Warehouse order picking

Bachelor’s Thesis

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ABSTRACT

Warehouses’ management is becoming more important inside the logistics’ world lately, an optimal management implies a working time reduction and it leads to a cost reduction.

The objective of this thesis is to discover the world of warehouses’ management, and especially the warehouse order picking field. For that reason it will be divided into two parts. The first one will be theoretical, and the goal is to acquire a theoretical base. The second one will be more practical, firstly a statistical analysis will be carried out through a factorial design in order to understand the performance of the different routing strategies and when is better to use each. Secondly, the relationship between the response and the travel time will be studied through a correlation study.

In the first part results show that the performance of the optimal routing is much better than the heuristics in all the situations, and as it is commented in the theoretical part an increase in the number of cross aisles benefits all the methodologies, but with some exceptions. It is also proved that using a storage method, the travel time is reduced. While in the second part, the correlation study shows that all the factors have a strong relationship with the travel time.
La gestió dels magatzems cada cop està tenint més importància dintre del món de la logística, una gestió òptima implica una reducció del temps de treball que es pot traduir en una reducció de costos.

L’objectiu d’aquesta tesi és descobrir el món de la gestió de magatzems, i en especial el de la recollida de comandes dintre d’un magatzem. Per això aquesta estarà dividida en dues parts. La primera teòrica, on l’objectiu serà assolir una base teòrica. I una segona de caire més pràctic, on primer es farà una anàlisi estadística a través d’un disseny factorial per tal de conèixer el comportament de diferents estratègies de recollida de comandes i quan es millor utilitzar cadascuna. En segon lloc es farà un estudi de correlació per veure la relació que hi ha entre la resposta, que és el temps fins a recollir una ordre, i diferents factors.

A la primera part els resultats obtinguts proven que el rendiment de la metodologia òptima està molt per sobre de les heurístiques per a tots els casos, i que com es deia a la part teòrica l’increment de passadissos transversals afavoreix la circulació per totes les metodologies. També es pot comprovar que fer servir un mètode d’emmagatzematge redueix el temps de viatge (travel time). Mentre que a la segona part, a l’estudi de correlació s’observa que tots els factors analitzats i el temps de viatge estan relacionats estretament.
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1. Introduction

1.1 Motivation

Lately, the growth of e-business is on the rise and according to some analysis of different consultants firms, such as BCG, predict that it will go on growing. See Figure 1.

As an Industrial Engineer student, one of the ways for being related to this sort of business is logistics, specially, warehouses. An efficient warehouse management and the optimization of the processes is one of the key factors for a company to succeed in this market. Managers are realising that they need warehouses professionals for their company if they want to survive and be competitive.

Not only this consideration made me chose this topic, but also having a department specialised in logistics and especially a researcher who carries out his investigation in this field in the university where I did my Erasmus made me looking forward to developing this thesis.

1.2 Goals

One of the main goals of this thesis is to discover the Warehouse order picking’s field. Creating an overview of all operations that can be carried out inside warehouses in order to optimize picking processes, with the intention of being able to work in the near future more in depth. To sum up, acquire a theoretical base.

Another of the goals that follows this thesis, from a practical point of view, is to discover which is the performance of the different picking routing strategies under different situations and determine which is the best one for each situation.

And the last one is to determine if exist correlation between the travel time and some related variables.
2. Warehouse operations

Nowadays, warehouses are not only buildings for storing goods, they have become an integral part of the supply chain, and their efficient management is in the point of view of several companies. In some fields, such as in e-commerce, this is a key factor for the companies’ success. Warehousing increases the value of goods by providing means to have the right products available for the customer.

In a warehouse many operations take place, and the sort and number of operations will depend on the kind of warehouse. However, these are the typical standardized operations:

- **Receiving**: With the receiving of products normally start the inventory control. All essential data about the product should be gathered. The main functions at this stage are: verifying product quantity, preparing receiving reports, and routing those reports to designated departments. Receiving operations also include the preparation of received products for later operations.

