Specialization: Production Engineering and Logistics

Report number: 2013.PEL.7785

Title: Warehouse design: The storage location assignment problem

Author: Jasper van Dooijeweert

Title (in Dutch) Het toekennen van opslagruimte in een magazijn

Assignment: literature

Confidential: no

Supervisor: prof.dr.ir. H.P.M. Veeke

Date: June 14, 2013

This report consists of 31 pages. It may only be reproduced literally and as a whole. For commercial purposes only with written authorization of Delft University of Technology. Requests for consult are only taken into consideration under the condition that the applicant denies all legal rights on liabilities concerning the contents of the advice.
In this literature assignment the design process of a warehouse will be modeled using DSA. Using this model an overview will be given of the various factors that influence the storage location assignment policy selection.
Preface

This literature assignment has been written as part of the master study Mechanical Engineering at the TU Delft.

At the age of 16 I started working as a picker in the warehouse of a large pharmaceutical company, during the job I gained a lot of experience as a picker. Long walks, or arriving at your designated destination just to find an empty shelf where all part of the job.

Almost a decade later I was reading an article on Amazon’s warehouses and it caught my attention. This warehouse was nothing like the one in which I had worked: product where placed inside the storage at random. Why would Amazon choose for strategy like this? I decided to investigate. Two months later the literature research you are reading now is the result of this research.

An Amazon warehouse near Milton Keynes

14 June 2013
Jasper van Dooijeweert
Master student Mechanical Engineering: Production Engineering and Logistics, TU Delft
Summary

Warehouses are a vital part in today’s supply chain because of the increasing need for short lead times and the wide variety of products. 60% of all warehouse costs are caused by the picking process, to lower these costs a lot of research has been done which can be divided into three general design problems: (1) routing policies: finding the optimal route to travel, (2) batching policies: which items to batch into a single pick order and (3) storage assignment policies: how to assign items that need to be stored to a free warehouse locations.

Of these three design problems the storage assignment policy has the biggest influence on the warehouse performance. Although there can be found a lot of literature on the subject of storage assignment policies, there is very little literature to be found on the role of the storage assignment policy in the overall warehouse design process. Most literature on the subject deals with comparing two or more policies in very specific cases. The goal of this literature assignment is to research what role the storage assignment policy plays in the designing of warehouses and more importantly how related design problems influence the choice for the optimal storage assignment policy. Using the Delft Systems Approach a model was made which shows what factors influence the storage assignment policy selection. This is based on literature that can be found on the subject of designing warehouses and storage assignment policies.

Storage is expensive and this is why a lot of companies try to minimize the use of storage throughout the production process. The production and assembly process can be divided into three zones: the input, transformation and output zone. In each of these zones storage fulfils a different function and thus has its own unique characteristics.

After zooming into the actual storage process we can see that this process is actually made up out of various processes: Products are first received and brought to the receive area of the warehouse, here inspection takes place and product information is entered into the warehouse management system. After the item is prepared for storage (packing) there needs to be decided where to store the item. To assign the optimal location to the item the storage assignment can be modelled as a vector assignment problem (VAP), but a VAP cannot be solved for large instances so a different approach is needed, the use of a storage assignment policy.

Storage assignment policies can be divided into three categories: (1) random storage, (2) dedicated storage and (3) class-based storage policies. With random storage all products are in a single class, in a dedicated storage policy all products have their own separate class and with class-based storage groups of products get assigned to a certain class. Each class then gets assigned to a dedicated area of the warehouse. The biggest advantage of a random storage policy is that locations are not reserved for a certain type of product, because of this space utilization can be very high compared to other policies. The biggest downside of a random storage policy is that no optimization of the storage location is possible, compared to other policies the operational costs (picking) are often higher. Although space utilization is low when using a dedicated storage policy, optimization of the storage locations is possible lowering operational costs by lowering the average travel time. A popular
dedicated policy is the one based on the cube per order index algorithm. This algorithm gives the most popular products with the smallest space requirements the best locations in the warehouse.

Class based storage policies can be divided into two categories. The first type of class based storage policies are those based on product characteristics. As with the dedicated policy, the COI, algorithm is often used. Another common policy is using Pareto’s law to divide products into three different classes. The second type of class based policies are policies based on the item characteristics. A policy based on item characteristics is the duration of stay (DOS) policy, for a balanced warehouse this policy gives optimal performance.

Designing warehouses is a highly complex process. This design process was modeled and using this model it was shown how the requirements, performance indicators, order flow, product flow and resource flow influence the decision for the right storage assignment policy.

As a conclusion one can say that a dedicated policy is optimal if operating costs are the most important, for warehouse where storage costs are the most important factor a random policy should be used. If both operating as well as storage costs are important a class based policy should be picked. However, this is just a rough guideline that can be influenced by many factors. After the initial selection of a storage location assignment policy simulation should always be used to check the feasibility of the design choices and time-depended behavior.

