2013.

Further, I omitted SKUs stored on racks dedicated, and the racks themselves in the analysis; for very small SKUs (rack 70-72, 97-98 (storage elevators)), racks that are dedicated to very big/heavy SKUs (rack 19), and storage locations that are dedicated to a specific purpose (rack 1-9, 20, 43-52, 64-66, 96, ADHO). This due to the fact that some very large SKUs can't be stored in the "normal" racks and the "normal" SKUs can't be stored in the small shelf racks and elevators.

The data I ended up with using now contained 11908 picking orders, with a total of 30157 pick order lines, 60995 items divided on 1599 SKUs.

The goal of this research is to reduce time spent on handle goods in the main warehouse. As time spent to handle different SKUs vary due to different size, weight shape etc. This research use travel distance as an indicator for time spent. For all analyzes it's assumed that vertical and horizontal travel speed is equal. The distances in the warehouse was not available, and I ended up with the use of approximate distances between all gates and all racks used, using a technical drawing of the warehouse as a basis (Appendix E). The list of gates, racks and the corresponding distances are given in Appendix A.

Since the distances are approximate they are only usable to show the difference between scenarios, not as a real measurement for actual travel distances.

All ABC-analysis' use frequency as a measurement, both because this is the measure most commonly used in literature read and data for unit cost were not available. This means that A-articles are the most frequently picked ones, B-articles less frequent, and C-articles the least frequent.

When doing calculations and models of possible storage assignment scenarios I have taken the assumption that there are stored one SKU per pallet.

For the modelling part, I have assumed one pallet of each demanded SKU to calculate storage zones. Since the storage within the class-zones is random, the distances would also become random when calculating distances for demand of more than one of each SKU. Hence, there are no calculations of the total distances using total demand for each SKU as a multiplier.

With the current situation where the pickers transport incoming goods to their workstation to register it and print label before it is transported to its storage location, I use the workstation as a starting point for the SKUs when calculating distances. This is the same whether the SKUs come from external suppliers and are received at gate 6, or have been fabricated internally and collected at the rack by gate 27.

For distances out of the warehouse I use the approximated distances from the storage location to the gate of destination.

4.2.2 Analysis for parts heading for assembly

There are a total of 924 SKUs transported to the assembly area. I prioritize these SKUs highest, as they account for the majority of both SKUs and number of picks.

When looking at current storage assignment for these SKUs, with assumption that all SKUs start at picker's workstation, I get a total distance of 66435 meters. However, this only covers distance to and from the front of the racks, not the horizontal and vertical distances within the racks.

Applied the following model using AMPL in order to minimize the travel distances by using storage assignment as a variable:

Objective: $$\min \sum_{t \in T} \sum_{n \in N} \sum_{r \in R} \sum_{d \in D} \sum_{s \in S} X_{t,r,d,s} \; c_{n,r,d,s}$$

Subject to:

(1). $$\sum_{t \in T} X_{t,r,d,s} \le u_s \quad , \forall r \in R, \forall d \in D, \forall s \in S$$

(2). $$\sum_{r \in R} \sum_{d \in D} \sum_{s \in S} X_{t,r,d,s} \ge d_t \quad , \forall t \in T$$

(3). $$X_{t,r,d,s} \ge 0 \quad , \forall t \in T, \forall r \in R, \forall d \in D, \forall s \in S$$

Sets:

T - a set of products

N – a set of nodes, in this case supplier and destination

R - a set of racks

D - a set of depths

S - a set of shelves

Parameters: $c_{n,r,d,s}$ = distance between every node n, rack r, depth d, and shelf s

u_s = SKU capacity for every shelf s

d_t = demand for every product t

Variables: $X_{t,r,d,s}$ = amount of products t to be stored in rack r, depth d, and shelf s

When trying to include constrains telling this model that some racks have fewer levels of depths and/or shelves it became too complex to solve in AMPL, it ran out of memory due to the problem became mixed-integer. Due to this, this model assumes that there are four rack-depths in each rack, each depth has six shelves vertically, and each of these shelves has a capacity of three pallets. Hence, the model is slightly inaccurate when solving it with many SKU's so that the constrained racks are being filled up.

This model optimized the storage locations of the 924 SKUs and had a total distance of 45240 meters to and from the front of the racks.
A reduction in SKU travel distance of 31.9% compared to the current situation of 66435 meters.

When expanding the analysis to include distances within the racks, I made a more accurate model which also included capacity constraints for racks. This model consists of 828 storing shelves, each with a capacity of three SKUs.

In the current storage assignment some SKUs are given a less strict storage location, meaning that they are not assigned to a specific depth and/or shelf number (labeled with "00" as depth and/or shelf). For these SKUs I have used the distance for depth nr 02 and shelf 04, corresponding distance in meters for depth is then 5m, and shelf 3m, as a measurement since this represent the median locations.

When observing the storage assignment including distances within the racks I find a current distance of 81261 meters and an optimized distance of 60654 meters. A reduction of 25.35%.

Accurate model with capacity constraints used to optimize distances including distances within the racks:

Objective: $\min \sum_{(a,b,c)\in G} X_{a,b,c}\ c_{a,b,c}$

Subject to: (1). $\sum_{s\in S} X_{s,d,p} \geq d_{d,p} \quad , \quad \forall d \in D, \forall p \in P$

(2). $\sum_{s\in S} X_{k,s,p} \leq s_{k,p} \quad , \quad \forall k \in K, \forall p \in P$

(3). $\sum_{k\in K} X_{k,s,p} \geq \sum_{d\in D} X_{s,d,p} \quad , \quad \forall s \in S, \forall p \in P$

(4). $\sum_{k\in K}\sum_{p\in P} X_{k.s.p} \leq u_s \quad , \quad \forall s \in S$

(5) $X_{a,b,c} \quad \geq \quad 0 \qquad ,(a,b,c) \in G$

Sets: P – a set of products

K – a set of suppliers

D – a set of destinations

S – a set of shelves

G – (KxSxP)⋃(SxDxP), a set of products P from supplier K to shelf S union products P from shelf S to destination D

Parameters: $c_{a,b,c}$ = distance between supplier K, shelf S and destination D for every product P

$d_{d,p}$ = demand of every product P in destination D

$s_{k,p}$ = supply of every product P from supplier S

u_s = capacity in shelf S

Variables: $X_{a,b,c}$ = number of product P to be transported from supplier K to shelf S and to destination D

Model is adapted from Rasmussen (2007).

The latter model is less flexible in terms of changing and modifying data and only calculates total distances including within racks; however, it represents the warehouse more accurately, and will therefore be used for the remaining of this thesis.