- **Storage**: The basic function of storage is the movement of the products from the receiving area to their location. There are several methods that lead to the reduction of costs in storing products and will be explained in more detail below. [1]

- **Picking**: Described as the process of retrieving items from their storage locations. It is the most labour-intensive and expensive operation of a warehouse. It is said that picking is one of the most important operations, not only for being a labour-intensive and expensive task, but also for being the operation that fills customer expectations. For these reasons picking is going to be explained in more details throughout this thesis. [2]

- **Packing**: The products are consolidated according to some criteria, packed for transport and transported to the shipping area.

- **Shipping**: The last operation that takes place in a warehouse. Load the products into the transport means and ensure that products correspond to the shipping orders are the main tasks in this operation. [1]
In figure 1 can be appreciated the typical distribution of warehouse operating expenses.

To conclude, all warehousing operations aim these objectives: minimize product damage, reducing transaction time and improve accuracy.

![Figure 2 Typical distribution of warehouse operating expenses (Tompkins et al. 1996)]
3. Order Picking

As mentioned above, picking is the most labour-intensive and expensive operation in a warehouse, it represents around the 55% of the annual expenses in a warehouse [3]. For this reason, researchers pay especial attention to the improvement of picking operations.

With the aim of improving warehouse picking operations efficiency, a 1988 study in United Kingdom revealed that 50% of all activities in picking operations could be attributed to travelling activities. Because of this, researchers have developed routing, storage and orderbatching strategies allowing reducing the travel distance, and in consequence, reducing the costs related to travelling activities.

![Figure 3 Typical distribution of an order picker's time (Tompkins et al. 1996)]

3.1 Order picker’s costs

One of the main aims of every company is to reduce costs in order to increase their profits. In a warehouse where picking operations take place, the main costs involved are the following:

1. Travelling cost: it is related to the distance that the picker has to travel in order to pick the item. In figure 2 we can observe that it is the most time consuming order picking operation, up to 50%. [2] Shows that travel distance can be reduced by 45%.
2. Stopping cost: it is associated with the number of different picking stops, directly related to orderbatching problems.
3. Grabbing cost: it is associated with the number of cartons that picks at each stop.
4. Closing cost: it includes all the activities related to operations at the computer station. [2]
### 3.2 Warehouse layout

Before explaining storing, orderbatching and routing methods is convenient to have an overview of the layout of a warehouse and its principal elements.

Warehouses are divided by aisles, and the aisles contain shelves, where the products will be stored. The goal of warehouse layout is to optimise warehousing operations and achieve high efficiency. In order to achieve it, some elements play a key role. A brief description of these elements is given below.

![Figure 4 Warehouse layout with two blocks](image)

**Depot**

Normally, pick lists are generated or received electronically at the depot, and then the picker starts to retrieve products. Depending on the situation of the depot, and the facilities used in the warehouse there are different sort of depots:

- **Central depot:** The picker only can start and end at the same point. Commonly, it is located in the front end of the aisles.

- **Decentral depot:** It is the alternative for central depot. It is used when terminals or RF scanners and conveyor operate in a warehouse. Conveyor allows drooping off products at any location of itself; therefore, it facilitates the picking process. In order to maximize the advantages of decentral depot the starting point needs to be larger than in central depot.

![Figure 5 Central depot (left) and decentral depot (right) warehouses](image)
Aisle

The aisles of a warehouse are the main spaces where pickers travel in order to retrieve products from the shelves. Some of the variables related to aisles are:

- Length: Is the distance between the front end and the rear end.
- Distance between aisles: Is the distance between the centre of one aisle and the centre of the next aisle. Depending on the width, aisles can be sorted as:
  - Narrow aisles: The picker can retrieve products from both sides of the aisle, without need to realize any lateral displacement.
  - Wide aisles: As opposed to narrow aisles, in this kind of aisles, due to a major distance, the picker has to realize lateral displacements in order to pick products from both sides.