List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS/RS</td>
<td>Automated storage and retrieval system</td>
</tr>
<tr>
<td>COI</td>
<td>Cube per order index</td>
</tr>
<tr>
<td>DOS</td>
<td>Duration of stay</td>
</tr>
<tr>
<td>KPI</td>
<td>Key performance indicator</td>
</tr>
<tr>
<td>ROI</td>
<td>Return of investment</td>
</tr>
<tr>
<td>SKU</td>
<td>Stock keeping unit</td>
</tr>
<tr>
<td>SLAP</td>
<td>Storage location assignment problem</td>
</tr>
</tbody>
</table>
# Table of contents

Preface ................................................................................................................... iii
Summary .................................................................................................................. iv
List of abbreviations ............................................................................................... v

1. Introduction ....................................................................................................... 1-1
   1.1 Storage assignment policy ......................................................................... 1-2
   1.2 Problem definition ...................................................................................... 1-3
   1.3 Constraints .................................................................................................. 1-3
   1.4 Structure of the report ............................................................................... 1-3

2. Introduction to warehouses ............................................................................... 2-4
   2.1 Use for storage in a production/assembly company .................................. 2-4
   2.2 Storing and picking goods ......................................................................... 2-7
   2.3 Forward and reserve area .......................................................................... 2-9
   2.4 The location assignment problem .............................................................. 2-10

3. Storage assignment policies ............................................................................. 3-12
   3.1 Randomized storage .................................................................................. 3-12
   3.2 Dedicated storage ....................................................................................... 3-14
   3.3 Class based storage .................................................................................... 3-15
   3.4 Other policies ............................................................................................. 3-17

4. Developing the storage assignment policy ....................................................... 4-18
   4.1 The warehouse design process ................................................................... 4-18
   4.2 Factors influencing storage assignment policy choice ............................. 4-20

5. Conclusion ......................................................................................................... 5-24

References ............................................................................................................. 5-25
1. Introduction

The world around us is quickly changing, more and more traditional companies need to compete with online competitors. E-commerce has grown enormously in the last decade, and this growth won’t stop anytime soon. Online customers expect products to arrive the next day and want to be able to choose from a wide variety of products. Because of this short lead times and a large product inventory have become more important, putting an enormous amount of pressure on today’s supply chain.

According to a study done in 2004 the capital and operating costs of a warehouse take up to 25% of the total logistics costs (ELA & Kearney, 2004). One would expect that a lot of research has been done on how to design a warehouse, particularly since warehousing costs are to a large extent determined at the design phase (Rouwenhorst et al., 2000). However, conclusions that can be drawn from literature show something different:

- There is a wealth of material written on analyzing particular aspects of warehouse design, such as layout, order picking policies and equipment choice. It is the synthesis of these techniques that appears to be lacking to act as a basis for the overall warehouse design (Rouwenhorst et al., 2000).
- A comprehensive, modeling based engineering methodology for warehouse design does not yet appear to exist (Marc Goetschalckx, 2012).
- Terms such as “eye-ball the data”, and “makes some initial design decisions based on intuition, experience and judgment” are typical of the (warehouse design) process described (Baker & Canessa, 2009).

And the list of research papers that conclude something similar goes on. While there has been done a lot of research in the area of warehousing, almost all of these studies have been done in very specific areas. This doesn’t provide warehouse designers with a tool or model they can use to design a warehouse from scratch. On the other hand, books on the subject for example by Manzini and Goetschalckx (2012) or ten Hompel and Schmidt (2006) tend to handle the subject of designing warehouses in very a broad way. As a result the reader gets a general idea on what factors play a role in designing warehouses, but it is hard to put this knowledge into practice.

![Figure 1: Warehouse costs per activity](image)
A research done by Van den Berg and Zijm (1999) shows that over 60% of the costs a warehouse makes are caused by the picking activity (Figure 1: Warehouse costs per activity). Three different operating policies determine the operational efficiency of the order picking process:

1. Routing – Routing deals with the optimal route a picker should take from location to location.
2. Batching – Batching policies determine which orders should be combined into one single picking route.
3. Storage assignment – The storage assignment policy is used to determine how to assign goods to a storage location.

Of these three operating policies, the storage assignment policy has the biggest influence on the picking performance (Chan & Chan, 2011).

1.1 Storage assignment policy

A storage assignment policy is used to determine where to store an item inside the warehouse. Warehouse storage assignment influences almost all key performance indicators of a warehouse such as order picking time and cost, productivity, shipping and inventory accuracy and storage density (Frazelle, 2002). This is why the choice of storage assignment policy is one of the major decisions that need to be made during the design process of a warehouse. There has been done a lot of research in the area of storage assignment policies. When looking at the various studies done in this area something similar can be concluded as seen in the general research of warehouses as stated above. Some examples:

- Particularly, the areas of storage assignment and routing appear to have matured the last decade. Few authors address combinations of the decision problems. Yet, this is necessary as there is obvious interdependency in their impact on the order picking objectives (de Koster, Le-Duc, & Roodbergen, 2007).
- An important part of this step (determine assignment policies) is the decision as to the zones into which the warehouse should be divided (zones for different product groups or Pareto classifications). Again, this appears to be left to the experience of the warehouse designer. (Baker & Canessa, 2009)
1.2 Problem definition

We can conclude that while the storage assignment policy is one of the major factors that determines the costs of storage, at the moment there is a lack of a clear method that describes how to select the optimal storage assignment policy during warehouse design.

In this literature study the various factors that influence the storage assignment policy selection will be researched. By using the Delft Systems Approach (Veeke, Ottjes, & Lodewijks, 2008) a model will be developed that shows how these factors relate to the storage assignment policy.