4.2.2.1 ABC analysis

ABC analysis usually divide the classes in a way so that the A-class consist of 20% of the SKUs and covers 80% of the picks, B-class consists of the next 30% of the SKUs and 10-15% of the picks, and C-class consists of the last 50% of SKUs and consists of only a few percentages of the picks. ABC analysis can be done with more than three classes, but Petersen et al. (2004) claims that three classes attains 90% of the benefits compared to an optimal dedicated storage policy, which is harder to administer.

When analyzing the data retrieved by Brunvoll for parts heading to assembly I find that of the total 924 SKUs, 185 SKUs fit in the A-class. This is exactly 20% of the SKUs, but only covers 65% of the picks.
B-class consists of the next 293 SKUs, representing 31% of SKUs and 25% of the picks.
C-class represents the last 446 SKUs, 49% of the SKUs and 10% of the picks.

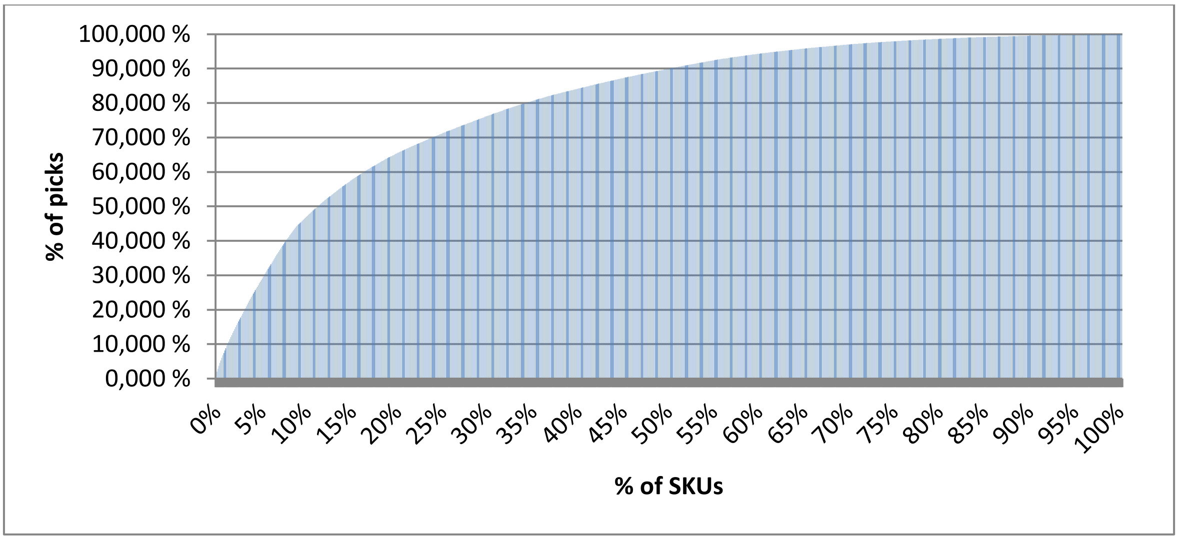

Figure 9. Demand distribution for SKUs heading to assembly.

When using AMPL to optimize the storage assignment for the parts going to assembly I get the following layout of the assignment for each class:

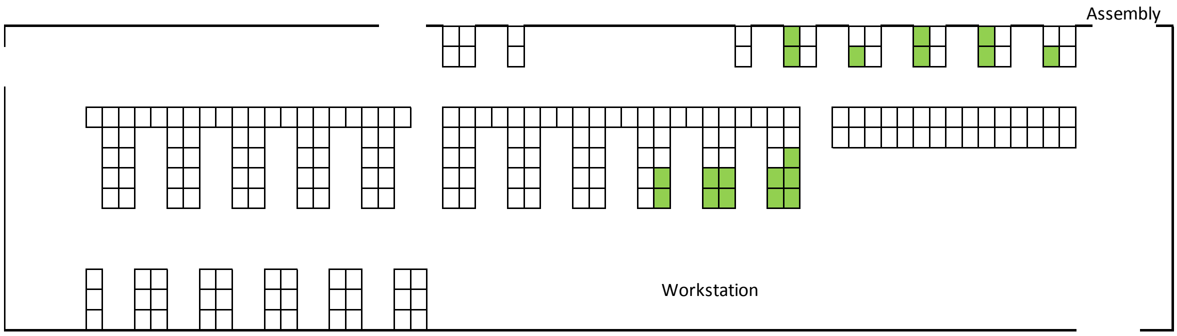

Figure 10. Optimal assignment of A-class

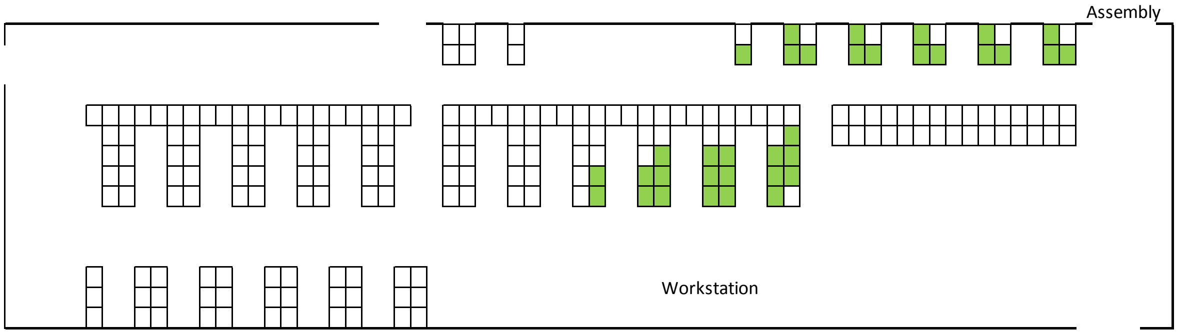

Figure 11. Optimal assignment of B-class

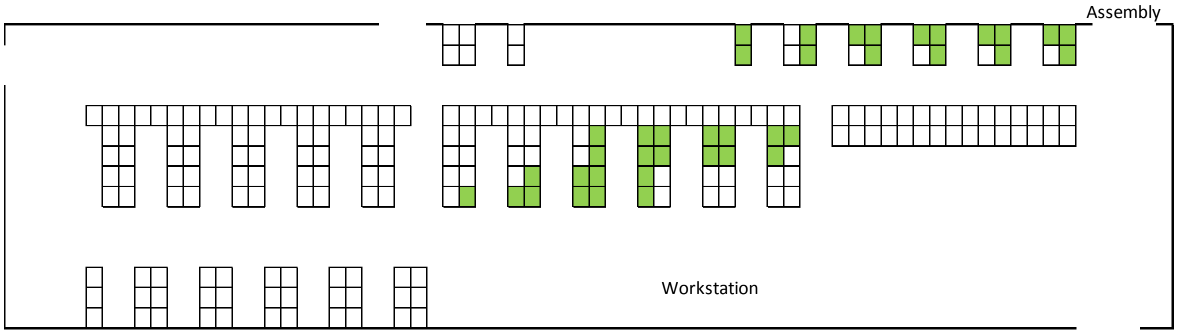

Figure 12. Optimal assignment of C-class

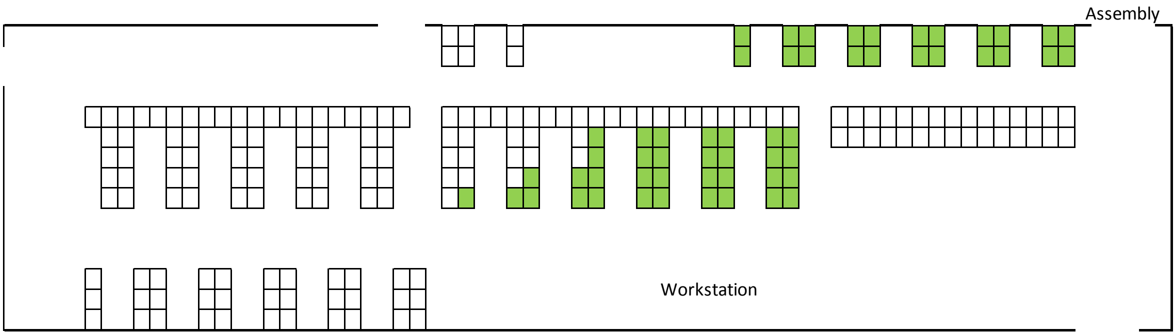

Figure 13. Optimal storage assignment of all SKUs heading for assembly

One can see that some classes are assigned to the same locations, this happens because the figures do not visualize how high in each rack the classes are assigned. Generally one can say that the ranking of heights in the rack, from low in rack to high in rack, are A-B-C. A detailed layout of the classes is given in Appendix B, Appendix C, and Appendix D.

When comparing this to the current storage locations, shown in Figure 14, one can see that the SKUs are in general located further away from both the assembly and the workstations. This explains some of the difference in travel distances (25.35%).

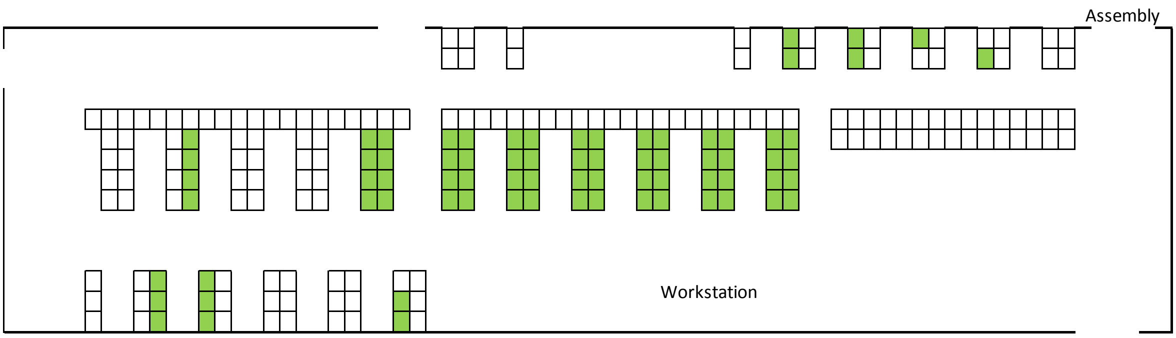

Figure 14. Current storage assignment for all SKUs heading for assembly

Interpreting the results from AMPL I observe that the storage assignment take a diagonal shape with respect to the workstation and the destination. This is the equivalent as Petersen and Schmenner (1999) found in their studies. They found that the diagonal storage policy was optimal when using return routing heuristic. It is noteworthy to mention that they found the across aisle storage policy method to be within 4% of the diagonal storage policy when using return routing heuristic. However, this study used depot and pickup point at the same location.

4.2.2.2 Analysis when including travel back to workstation

So far the analysis have only concerned the distances of the SKUs. If one observes the current travel pattern of the pickers, they travel back to the depot after storing a SKU in order to retrieve a new picking order. This means that the pickers travel back and forth to the SKUs a total of three times; one when storing it, one to get back to the workstation, and one to get to the SKU when it is time to pick it. When adding a triple multiplier to the distances between the workstation and the racks in order to correct for this I find the following storage assignment to be optimal for parts heading to assembly:

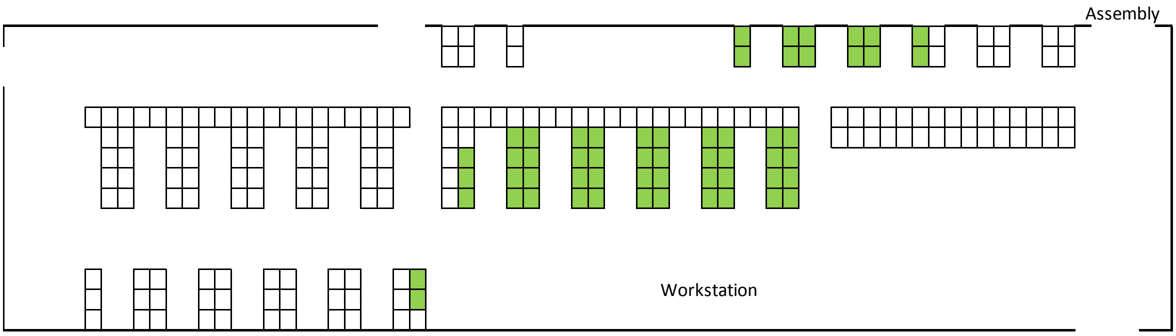

Figure 15. Optimal storage assignment for all SKUs heading to assembly, 3X multiplier to workstation.

The total distance traveled in the optimal model is 84441 meters, compared to the current situation of 110179 meters. A reduction of 23.36%.

This model clusters the SKUs closer to the depot and adopts the higher shelves to a greater extent.

4.2.2.3 Plausible storage assignment

So far in the analysis I have treated the SKUs coming from gate 6 (from external suppliers) and gate 27 (fabricated internally) as the same, entering the model at the workstation, for reasons mentioned earlier. A possible option for Brunvoll is to invest in equipment so that the pickers don't have to transport the SKUs retrieved at gate 27 back to the workstation in order to register it and print label. This can for instance be done by the PDAs they currently have, equipped with a portable label printer. By observing the data I find that of the 924 SKUs heading for assembly, 379 SKUs are coming from external suppliers through gate 6, and 545 are fabricated internally and collected at gate 27. Optimizing the model with this modification I find an optimized distance of 60432 meters, which is 25.63% less than the current situation and only 0.36% less than the model where all SKUs enter the model at the workstation. However, this model does not take into the account the distance from gate 27 to the workstation which in this latter case is not travelled. Whether this is a feasible method, or not, to handle the storage assignment will be left to the managers of Brunvoll to decide.