The total width of a warehouse is the distance between aisles multiplied by the number of aisles.

- Number of aisles.

Cross aisle

Is an aisle perpendicular to the aisles used to storage products, the main aisles. It enables aisle changing and facilitates moving around the warehouse. If a warehouse has cross aisles it is divided in blocks by the cross aisles. The variables related to cross aisles are:

- Width: Is the distance between different blocks.
- Number of cross aisles. [4]

3.3 Storage methods

Products need to be stored, and there are several methods for assigning storage locations to the received items, they are explained below:

- Random: items are randomly assigned to an available location. On the one hand, random storage increases the average travel time compared to other storage methods. On the other hand, it reduces aisle congestion and increases the uniform utilization of the warehouse. Nowadays, random storage is one of the most common storage method used, it is due the fear of managers to face new storage methods.
- **Closest-open-location**: This is probably the simplest storage method. Incoming items are allocated to the closest empty location. Some studies show that in a long run random and closes-open-location methods converge. This method is mainly used when order pickers have to decide locations by themselves. The main problem of this method is that in a long term items are scattered over the warehouse.

- **COI-based**: this method defines COI of an item as the ratio of the required storage space to the order frequency of the item. Items are stored by increasing COI ratio and locations on increasing distance from the depot. [4,5]

- **Volume-based**: it assigns items to storage location based on their expected order or picking volume. The most accessed items are located near to the depot area. The main advantage, compared to random storage, is the reduction in travel time. However, uniform warehouse utilization and aisles congestion increase. There are different patterns of volume-based storage [6]:
  - **Diagonal**: The items with the highest volume are located closest to the depot area, meanwhile those with lowest volume are located farthest. The pattern as its own name suggests is a diagonal.
  - **Within-Aisle**: High volume items are placed in the first aisles closest to the depot, and the low volume items are placed in the last aisles, farthest from the depot.
  - **Across-Aisle**: In this kind of pattern the highest volume item is stored in the first location of the first aisle closest to the depot area, the next highest volume item is stored in the first location of the second aisle, until all first location in the aisles are assigned. Then, second location of each aisle will be assigned an item and so on until the last location.
  - **Perimeter**: The high volume items are stored around the perimeter of the warehouse, as its own name indicates. The low volume items are stored within the middle of the aisles. [6,7]

Both COI and Volume based are classified as a sort of dedicated storage assignment.
- **Class-based** (or ABC storage): It is based on the division of items and storage locations in the same number of classes, in order to assign the items to one location. Class-based storage fuses randomized and volume-based methods.

The difference between this method and the volume-based is that this one assigns items to storage location following a group basis; however, volume-based follows an individual basis. And regard to randomized, it provides a saving on travel distance.

In order to divide items into classes Pareto’s method is used. The items are subdivided into three categories, based on the nature as well as the size:

  - Category A: for items which turnover rate is high and the number of locations is small, these items are stored near to the depot area.
  - Category C: items which average storage time is much longer than the storage of A’s items, these products need much space in the warehouse.
  - Category B: these items are between category A and C, concerning turnover rate and space needed.

Items from category B and C are slow moving products, and are stored at the back of the warehouse. [4]
Intelligent storage methods

Some of the strategies described above are suboptimal from the point of view of space utilization. In several markets consumer's demand is cyclical, this leads to an optimal space utilization during peak seasons but to an inefficient during the majority of the year. Another problem of these strategies is that they do not take into account consumer purchase.