1.3 Constraints

To cut costs and decrease delivery times new forms of warehouses have become popular in the last few decades. For these warehouses, of which the most popular ones are called distribution centers or cross docks, the primary function has shifted from storing goods to transshipment. This is, the combining of loads, dividing loads into smaller loads or change off transport modality. In this literature study the focus will be on the actual storage, this is why the focus will be on the more traditional warehouses that have storage as their primary function.

One can divide warehouses into public and private warehouses. Private warehouses are warehouses that are owned by the company. There are many advantages of using a private warehouse, they offer a higher degree of flexibility and control compared to public warehouses, and the stock-keeping costs are lower. A downside is that a private warehouse needs a huge capital investment. In a public warehouse space is rented, although there is no need for an initial capital investment, flexibility is limited and stock-keeping costs are higher compared to that off a private warehouse. In this literature research we will only focus on private warehouses.

One of the most common private warehouses that are used for storage are those found in a production and assembly company, for example a bicycle factory. The various factors that influence the decision for the storage assignment policy in such a company will be researched in this literature research.

1.4 Structure of the report

This literature assignment starts with a general introduction to warehouses. In the first part of chapter two one can read why although storage is expensive, it is sometimes necessary. In the second part of chapter two it is described how storage costs are to a large extend influenced by the location on which products are stored. Chapter two ends with an introduction to the storage assignment policy that is used to determine storage locations. In chapter three various storage assignment policies are discussed. Chapter four starts with an introduction to design process of a warehouse, after which the role of the storage assignment policy within this process will be modeled. The conclusion can be read in chapter five.
2. Introduction to warehouses

This chapter starts with a general introduction in the world of warehousing. In the first part of this chapter one can read while warehouse cost a lot, they are sometimes necessary. In the second part of this chapter the use of the storage assignment policy will be explained.

Storage is expensive, as said in the introduction storage makes up 25% of the total logistical costs. This is caused by the following:

- **Capital**: storage takes up a lot of space and thus increases the need for bigger buildings.
- **Administration**: To prevent goods from getting lost inside the storage the products need to be tracked. While there a lot of different automated systems available on the market that make administration easier, it still costs manpower and investments to develop and maintain these systems.
- **Loss of value**: There is a risk involved with having lots of products inside the inventory, what if the demand for the product suddenly goes down? There are also a lot of goods like food or flowers that deteriorate over time. Keeping items like this in storage for too long, can make them loose their value.
- **Labor**: Putting goods inside the storage and removing them from storage requires a lot of manual or automated labor.
- **Protection**: Products in storage need to be protected against theft, but also against damage that can occur during the handling of the goods by equipment or personnel. This is why a lot of products need to be packed before they can be put into storage.

Storage of goods also increases the throughput time making it difficult to trace back and fix problems that occurs during the production process.

In theory the high costs and non-value-adding times are good reasons to keep storage to a minimum, this is why in production practices like lean manufacturing heavily focus on removing storage wherever possible. However in practice there are various reasons to store goods, in the next part of this chapter it will become clear why storage is sometimes beneficial or even necessary.

2.1 Use for storage in a production/assembly company

A basic production/assemble company can be modeled as followed: Some products (raw materials or partly finished goods) enter the company, during the transformation process value is added, after which the product can be sold to either businesses (B2B) or customers (B2C). During the primary process, one can distinct three different kinds of buffers; one in the input zone, one in the transformation zone and one in the output zone.
Using the Delft Systems approach (Veeke et al., 2008) a steady state model of a production company has been made, the model can be seen in Figure 2. Using this model the benefits of having buffers throughout the process becomes clear.

**Input zone buffer**

All production companies have some sort of input. This can be in the form of raw materials like wood or iron ore, but also in the form of partly finished goods. There are various reasons to use storage in the input zone:

- Certain raw materials are only available during specific parts of the year. This is mostly the case for plants that are harvested once a year like sugar beets or Maize. After the harvest large quantities need to be stored to have a supply during the rest of the year.
- Make use of economics of scale. Sometimes it is possible to get a discount when ordering large quantities, because of this it can be a smart move to order more than needed and store the surplus until it is needed. This can also be the case for transport costs, it is smarter to order a full truckload of something that a partly filled truck.
- Most production/assembly companies produce just-in-time to keep stock levels to a minimum. Because of this the whole production process is highly sensible to disturbances (for example a supplier that doesn't deliver on time). In some cases it might be wise to have a small buffer to handle these disturbances.
- Make use of low prices or discounts. Prices of raw materials fluctuate throughout the year. Economically it can be smart to buy large quantities of certain products if prizes are lower than normal and the discount out weighs the costs of storage.
- When the product arrives at the company, it almost always has to be inspected. How is the quality of the delivered product? And is the quantity as ordered? The capacity of the inspection might be limited, causing arrived products to wait before they can be inspected. If something is found wrong, the products also need to be stored somewhere before the problem can be solved.
Transformation buffer

Most transformation processes are made up out of a combination of different transformation processes. In general one can distinct two types of processes: fabricating parts and assembling these parts. There are various reasons to use storage during the transformation process:

- In some cases just storing the product can increase its value. This is true for products that need to mature during storage (plants).
- Economics of scale. During many transformation processes machines are used. To spread out the setup costs of these machines across products it can be a smart decision to create more products than are needed and store these products for later use.
- While manufacturers try to minimize production problems using popular methodologies like six sigma, problems can occur during production. Buffers are a simple way to prevent problems from causing the entire production line to stop.
- In an ideal situation a company would start manufacturing and assembling the product once it has received an order, this way no storage is needed and there is no chance that the product won’t be sold after it has been produced. However, this is not always possible since the whole production/assembly process might take longer than the customer wants to wait for its product. A solution for this is to move the Customer order decoupling point (Visser & Goor, 1994) further away from the customer. A part of the product is made in advance and stored, once a customer orders the products the partly finished product is taken out of storage and finished the way the customer has ordered. In a bicycle factory this could mean that the frame is produced in advance and when the customer orders a bike the frame is finished as ordered (painting, tires, gear, etc.).