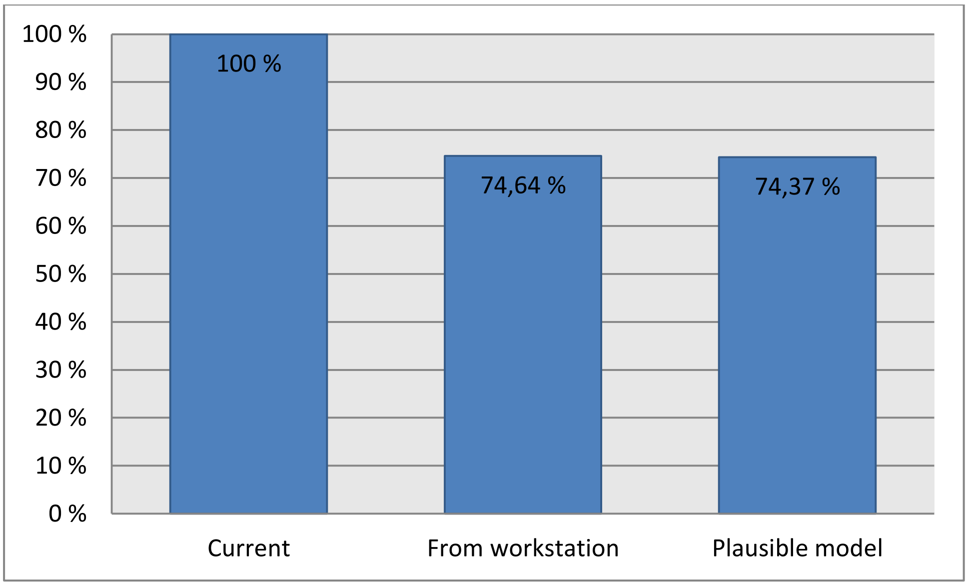

Figure 16. Comparison between the different alternatives for SKUs heading to assembly.

4.2.3 Analysis for all SKUs

When extending the analysis to include all SKUs heading for all destinations I start out by removing the shelves already occupied with SKUs heading for assembly in order to optimize the distances for SKUs heading to fabrication through gate 27. Then I repeat this process in order for optimize the remaining SKUs heading to fabrication through the gate to the new machining hall. The reason why I choose to assign SKUs heading for the new machining hall at the end is both because it is the smallest amount of SKUs and because the layout of the warehouse forces the pickers to travel through the whole warehouse in order to deliver SKUs there, and by that pass by all racks. I have excluded SKUs with destination back out to gate 6, as many of these SKUs are heading for service and are already assigned a storage location in one of the above mentioned destinations.
This model assumes the workstation as entry point for all SKUs.

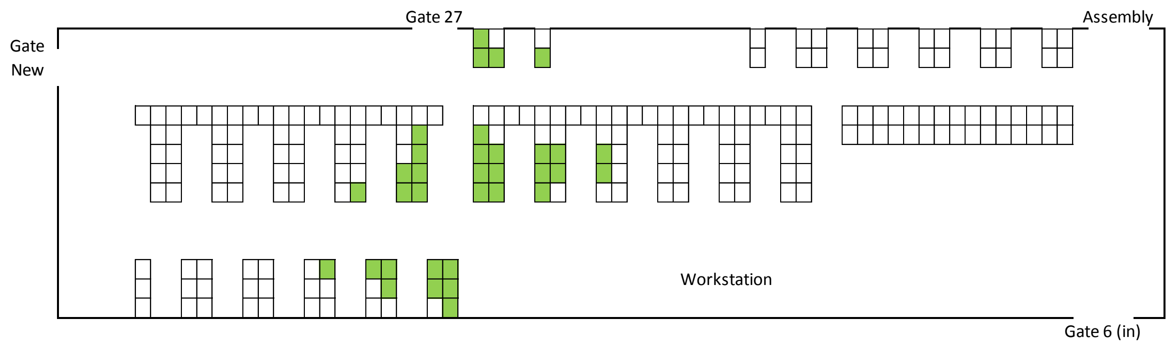

Figure 17. Optimal assignment for SKUs heading to gate 27

The optimal assignment for SKUs heading to gate 27 becomes 17313 meters, compared to the current 39373 meters (56.03%).

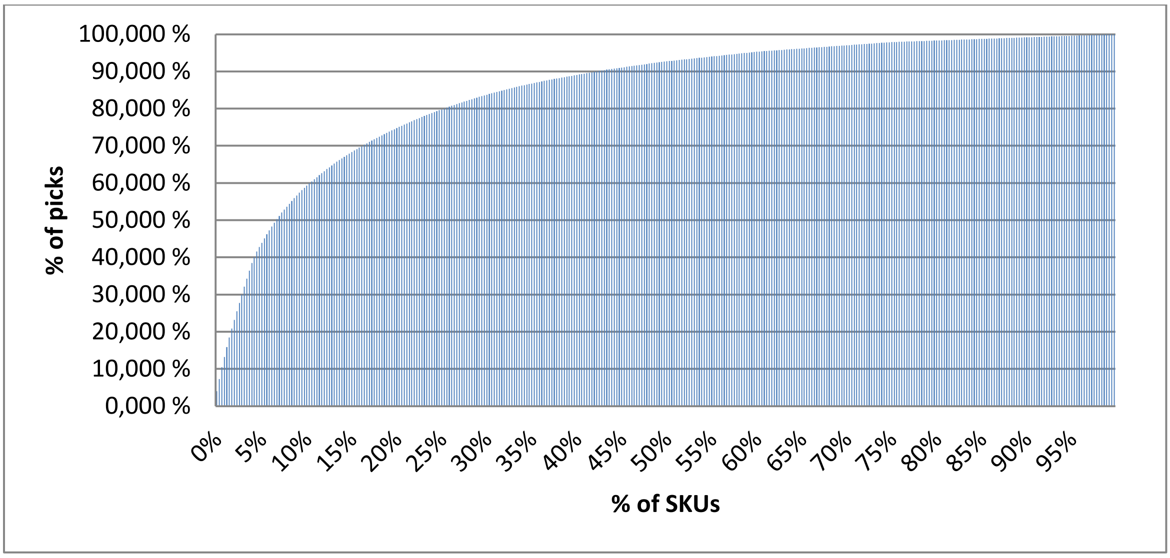

Figure 18. Demand distribution for SKUs heading for gate 27.