Take into account consumer purchase can lead to a reduction of travel distance, for this reason some alternative storage methods were developed. Despite of these methods can increase savings, they have received little attention, however, a brief explanation is made below:

The cloud

This strategy distributes items randomly to several different warehouses zones, which are called clouds. The objective of this strategy is to create clouds that at any point in time contain the majority of all items necessary to fulfil a customer order. Thanks to disperse the items in different clouds the travel distance is minimized, therefore savings increase. The benefits of this strategy outweigh the additional costs that can result of storing the items in several zones. Rubenstein (2006) predicted a 10-15% cost saving applying this storage method for an Amazon's Fulfillment Center. [8]
Product group affinity

Product group affinity directs items to virtual warehouse zones based on product group, it is very similar to class-based storage. This strategy is based on the hypothesis that customers tend to order items of the same category, therefore thanks to this the distance travelled between picks will decrease and productivity will increase. Another feature of this method is that items are stored randomly in the virtual warehouse zones, therefore it fuses the best of direct and random methods. [8]

3.4 Orderbatching methods

There are different methods to collect customers’ orders. When orders are large, each order can be picked independently from others, meanwhile, when orders are smaller is more efficient to pick a set of orders in one route. The number of stops in each route is limited by the capacity of the picking device and by the capacity requirements of the items to be picked. Therefore, batching is the process of combining one or more orders into one or more pick orders, in order to reduce travel time, thus increase productivity.
Orderbatching problems are solved through heuristic approaches. Although the best combination could be found trying different combinations, in practice heuristic methods are used because are less time consuming than optimal solutions. Below are explained three of the most used heuristic methods.

First come, first served

This algorithm is very simple because as the title suggests, the sequence of the orders’ arrival determines how the orders are grouped. The first order arriving is the order to which the next orders are added, as long as the capacity of the picking device is not exceeded. When the capacity is exceeded a new batch is created.

Seed algorithm

There are distinguished two phases: seed selection and order congruency. In the seed selection an initial order, which is called “seed”, is chosen for a batch. It is very important to choose the best seed in order to obtain good batches and there is a large variety of rules for the seed selection that can be found in the table 1. Order seed can also be determined in a single mode, where only the first order in the batch defines the seed or in a cumulative mode, where all order in the batch defines the seed. Then in the order congruency phase, unassigned orders are added to the seed, following an order congruency rule. Normally, the selection criteria are based on a measure of the distance from the order to the seed.

<table>
<thead>
<tr>
<th>Seed rule</th>
<th>Seed Selection</th>
<th>Order Adding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>Arbitrarily</td>
<td>Number of similar locations</td>
</tr>
<tr>
<td>Cumulative</td>
<td>Furthest/Nearest item</td>
<td>Sum item distances, basis: seed order</td>
</tr>
<tr>
<td>Largest/Smallest number of aisles</td>
<td>Sum item distances, basis: candidate order</td>
<td></td>
</tr>
<tr>
<td>Largest/Smallest time to pick</td>
<td>Center of gravity</td>
<td></td>
</tr>
<tr>
<td>Largest/Smallest number of items</td>
<td>Saving of time</td>
<td></td>
</tr>
<tr>
<td>Largest/Smallest distance between the left and right aisle</td>
<td>Additional Aisle</td>
<td></td>
</tr>
</tbody>
</table>

*Table 1* Examples of seed, selection and adding rules, Erasmus University of Rotterdam.

Time saving algorithm

With this algorithm a saving on travel distance is obtained by combining a set of small tours into a smaller set of larger tours.

The time saving algorithm is divided in several steps that have to be taken:
1. Select the combination of orders which generate the highest saving, determining the saving in time when you batch the orders compared to a separate pick of the orders for every pair of orders.
2. Form a new batch when the orders are not already assigned to a batch and there is enough capacity.
3. If one of the two combined orders is already assigned to a batch check if is possible to assign the other order to the same batch, if it is not possible create a new batch. [4,9]

3.5 Routing strategies

3.5.1 Routing strategies for one block

A routing strategy is a strategy which determines the route to pick up all the items. There are several routing strategies and the goal of all of them is to minimize the travel distance, thus minimize travel time. Below are explained some of the most used, heuristics and optimal, routing strategies for warehouse with a single block, narrow aisles and without cross aisle:

S-shape or Transversal strategy

This is one of the simplest strategies, and it is used frequently because is very easy to understand. In this strategy the picker enters an aisle containing picks from one end and leaves from the other. Aisles with any item to pick are skipped. For this reason this strategy is also called S-shape.