Output buffer

When products leave the transformation zone they enter the output zone. In this zone there are various reason to add a buffer.

- Some customers might order multiple products. By waiting for all the products to be produced, they can all be shipped at the same time saving transportation costs.
- To cope with unexpected demand, products can be produced for stock so the company never has to do any backlogging, or worse loses customers.

As seen in the section above, storage can occur for various reasons. All buffers fulfill a different function. Chapter 4 shows what kind of effect these various functions have on the way the storage is designed.
2.2 Storing and picking goods

When zooming in onto one of the buffers, for example the input buffer as seen in Figure 2, the following model can be made:

![Figure 3: buffer model zoom](image)

**Receive**
Goods are unloaded from their transportation modality and delivered to the receiving area of the warehouse. The transportation document is handed over and compared to what was ordered. The rate of return for products sold using mail-order trade can be up to 30% (ten Hompel & Schmidt, 2006). These returned products are processed during this step as well.

**Inspection**
After the goods arrive at the receiving area they are often inspected. During this inspection the quality and quantity is compared to certain norms. This quality control is mostly done using random checks or might be skipped at all. Inspection can be done by a visual check or for example a laboratory test. In case of new products the specifications (weight, size, etc.) need to be determined and entered into the warehouse software so this information can be used throughout the process. For other goods, like perishable goods, other information like the expiry date needs to be entered into the system.

**Prepare**
At the beginning of each logistical chain, products are packed to prevent them from being damaged during transport, storage or transhipment. This packaging also fulfils other functions like protecting employees if the product is hazardous and making it easy to recognize the product just by looking at the package material. During the preparation these packed goods are often combined into a logistical unit. These logistical units are used to handle large quantities of products in the most optimal way.
Figure 4 shows an often seen logistical unit. Single articles are stored into a box. Multiple boxes are stored into a single container. Multiple containers are then stored on a pallet allowing for efficient storage and handling using a forklift truck.

**Store**
After the inspection and preparation the product is ready to be put into storage. First the backlog of the transformation process is checked, the product might be needed right away so storage isn’t needed and it can be moved to the transformation process right away.
If the product is not needed right away it can be put into storage. First a location needs to be assigned to the product as well as a resource that actually puts it into storage. This could be personnel, an automated system, or for example a forklift truck with driver. The product is moved to the right location. When the product has arrived at the right location there often is a check to make sure the product is placed in the right location (for example by scanning the barcode on the product and scanning the barcode of the location).

**Storage**
The product is in storage.

**Order picking**
When the product is needed again it has to be taken outside of storage. This part to a large extend determines the costs associated with storing products into a warehouse. The costs are determined by the location of the product, the route the picker takes to get to the product and the order picking strategy. All three of these factors have been subject to a lot of research in the last few decades. Both the routing and order picking optimizations are outside the scope of this literature research.
2.3 forward and reserve area

One of the most popular strategies to reduce warehouse costs is to divide the storage into a forward and a reserve area. The forward area is used for broken case picking and allows for fast order picking. The reserve area is used for pallet picking and acts as a reserve for the forward area.

Figure 5: Picking is done from the forward area, while the reserve area above it holds full pallets

As seen in Figure 5 the reserve area can be close (above) the forward area, but this doesn't have to be the case. Sometimes the forward area is placed close to the area where the product is needed, while the reserve area is placed further away from this area.

Figure 6: Model of the forward and reserve buffers
When the storage of a warehouse is divided into a forward and reserve area, the model as described in Figure 3 isn’t valid anymore. In Figure 6 a model for warehouse with a forward and reserve area is given. When a SKU needs to be stored the system first checks if the forward area needs to be refilled, if not the product is placed into the reserve area. When the amount of products in the forward area drop below a certain threshold the forward area is refilled from the reserve area. This refilling is mostly done during times when there is overcapacity.

Deciding which products and in what quantity to store in the forward area is known as the forward-reserve problem. Lots of research has been done on this problem, for example by van den Berg, Sharp, Gademann, and Pochet (1995), but this problem is outside the scope of this research.

2.4 The location assignment problem

It has become clear that the location on which a product is stored determines to a large extent the costs associated with storage. According to Manzini and Goetschalckx (2012) this assignment problem can be modeled as a vector assignment problem (VAP) that minimizes the costs as followed:

\[
\min \sum_{i=1}^{M} \sum_{j=1}^{N} 4 \cdot c_{ij} \cdot x_{ij}
\]

Constraint to:

\[
\sum_{i=1}^{M} b_{i} \cdot x_{ij} < 1 \quad \forall i
\]

\[
\sum_{j=1}^{N} x_{ij} = 1 \quad \forall j
\]

\[
x_{ij} \in (0,1)
\]

Where \(x_{ij}\) is the decision variable if unit \(i\) is stored in location \(j\), \(c_{ij}\) are the expected travel costs associated with storing unit \(i\) on location \(j\) and \(b_{i}\) is the residence vector of a unit load \(i\).