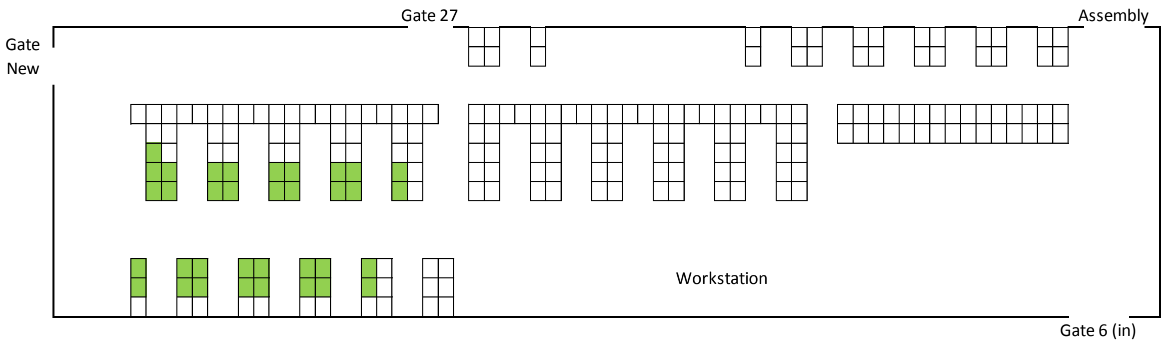

Figure 19. Optimal assignment for SKUs heading to new machine hall

Optimal assignment for SKUs heading for the new machining hall is 24101 meters, compared to the current 35096 meters (31.33%).

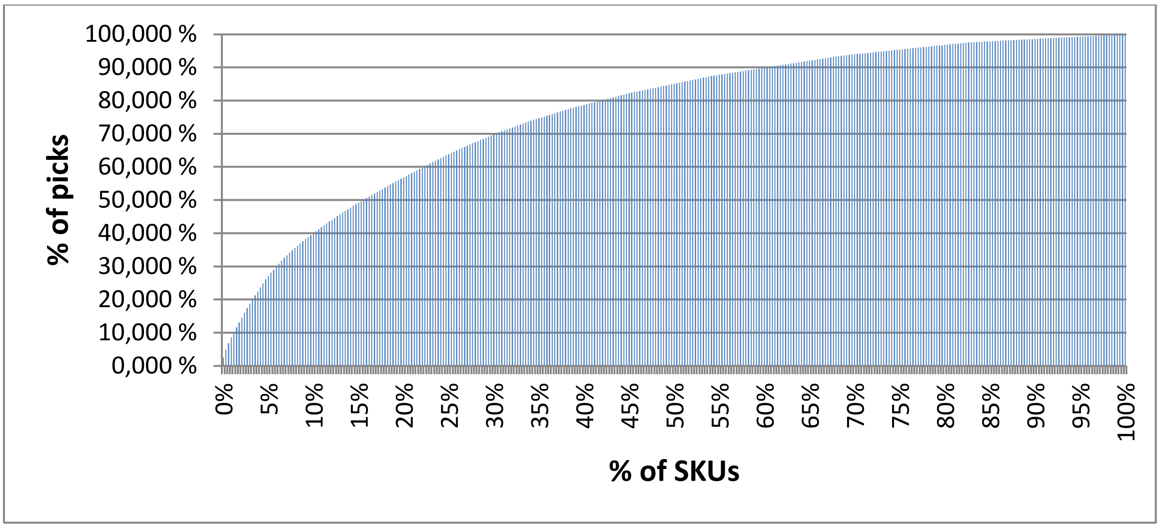

Figure 20. Demand distribution for SKUs heading to the new machining hall.

When adding these distances the total optimized distance become 102068, while observed current distance for the same SKUs are 155730. A difference of 34.46%; however, when looking into the current situation I observe that there are up to twice the amount of SKUs in some racks compared to what I allowed in the optimization model, due to small size/weight SKUs. So the possible reduction could be even higher.

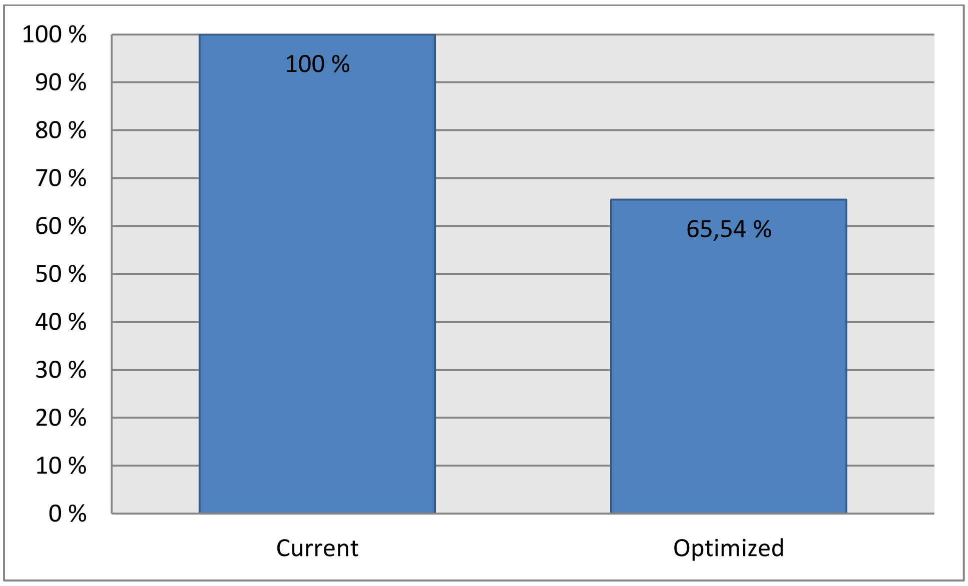

Figure 21. Comparison between current situation and optimized model.

4.2.4 Dedicated purposes

Some SKUs are more likely to be picked at the same picking order. But since one of the SKUs might be a component in several products this does not necessarily mean that they are in the same storage class. When using Affinity Analyzer (Bartholdi 2013) to check for relationships in picking orders for SKUs heading to each gate, I find that most of the times the SKUs are in the same storage class. However, there are some exceptions in the picking orders heading to assembly and gate 27. For SKUs heading to the new machine hall there are only 7 picking orders where the same SKUs reoccur during 2013, these are not analyzed because of the low amount. Outcome of the top pairs of SKUs that recur in the same picking orders for SKUs heading to assembly and gate 27 are given in Appendix F and Appendix G.

One could promote or demote a SKU to another storage class in order to be certain that the SKUs that recur on the same picking orders are stored close to another in order to reduce the distance travelled.