Return strategy

Return strategy is other of the simplest routing strategies. The aisles are always entered from the front and left on the same side after picking the items. Aisles with any item to pick are not visited. The only aisles that are traversed entirely are the first and the last, in order to access to front and rear ends.

Midpoint strategy

For this strategy the warehouse is imaginary divided into two halves. If the items to pick are in the front half, they will be accessed from the front end, meanwhile, if the items to pick are in the back half, they will be accessed from the rear end.

Largest gap strategy

In the largest gap strategy a picker enters an aisle only as far as the largest gap within aisle. The gap represents the separation between any two adjacent picks, between the first pick and the front aisle or between the last pick and the back
aisle. Therefore, if the largest gap is between two adjacent picks, the picker performs a return route from both ends of the aisle. Otherwise, the picker will perform a route from the front or back aisle. This strategy is used when the additional time to change aisles is short and the number of picks per aisle is low.

**Composite strategy**

This strategy fuses S-shape and return strategies, and seeks to minimize the travel distance between the farthest picks in two adjacent aisles. For each aisle determine the best strategy, S-shape or return strategy, which means to travel the aisle entirely or to make a turn in it, respectively.

**Combined strategy**

Combined strategy is very similar to composite strategy. However, every time all items of one aisle are picked a dynamic program, developed by Roodbergen and De Koster (1998), has to compare what alternative is shortest, go to the rear end of the aisle, or return to the front end. The shortest route is chosen.

**Optimal strategy**

As its own name suggests it can calculate the shortest route, thus the optimal. An optimal route is usually a hybrid of s-shape and largest gap strategies. Using the optimal strategy could seem the most logical option, but it has several disadvantages:

1. It produces routes that may seem illogical to the order pickers, thus it can create confusion, and as a result deviation from the specified routes.

2. Its only available for standard layouts (i.e. rectangular, single or two blocks).

3. It has to be executed for every route.

4. It does not take into account aisle congestion neither that the aisle or direction changing may be time consuming in practice.

For these reasons heuristics routes are preferable in practice.
Comparison between routing strategies

Heuristic strategies are used in practice because they are easy to understand, and it reduces the risk of missed picks, and they also provide a saving in time. However, there are some factors that can determinate if a strategy will be suitable or not, such as pick density. For instance, Hall (1993) carried out a comparison between the largest gap and S-shape strategy for a random storage. His analysis showed that largest gap was better if the density was approximately less than 3.8, while the S-shape outperformed the largest gap when the pick density was greater than 3.8.

Another factor to consider when choosing between routing strategies is the equipment. For instance, if there is a vehicle that has a low speed in the cross aisles the best option will be select a strategy that minimize cross aisles travel.

The heuristic selection should also take into account product properties. Sometimes there are some items that impose physical restrictions, for example weight restrictions; heavy items cannot be stacked on light items.

A comparison between routing strategies only make sense if it is performed with a predefined storage method, there is a strong interaction between routing and storage methods. Batching and storage also have a strong relation. Batching has an additional effect on the decision concerning the routing strategy because it influences the number of picks per route.

Finally, another key factor is the layout. For example, depending on the width or the number of cross aisles one routing method will be better than another. [3, 4, 5]
3.5.2 Routing methods for more than one block

In practice, not all warehouses consist of a single block. There are several warehouses consisting of cross aisles, which facilitate moving around the warehouse. In this sort of warehouse, consisting of more than one block, some of the routing methods explained above cannot be used. For this reason some routing methods adapted to this kind of warehouses are going to be explained below.