An optimal solution for this problem can be found by solving it as a mixed integer programming problem by making use of linear relaxations. However, using modern hardware and software solutions for this problem can only be found when a small amount of products need to be placed inside the warehouse. Larger problems become too complex and cannot be solved, so a heuristic approach is needed. A heuristic storage policy can be developed that:

1. Sorts all products to be stored by increasing departure time and sorts all storage locations by increasing (expected) travel time.
2. Assigns products with increasing index to storage locations with the lowest index that based on the policy allows for the product to be stored.
This policy only requires two algebra operations and can be applied to even the largest of assignment problems. This policy together with additional information can be used to determine the optimal storage location, as seen in Figure 7.

![Diagram](image)

**Figure 7: Determining the storage location**

After zooming into the location information flow as seen in Figure 3 we get the model as seen in Figure 7. A location is assigned to a product based on three different factors:

1. **Product characteristics**: The products characteristics need to be known since these can influence where the product can be stored. Product characteristics are stored in a warehouse management system.

2. **Free storage location**: For the heuristic storage policy to work, travel time to all storage locations needs to be known. Next to this there also needs to be known which storage locations are still available (using for example a warehouse management system).

3. **Storage assignment policy**: A storage assignment policy is developed during the design phase of the warehouse. As explained in the previous section, this policy determines how to match the free locations with the products to be stored.

In the first part of this chapter it was shown that while warehouses are expensive and storage should be kept to a minimum, storage is sometimes beneficial or even necessary. In the second part it was shown that the costs of storage are to a large part determined by the chosen storage location assignment policy. According to in 't Veld (2002) a policy like this should include the way something should be done, the people and resources that are used and prioritize between goals. In the next chapter various storage assignment policies will be discussed.
3. Storage assignment policies

The storage assignment policies which assign products to storage locations generally fall into three broad categories: (1) random storage, (2) dedicated storage and (3) class-based storage (Hausman, Schwarz, & Graves, 1976). With random storage all products are in a single class, in a dedicated storage policy all products have their own separate class and with class-based storage groups of products get assigned to a certain class. Each class then gets assigned to a dedicated area of the warehouse.

In this chapter various storage assignment policies will be discussed and an overview of useable literature regarding these various policies will be given.

3.1 Randomized storage

Randomized (also known as chaotic storage) is a policy where every product can be assigned to every free location in the warehouse.

![Figure 8: A warehouse making use of random storage assignment policy](image)

The biggest advantage of the random storage policy is that it requires the least amount of space compared to other policies. With other policies space is reserved for a certain type of product, if storage for that particular product is not needed, the space is left empty. When using a random storage policy less warehouse space is needed, this results in smaller warehouses and thus shorter travel distances. This might seem ideal at first, but in reality random storage also has a few downsides.

The reduction of travel distances might be completely negated if pickers need to search for the product in the storage, or need to search for free space to store products. Since the storage is chaotic the same product will almost never be stored on the same location twice, so employees can’t rely on knowledge like this when picking products. An (digital) accurate inventory map needs to be maintained and be available to employees at all time to minimize searching. Efficiently operating a randomized storage without using a warehouse management system is close to impossible.
One restriction to being able to use a random storage policy is that all products in the product inventory can be stored on all locations of the warehouse. If for example some products need to be cooled while other products don’t, a random storage policy is not the way to go.

Since a location is selected from all free locations with equal probability, no optimization is done regarding the location of products. Because of this, even though the small warehouse size, the average traveling distance is longer compared to that in other policies (Choe, Sharp, & Serfazo, 1993).

There are a few ways the random storage policy might be improved, instead of selecting a storage location at random, three other options are possible:

- Closest open location – Assign products to the available storage location that is closest to the dock.
- Farthest open location – Assign products to the available storage location that is farthest from the dock.
- Longest open location – Assign products to the storage location that hasn’t been used for the longest.

It is not known if there is any significant performance difference between them (Gu, Goetschalckx, & McGinnis, 2007). For a specific case, simulation can be used to determine the optimal solution for that situation.
3.2 Dedicated storage

Dedicated storage is the complete opposite of randomized storage. With a dedicated storage policy, every product has its own location on which just that product can be stored.

In a warehouse using a dedicated storage policy every product that needs to be stored during the planning horizon gets assigned to a dedicated area in the warehouse. For every product enough space has to be reserved so that the maximum inventory level for that product can be stored inside the warehouse. When the product is out of stock, the space is reserved and no other product can be stored in that area. Using a dedicated storage assignment policy the space utilisation is the lowest compared to other policies.

An advantage of this policy is that products are always placed in the same location. A learning curve can be noticed; the longer an employee has worked in the warehouse the faster he will be able to find products. Not all products that are to be stored in the warehouse might have the same product characteristics; another advantage compared to the chaotic storage policy is that this doesn’t matter with a dedicated policy. For example, products that need to be cooled can be placed in a dedicated area that is cooled. If products sizes vary greatly, the smaller products can be assigned to smaller shelves, while larger products can be stored in shelves that are bigger.