4.2.5 SKUs with zero demand

Brunvoll have a policy to provide spare parts for obsolete propulsion systems, in addition to current products, in order to have a very high level of service to their customers. This leads to storing numerous of SKUs, in all sizes, until it is requested.
In the data obtained from Brunvoll there are 2768 SKUs with zero demand in 2013 stored in the main warehouse, with an actual balance.
Comparing this to the 2687 SKUs with transaction in 2013 one see that 50.74% of the SKUs registered with a balance in the main warehouse has zero demand. These SKUs occupy a large amount of the warehouse, constraining the capacity and reducing the efficacy of the SKUs which actually are demanded. The inactive SKUs are stored in shelves around the warehouse, including some shelves with short distance to the workstation and in the storage elevators. In fact, 1952 of these SKUs are located in the storage

elevators. Making them more of a storage for obsolete parts, than the picking efficient storage for fast moving small parts that they are intended to be.

Brunvoll could, and should, relocate these SKUs to more remote areas of the warehouse in order to decrease handling time for the more frequent demanded SKUs, or consider the possibility to store these SKUs in another location in order to also free up space in the main warehouse.

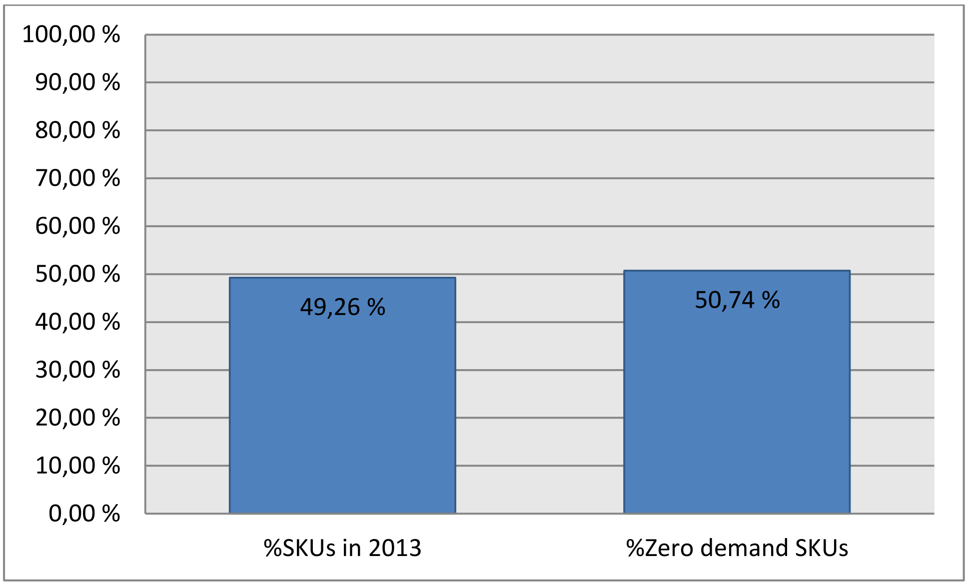

Figure 22. Comparison of SKUs with and without demand in 2013.

4.2.6 Other factors of implementation

A challenge with the implementation of CBS system compared to the current dedicated storage system would be the actual storing process. Now, the pickers get the storage location from M3 and in addition this is printed on the label when they register a SKU for storing. When using a CBS system the pickers will only get a storage class for the SKU. They then have to register the SKU, transport it to the zone, find an available shelf, place the SKU in the shelf, get back to the workstation and register in what shelf they stored the SKU. To improve this process a solution could be to use the PDAs available in a more extensive way than they are today for registering the storage location. If they also invest in some kind of portable printer for the labels, the pickers could transport the SKU directly to the storage location without stopping at the workstation for registering and printing. To make the use of PDAs as efficient as possible Brunvoll could also consider making an easier to use UI for the PDAs so that the pickers can register picking orders, incoming goods, and change storage location in a convenient way.

In this research I have used distance as a measurement for time. The reach-trucks do not have the same speed when moving vertically in the racks as they have when driving on along the floor. If one adds a penalty on the vertical distance moved in the racks, the optimal storage assignment would shift the high frequency SKUs lower down in the racks and widen the class area horizontally, while the less frequent C-class would shift higher up in the racks.

Since the three lowest shelves are available to pick by hand for the pickers, Brunvoll could consider storing as many of the smaller and lighter SKUs far down in the racks. This would then make the vertical penalty become effective for shelves above the three lowest.

5.0 Conclusion

When observing the current storage assignment, this is far from optimal. Brunvoll could achieve substantial reduction in travel distances by reassigning storage locations, using the current dedicated storage policy. However, this would not increase storage utilization. The suggested option is to change to a class based storage policy, where they will achieve a reduction in travel distances, compared to the current situation. This will in addition have increased storage utilization over the dedicated storage policy.
There are also potential disadvantages with the class based storage policy, namely the possibility of aisle congestion. However, with the routine of splitting tasks the pickers at Brunvoll have, this should not be an extensive issue.

There are potential of reducing travel distances by using the PDAs to a higher degree than today. If the pickers don't have to stop at the workstation in order to register SKU transactions and print labels, the SKUs could be transported directly from location to location.

There are observed a high amount of non-moving SKUs in the main warehouse. Many of these are stored in the storage elevators, and some at other central storage locations in the warehouse. By relocating these SKUs to more remote areas of the warehouse, Brunvoll would free up central storage locations for more frequently picked SKUs, and by that reduce total travel distance.

6.0 Limitations and further research

6.1 Limitations

Unit weight and size have an impact of where to store the product. Even if unit weight were available, there was no information about the size. Since weight and size is not considered in this research, the optimal assignment suggested might not be possible in practice. Also it might be possible to improve the optimal assignment by reduce the distances between shelves in some racks, and by that increase the capacity for smaller SKUs.

Without accurate distances, this research is only usable to measure percentage differences between scenarios. Also, distance is used as a measure for time. Vertical and horizontal speed might be different, this is not calculated in this thesis.

This research has been done without information about costs of products or any of the warehouse operating costs. This means that there are no actual savings to compute, only reductions in distance.

6.2 Further research

When writing this thesis I found some topics for further research. Average product turnover time at Brunvoll is quite high. A research of purchasing and replenishment routines, and acquiring of new parts for projects could reveal some of the reasons why this is. Also, a research of production planning and fabrication batch sizes could reveal some of the cause.

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8.0 Appendices

Appendix A. Approximate distances used to calculate and optimize storage locations. “Depth” describes horizontal distance and “Shelf” describes vertical distance within each rack.

	Rack	From workstation	To assembly	To gate 27	To gate new	To gate 6
	AD10	33	45	5	30	55
Depth = 2	AD11	38	40	10	35	50
Height = 6	AD13	28	30	20	45	40
	AD14	23	25	25	50	35
	AD15	28	20	30	55	30
	AD16	33	15	35	60	25
	AD17	38	10	40	65	20
	AD18	43	5	45	70	15
	AD21	45	90	40	10	80
	AD22	40	85	35	22	75
	AD23	40	85	35	22	75
	AD24	35	80	30	27	70
	AD25	35	80	30	27	70
	AD26	30	75	25	32	65
	AD27	30	75	25	32	65
Depth = 4	AD28	25	70	20	37	60
Height = 6	AD29	25	70	20	37	60
	AD30	20	65	10	42	55
	AD31	20	65	10	42	55
	AD32	15	60	20	47	50
	AD33	15	60	20	47	50
	AD34	10	55	25	52	45
	AD35	10	55	25	52	45
	AD36	5	50	30	57	40
	AD37	5	50	30	57	40
	AD38	0	45	35	62	35
	AD39	0	45	35	62	35
	AD40	5	40	40	67	30
	AD41	5	40	40	67	30
	AD42	10	30	45	72	20
	AD53	42	87	38	20	77
	AD54	42	87	38	20	77
	AD55	37	82	33	25	72
	AD56	37	82	33	25	72
Depth = 3	AD57	32	77	28	30	67
Height = 4	AD58	32	77	28	30	67
	AD59	27	72	23	35	62
	AD60	27	72	23	35	62
	AD61	22	67	18	40	57
	AD62	22	67	18	40	57
	AD63	17	62	18	45	52

Depth	
01	2
02	5
03	8
04	11

Shelf	
01	0
02	1
03	2
04	3
05	4
06	5

Appendix B. Optimal storage locations for A-class items heading to assembly.

A-class

AD140101	AD390103
AD140102	AD390104
AD140103	AD390105
AD140104	AD390201
AD150101	AD390202
AD150102	AD400101
AD150103	AD400102
AD150104	AD400103
AD160101	AD400104
AD160102	AD400105
AD160103	AD400201
AD160104	AD400202
AD160201	AD410101
AD170101	AD410102
AD170102	AD410103
AD170103	AD410104
AD170104	AD410105
AD170201	AD410201
AD180101	AD410202
AD180102	AD420101
AD180103	AD420102
AD180104	AD420103
AD380101	AD420104
AD380102	AD420105
AD380103	AD420106
AD380104	AD420201
AD380105	AD420202
AD380201	AD420203
AD380202	AD420204
AD390101	AD420301
AD390102	AD420302

Appendix C. Optimal storage locations for B-class items heading to assembly.

B-class

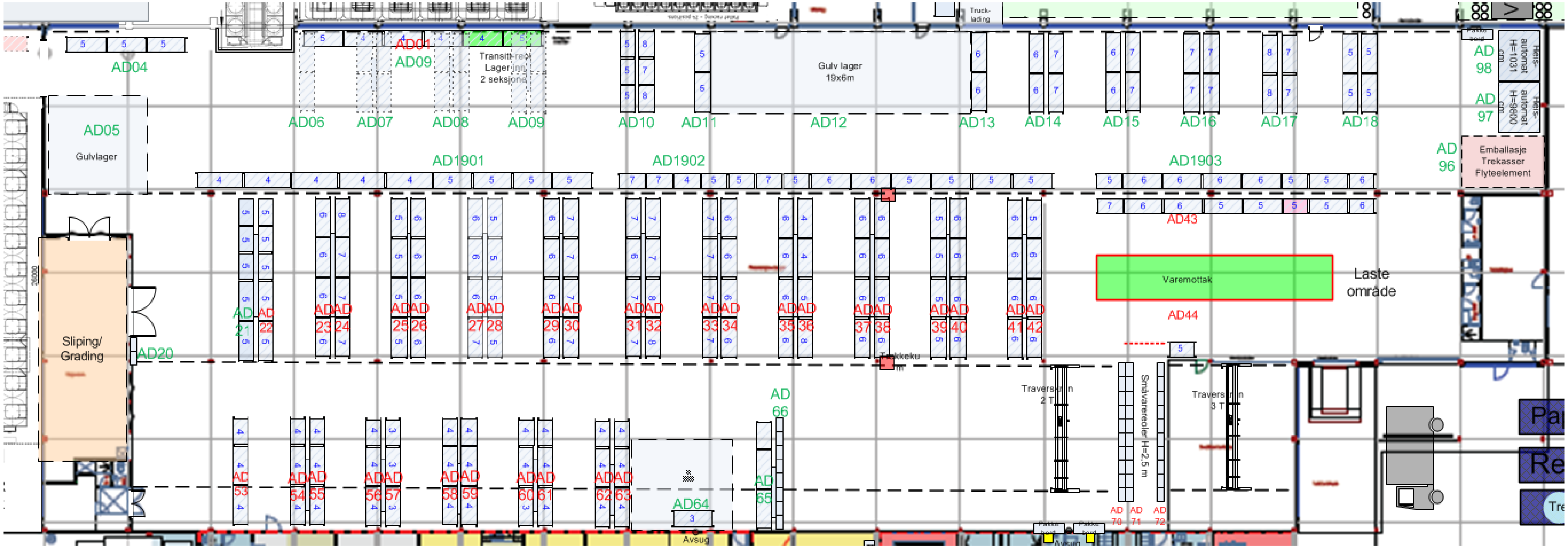
AD130101	AD170204	AD390203
AD130102	AD170205	AD390204
AD130103	AD170301	AD390205
AD140105	AD170302	AD390206
AD140106	AD180105	AD390301
AD140201	AD180106	AD390302
AD140202	AD180201	AD390303
AD140203	AD180202	AD400106
AD140204	AD180203	AD400203
AD140205	AD180204	AD400204
AD140301	AD180205	AD400205
AD140302	AD180301	AD400206
AD150105	AD180302	AD400301
AD150106	AD360101	AD400302
AD150201	AD360102	AD400303
AD150202	AD360103	AD410106
AD150203	AD360104	AD410203
AD150204	AD360201	AD410204
AD150205	AD370101	AD410205
AD150301	AD370102	AD410206
AD150302	AD370103	AD410301
AD160105	AD370104	AD410302
AD160106	AD370201	AD410303
AD160202	AD370202	AD420205
AD160203	AD380106	AD420206
AD160204	AD380203	AD420303
AD160205	AD380204	AD420304
AD160301	AD380205	AD420305
AD160302	AD380206	AD420306
AD170105	AD380301	AD420401
AD170106	AD380302	AD420402
AD170202	AD380303	AD420403
AD170203	AD390106	

Appendix D. Optimal storage locations for C-class items heading to assembly.