The biggest advantage over random storage is that optimisation of the location is possible. After adding all products to their dedicated class, the next task is to assign these classes to certain area’s in the warehouse. Different criteria can be used to assign a product (class) to storage locations. The three most frequently used criteria according to Frazelle (2002) are:
- **Popularity** (#storage and retrieval operations per time period). Product classes with the highest popularity will get the most favourable locations (most often closest to the dock).
- **Maximum inventory** (amount of warehouse space needed for a certain class). Product classes with the lowest maximum inventory get the most favourable locations.
- **Cube per order index** (maximum inventory / popularity). The cube per order index (COI) takes both the popularity and space requirements into consideration, products with the lowest COI get the most favourable locations (Heskett, 1963).

At first the COI algorithm was conceived as a heuristic. In the last few decades it has been proven that the COI algorithm is the optimal algorithm for a dedicated class policy in the case of a single command, dual command, multi command or carousel system (Gu et al., 2007, p. 9). Hausman et al. (1976) showed that compared to a random storage, a COI based dedicated storage policy can reduce travel times by 26.3% to 70.6%, depending on the demand distribution.

### 3.3 Class based storage

The main idea of class based storage is to divide goods into classes. These classes than get assigned to a certain area in the warehouse.

![Figure 10: A warehouse making use of a class based storage assignment policy](image)

One can see randomized and dedicated storage as extreme cases of the class based policy. In randomized storage all the goods are put into one single class, after which that class is assigned to the entire warehouse. While this optimizes space requirements it is not possible to optimize travel times. For the dedicated storage every type of product gets assigned to a dedicated class and storage area. This allows various algorithms to be used to improve travel times, but space requirements are larger compared to that of a randomized storage policy.

A class based storage policy gives is often optimal when both space requirements as well as travel times are important. Rosenblatt and Eynan (1989) report that a four-class system results in 90% of...
the benefits of full turnover-based dedicated storage assignment, while decreasing space requirements compared to that of a dedicated policy.

Class based storage policies can be divided into two general categories based on:

1. Product characteristics: Policies based on the characteristics of a product type like size or turnover rate.
2. Item characteristics: Policies based on the characteristics of an individual stored item like time in storage.

Policies based on product characteristics are similar to those discussed in chapter 3.2. Different products first get sorted based using some algorithm. Groups of products are than divided into different classes. The amount of classes can vary but 3-5 classes are normal. After the classes are made storage area is divided amongst the classes. An analytical method to determine the optimal amount of classes has been developed by Manzini and Goetschalckx (2012). Storage for the individual items inside the class areas is done randomly. As with the dedicated policy, the COI algorithm is a popular algorithm to sort the items. Another popular product based policy is to divide products into classes using Pareto’s law. This law divides items into three different classes: A, B and C. Class A is formed out of the 20% of items that cause 80% of the Storage/Retrieval activities. Class B includes 30% of items that cause 15% of S/R activity, while class C includes the remaining 50% of items that cause 5% of all S/R activity. After dividing the products into the three classes, class A gets stored closest to the Input/Output point, while items in class B get stored farthest away.

When a warehouse is perfectly balanced, this means that for every product that enters the warehouse one product leaves the warehouse, M. Goetschalckx and Ratliff (1990) have shown that an algorithm exists based on items characteristics which outperforms product based policies. This is the Duration of Stay (DOS) storage assignment policy. When a single batch of products arrives at the warehouse, the first item of that batch will leave the warehouse quickly, while the last item in the batch will stay in the warehouse for a longer period. The DOS policy makes use of this by optimizing movement costs for the first items in the batch and optimizing for storage costs for the last items in a batch. Warehouse storage locations are ranked by increasing travel time and items are ranked by increasing stay of duration. After this step classes (normally 3-5) are formed and the class that holds items with the shortest DOS gets assigned to the storage section which has the lowest travel time. The DOS policy requires a perfectly balanced warehouse, but in real life scenarios this is rare so the DOS policy is often seen as a theoretical limit for the attainable performance. However, this does not mean that a DOS policy is not useable in an unbalanced warehouse, just that it might not give optimal results. A special case of a DOS policy is called cross docking. With cross docking all items are divided into two groups, the slow and fast movers. While the slow movers get put into storage, the fast movers are never stored and (almost) immediately move from receiving to shipping.
3.4 Other policies

Next to the policies described in the sections above there are also some policies that can be applied in special cases. These policies can be combined with a random, dedicated or class based policy to further improve these policies.

**Correlated storage policy**

Also known as family grouping, this policy is useful if certain products are often needed together (for example in a bicycle factory the lamp and lamp socket that together form the bike’s headlight). By placing these products close to each other picking of these products can be optimized.

**Cross distribution**

With cross distribution, the same item get stored on multiple locations in the warehouse. The main advantage of this is that picking performance can be improved since the item can be picked from multiple locations at the same time. Another advantage is that this minimizes risks, for example when one of the storage locations is an AS/RS that tends to stop working every now and then; the item can still be retrieved by hand from the other location.

**Pre-buffering**

During peak hours there might not be enough capacity to both refill the warehouse with incoming items as well as pick items. To free capacity for picking, incoming goods can temporarily be stored in front of the storage area. When capacity becomes available again the temporarily stored items can be stored on the right location in the warehouse.