C-class

AD130104	AD170305	AD360204	AD400306
AD130105	AD170306	AD360205	AD400401
AD130106	AD170401	AD360206	AD400402
AD130201	AD170402	AD360301	AD400403
AD130202	AD170403	AD360302	AD400404
AD130203	AD170404	AD360303	AD400405
AD130204	AD170405	AD360304	AD400406
AD130205	AD170406	AD360305	AD410304
AD130206	AD180206	AD360401	AD410305
AD140206	AD180303	AD360402	AD410306
AD140303	AD180304	AD370105	AD410401
AD140304	AD180305	AD370106	AD410402
AD140305	AD180306	AD370203	AD410403
AD140306	AD180401	AD370204	AD410404
AD140401	AD180402	AD370205	AD410405
AD140402	AD180403	AD370206	AD410406
AD140403	AD180404	AD370301	AD420404
AD140404	AD180405	AD370302	AD420405
AD140405	AD180406	AD370303	AD420406
AD140406	AD320101	AD370304	
AD150206	AD330101	AD370305	
AD150303	AD340101	AD370401	
AD150304	AD340102	AD370402	
AD150305	AD340103	AD380304	
AD150306	AD340104	AD380305	
AD150401	AD340105	AD380306	
AD150402	AD340106	AD380401	
AD150403	AD340201	AD380402	
AD150404	AD340202	AD380403	
AD150405	AD340203	AD380404	
AD160206	AD350101	AD380405	
AD160303	AD350102	AD380406	
AD160304	AD350103	AD390304	
AD160305	AD350104	AD390305	
AD160306	AD350105	AD390306	
AD160401	AD350106	AD390401	
AD160402	AD350201	AD390402	
AD160403	AD350202	AD390403	
AD160404	AD350203	AD390404	
AD160405	AD360105	AD390405	
AD170206	AD360106	AD390406	
AD170303	AD360202	AD400304	
AD170304	AD360203	AD400305	

Appendix E. Layout of Brunvoll's main warehouse



Appendix F. Top SKUs heading to assembly that recur on the same picking order.

SKU 1	SKU 2	#-containing orders	#-completing orders	%-order-completions	Class	
000029	016774	107	94	88	A	A
006266	006374	97	86	89	A	A
015276	033805	40	40	100	A	A
019916	032081	31	24	77	A	A
035230	035231	31	24	77	A	A
014108	031440	28	8	29	B	B
034820	034821	25	21	84	B	B
005512	034849	24	24	100	B	B
027768	035445	23	20	87	B	B
039337	039338	23	2	9	B	B
039336	039338	21	0	0	B	B
039336	039337	21	0	0	B	B
039334	039335	20	3	15	B	B
000029	014535	18	17	94	A	B
040476	040477	18	1	6	B	B
027767	035528	17	17	100	B	B
005366	006445	17	16	94	A	A
039335	039811	16	0	0	B	B
039977	039978	16	16	100	B	B
031440	040477	16	0	0	B	B
031440	040476	16	0	0	B	B
039343	039811	16	1	6	B	B
014108	040476	16	0	0	B	B
014108	040477	16	0	0	B	B
033806	033808	15	11	73	B	B
039334	039811	15	0	0	B	B
002316	003890	15	11	73	A	A
039335	039343	15	0	0	B	B
039334	039343	14	0	0	B	B
019424	026399	14	13	93	A	B
000078	002250	13	10	77	A	A
007609	031442	13	4	31	B	A
006266	016774	12	0	0	A	A
000029	006266	12	0	0	A	A
000029	006374	11	0	0	A	A
006374	016774	11	0	0	A	A
016101	035078	11	11	100	A	C
038296	038302	10	10	100	B	B
015277	015995	9	4	44	A	A
004901	006268	9	8	89	A	A
006271	027386	9	8	89	A	B

031442	036237	9	0	0	A	B
007609	036237	9	0	0	B	B
036577	036578	9	9	100	C	C
040402	040403	9	9	100	C	C
006380	006383	8	4	50	A	A
019373	019861	8	2	25	B	B
015284	019832	8	4	50	A	A
003887	030260	8	5	63	A	A
031394	036369	8	5	63	A	B
021449	021450	7	7	100	A	A
004569	006380	7	4	57	A	A
015234	015235	7	6	86	A	A
023024	027769	7	6	86	A	B
015284	032081	7	0	0	A	A
012927	030284	7	7	100	B	B
019374	019861	7	1	14	B	B
015284	019916	7	0	0	A	A
004901	006266	6	1	17	A	A
027934	027944	6	6	100	B	B
000045	019834	6	1	17	A	A
019373	019374	6	0	0	B	B
019836	019838	6	0	0	A	A
006410	018012	5	4	80	B	B
028989	031446	5	3	60	C	B
015277	015994	5	0	0	A	A
035023	035025	5	5	100	C	C
019883	019914	5	5	100	A	A
015994	015995	5	0	0	A	A
019542	019838	5	0	0	A	A
019542	019836	5	0	0	A	A
000029	004901	5	0	0	A	A
019560	027484	5	0	0	A	A
040328	040517	5	4	80	B	B
002316	006503	5	0	0	A	A
017613	019560	5	0	0	A	A
038076	038095	5	2	40	C	C
006270	035231	5	0	0	A	A
006270	035230	5	0	0	A	A
017605	030708	5	4	80	A	B

Appendix G. Top SKUs heading to gate27 that recur on the same picking order

SKU 1	SKU 2	#-containing orders	#-completing orders	%-order-completions	Class	
035965	035967	16	4	25	A	A
035965	035966	12	0	0	A	B
035966	035967	12	0	0	B	A
035963	035964	10	10	100	B	A
039981	039982	9	9	100	A	B
100298	100300	6	2	33	B	B
100302	100303	6	2	33	B	B
039215	039216	5	2	40	B	B
038672	038673	5	5	100	B	B
100300	100301	4	0	0	B	B
100298	100301	4	0	0	B	B
039994	039996	4	1	25	B	B
039994	039995	4	0	0	B	B
100297	100303	4	0	0	B	B
100297	100302	4	0	0	B	B
039214	039215	3	0	0	B	B
039214	039216	3	0	0	B	B
038691	038692	3	3	100	A	A
035450	035452	3	0	0	C	B
039995	039997	3	0	0	B	B
039995	039996	3	0	0	B	B
038695	038696	3	3	100	A	A
026139	027435	3	3	100	A	A
035447	035450	3	0	0	C	C
035447	035452	3	0	0	C	B
040543	040544	3	3	100	B	B
039994	039997	3	0	0	B	B
042022	042023	2	2	100	C	C
035446	035449	2	1	50	B	B
039215	039220	2	0	0	B	B
039510	039511	2	2	100	C	C
041270	041271	2	2	100	C	C
101269	101270	2	1	50	C	C
039996	039997	2	0	0	B	B
039216	039220	2	0	0	B	B
039214	039220	2	0	0	B	B
037179	037180	2	2	100	C	C
035964	102016	2	2	100	A	C