This chapter has described the characteristics of the most common storage assignment policies. Next to this an overview of literature in this area was given. The next chapter will focus on choosing the right storage assignment policy.
4. Developing the storage assignment policy

As seen in chapter two, a storage assignment policy is used to assign products to the available space in a warehouse. In chapter three various storage assignment policies were discussed. In the first part of this chapter the place of the storage assignment policy in the general warehouse design process will be discussed. In the second part of this chapter a model will be developed that can be used to determine what storage assignment policy should be used.

4.1 The warehouse design process

Designing a warehouse is a highly complex process. There is an almost endless supply of feasible solutions for every problem that needs to be solved during the design process. Because of this it might not always be possible to find the optimal solution and a solution that meets the given requirements will have to do. Next to this, most of the problems faced during the design of a warehouse are interrelated so reiteration is needed throughout the design process.

During the design of a warehouse decisions need to be made on a strategic, tactical and operational level. Solutions chosen at a higher level provide constraints for the problems that need to be solved on a lower level. This is why problems on an operational level are often the easiest to solve since these problems have less interaction with other problems and can be solved independently using optimisation techniques like simulations. The ideal design method clusters related problems at the same design level and derives a solution by simultaneously optimizing the various sub problems in order to reach a global optimum. It is important to recognize the relations between sub problems, in order to avoid sub-optimal solutions (Rouwenhorst et al., 2000, p. 7). Baker and Canessa (2009, p. 8) have proposed a framework consisting of 11 steps that form the entire warehouse design process:

1. Define system requirement: Research the functions the warehouse has to fulfil and explore the environment of the system.
2. Define and obtain data: Extract data from the past and develop data for the required planning horizon.
3. Analyse data: Analyse and interpret the found data.
4. Establish unit load: Taking the whole supply chain into account, select the optimal unit load.
5. Determine operating procedures and methods: Make strategic and tactical decisions
6. Consider equipment: Select equipment that can meet the requirements and constraints.
7. Calculate equipment capacities and quantities: Use analytical models and simulation
8. Define services and ancillary operations
9. Prepare possible layouts: Use CAD software to develop possible warehouse layouts.
10. Evaluate and assess: Validate operational and technical feasibility of the layouts.
11. Identify the preferred design: Select the optimal warehouse design.
Although the framework proposed by Baker & Canessa makes it seem that the design process is done step by step, this is not the case. The design process is an iterative process in which steps back in the process occur just as often as steps forward.

A model that shows the iterative process of the design process is proposed in Chapter 10 of the Delft Systems Approach (Veeke et al., 2008, pp. 181-196) and is displayed in Figure 11.

![Diagram of the design process](image)

**Figure 11: A conceptual model of the design process**

Function design is a strategic decision making process in which is answered what functions need to be fulfilled. Process design deals with decisions on a tactical level and answers how the functions are going to be fulfilled. The result of function and process design is a PROPER model.

Deciding which storage assignment policy to use is a tactical decision and this decision should be made simultaneously with other problems on the tactical level to avoid sub-optimal results.

![Diagram of design decisions on a tactical level](image)

**Figure 12: Design decisions on a tactical level (Rouwenhorst et al, 2000 p. 7)**

In Figure 12 the decisions that need to be made on a tactical level are displayed, next to these, there are many other factors that influence the choice of storage assignment policies. In the next section of this chapter the PROPER model seen in Figure 11 will be used to determine which factors influence the choice for the storage assignment policy.
4.2 Factors influencing storage assignment policy choice

The selection of storage assignment policy has an influence on many aspects of the warehouse. This is why when selecting the storage assignment policy, warehouse designers needs to have clear understanding what, and in what way the various aspects of a warehouse influence the storage assignment policy choice. As discussed in chapter 1.1 this understanding is now formed by experience of the warehouse designers.

In this paragraph a PROPER model (Veeke et al., 2008, pp. 101-105) will be developed. A PROPER model displays three aspects of a system: (1) order flow, (2) product flow and (3) resource flow and the relations between these aspects.

![Figure 13: PROPER model warehouse](image)

In Figure 13 a PROPER model of warehouse is displayed, using this model it becomes clear how the storage assignment policy interacts with the rest of the system. In the following sections the requirements, performance, order flow, product flow and resource flow will be discussed.

4.2.1 Requirements

At the start of the design process the requirements for the warehouse are determined.

Some of these requirements come from within the system (a higher echelon), for example limitations put on the system by decisions made on a strategic level.

Other requirements come from the environment in case of an open system. Depending on the type of products to be stored, the government might enforce laws to safeguard the safety of the employees and environment of the warehouse.
4.2.2 Performance

In order to evaluate a warehouse, performance indicators need to be established. The choice of storage assignment policy has a strong influence on these performance indicators. The following performance criteria can be found in literature: accuracy of the inventory, operating costs, investment costs, flexibility, throughput and capacity. During the functional design of the warehouse there needs to be determined for which performance indicators should be optimized, for example should the storage capacity or the storage throughput be more important.

As seen in chapter 2.1 Use for storage in a production/assembly company, storage in a production / assembly warehouse is needed to store raw materials, work in process and finished products. Because these three different buffers fulfill a different function, other performance indicators can apply. It is not hard to imagine that for a raw materials storage, storage capacity is the most important criteria since raw materials are often bought in bulk and are stored for a long period, so storage needs to be as cheap as possible. On the other hand, for the transformation buffer other performance criteria will apply. Products never stay in the transformation buffer for too long, so storage costs are less important in this buffer. An important performance indicator for the transformation buffer could for example be the time it takes to pick a product from the storage once its needed, the response time. In case of a forward and reserve area, different performance indicators also apply. The forward area is a small area with just a few products from which products are picked, so this area should be optimized for fast order picking. On the other hand in the reserve area large quantities of products are stored for a longer period, in the reserve area the storage costs are the most important.

When we look at the three general types of storage assignment policies as discussed in chapter 3 we can conclude the following:

- Random storage assignment policy: The optimal policy when storage density and thus minimizing the storage costs is important.
- Dedicated storage assignment policy: The optimal policy when a fast order picking time and thus operational costs are important.
- Class based storage assignment policy: The optimal policy when both operational as well as storage costs are important.

Based on the performance indicators a first selection amongst the various storage assignment policies should be made.
4.2.3 Order flow

Storage requests and requests to get something out of the storage make up the order flow.

If the input of a warehouse matches the output a warehouse is perfectly balanced. If this is the case a storage assignment policy based on duration of stay of the individual items minimises the combination of storage and operational costs.

A lot of policies depend on information like demand trends and turnover rates. This information might not always be available when designing a new warehouse. If this information isn't available a random storage assignment policy should be used, since for this policy this information isn't needed. The more information is known the better, since than simulation can be used to compare various policies.

When demand for a certain product is really high storing the product on just one location might cause capacity problems. If this is the case a cross distribution policy should be used so the product is stored on multiple locations and picking can be done on from various locations at the same time.

4.2.4 Product flow

The product characteristics are another important factor that influence the storage assignment policy.

- **Product size:** If the size of the different products that need to be stored varies greatly, it can be a wise decision to split the warehouse into sections with different rack sizes. This way smaller products can be stored in small racks which take up less space, while the bigger products get stored in the bigger racks. If product sizes vary only slightly this problem can be solved by making use of pallets. For the bigger products just a few products will be stored on one pallet, while for the smaller products a lot of products can be stored on one pallet.

- **Product weight:** The product weight is important for two reasons. The first reason is that product weight needs to be properly distributed amongst the storage racks. If a lot of heavy products are stored on one side of the storage rack, while the other side of the storage rack is left empty the storage rack might tip over. The second reason product weight is important is picking. If a picker has to pick multiple products it's best if the heavy products are picked first so they can be put onto the bottom of the pickers batch. Because of this it might be wise to put popular products that are heavy close to the S/R section of the warehouse.

- **Special requirements:** Some products have special storage requirements. For example some products might need to be cooled during storage. It is not wise to cool the entire warehouse if just a few products need to be cooled. A class based policy should be developed in which products that need to be cooled get put into one class which gets assigned to a cooled area, while other products get assigned to the rest of the warehouse. Other special requirements for example are fire, explosive or theft protection.
4.2.5 Resource flow

The resource flow is made up out of the following:

- The storage system: Items are stored in the storage system, it can be formed out of racks, shelves or highly automated storage and retrieval systems.
- Material handling equipment: Equipment used to pack, store and retrieve items. For example a forklift truck or trolley.
- Computer systems: To keep track of orders and items computer systems are needed. For example a warehouse management system (WMS) or ERP system.
- Personnel: While some warehouses are completely automated most warehouses still use personnel to store and retrieve items.

The use of a computer system to keep track of all items inside the storage is essential when using a random or class based policy since products are stored on random locations. The only warehouse that can be controlled without a computer system is one using a dedicated policy, since items are always stored in the same location and personnel can learn where products are stored.

When using a random storage policy all racks/shelves in the storage area should have the same size and be able to store every product. When using a dedicated or class based policy this is not the case and shelf and rack sizes can be optimized for certain product (classes).

Automated storage and retrieval systems (AS/RS) are a huge investment, costs largely depend on the size of the system so this should be kept to a minimum. When using an AS/RS system a complex computer system is already in place. Because of these two factors class-based storage policies are almost always used in automated systems.

In this chapter and overview has been given off the role of the storage assignment policy in the warehouse design process. A model was made that was used to give an overview of how various aspects of the warehouse influence the selection of the storage assignment policy.
5. Conclusion

Designing warehouses is a highly complex task because of the huge amount of interrelated design decisions and reiteration that is needed. In chapter 4 a model was developed that can be used by warehouse designers as a guideline to help them choose the right storage assignment policy.

As a rough guideline one can conclude the following:

- Dedicated storage assignment policy: Use for storage where operating costs and retrieval times are important.
- Random storage assignment policy: Use for storage where warehouse size should be kept at a minimum.
- Class-based storage assignment policy: Use when both warehouse size and operational costs are important.

As seen in chapter 4 it doesn’t stop at selecting one of the three main storage assignment policies, each of these policies have various different variations that need to be evaluated.

The selection of storage assignment policy should never solely be based on theory developed on paper. Next to the proposed PROPER model another important tool that should be used during the design process is simulation. Simulation is a great tool to check the feasibility of the design choices, gain insight in the performance under various circumstances and check the time-dependent behavior of the system.

Designing a warehouse should never be a onetime process, when the warehouse is fully operational the results of the system should regularly be evaluated. A warehouse isn’t a static system, the type of products, amount of products to be stored and many other factors might chance over time, asking for a different storage policy.
References