S-Shape

It is based on the same criteria that for a single-block warehouse. If an aisle contains at least one item is totally traversed and aisles with any items to pick are skipped. The steps to follow this heuristic are in appendix A.

Largest gap

It is also based on the same criteria that in a single-block. It uses an adapted definition of gap, in this case it is the distance between any two adjacent pick locations within a subaisle, or between a cross aisle and the nearest pick location. This strategy follows the perimeter of each block entering subaisles when needed. As in the S-shape, first goes to the farthest block and then proceeds block by block to the front of the warehouse. Each subaisle is entered as far as the largest gap, which is the largest of all gaps in a subaisle and divides the pick locations in a subaisle into two sets; one is accessed from the back cross aisle, and the other from the front cross aisle. If one or both sets are empty is not necessary to enter the subaisle from that side. The steps of this storage method are also in appendix A.

Aisle-by-aisle

The main feature of this strategy is that every pick aisle is visited exactly once. The order picker starts at the depot and goes to the left most aisle containing items. All items in this aisle are picked and then a cross aisle is chosen to proceed to the next aisle; these steps are repeated until all the aisles have been visited. If in one aisle there are any items to pick it is skipped. A dynamic programming is used to determine the best cross aisles to go from aisle to aisle.
Optimal

As in the case for a single-block warehouse the optimal strategy find the shortest picking route. Ratliff and Rosenthal (1983) developed an algorithm, which used dynamic programming, for warehouses with two cross aisles. Although in theory is possible to calculate optimal routes for any number of cross aisles by a branch-and-bound algorithm, the algorithm become non-trivial as the number of cross aisles grow.

*Figure 11* Example routes for four routing methods in a multiple block layout (Roodbergen and Koster, 2001)
4. Practical case

4.1 Comparison of different routing methods and situations

The goal of this practical case is to compare different situations with the purpose of demonstrating which routing method suits better in each situation. In order to achieve it, a tool developed by the Rotterdam School of Management and the Erasmus School of Economics has been used; it allows calculating order picking time in a self-area warehouse. This tool was selected among others because it is the one that allows changing more warehouse and picking parameters, thus realize an exhaustive study. Some of the parameters that can be changed are: aisle length, centre distance between aisles, number of aisles, number of cross aisles (blocks), depot location, average speed inside/outside aisles, additional time to change aisles, storage strategy (random/ ABC-1/ ABC-2), average number of lines/order, administration time/order, time to pick a line, routing strategy (s-shape/ largest gap, combined, optimal) and the number of simulations.

Minitab, which is a statistic package, has been used to analyse the data obtained from the picking calculating time tool and for trying to reach some conclusions.

The method that has been performed for analysing this experiment is a factorial design. It lets you study the effects that several factors can have on a response. It allows varying the levels of all factors at the same time instead of varying one at a time, and thanks to that the interaction between different factors can be studied.

Design of experiments (DOE)

Among all the possibilities that the simulation tool gives, three parameters have been chosen to experiment with them. Prior to the experiment it may be logical to think that the parameters that can influence more on the travel time are the aisle length, number of aisles and number of cross aisles, apart from the routing strategy. Therefore, the experiment will have four factors, and each factor will have four levels ($4^4$ experiment), in consequence 256 experiments. The simulation tool is able to generate the result of the four strategies routing at the same time, thus only 64 simulations are needed. In the following table the four factors and their levels are presented:
Table 2 Factors and levels that will be tested on the experiment.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aisle length (m)</td>
<td>50  100  150  200</td>
</tr>
<tr>
<td>Number of aisles</td>
<td>5   10   15   20</td>
</tr>
<tr>
<td>Number of cross aisles</td>
<td>1   2    3    4</td>
</tr>
<tr>
<td>Routing strategy</td>
<td>S-shape  Largest Gap  Combined  Optimal</td>
</tr>
</tbody>
</table>

Other considerations to take into account in all the simulations are: depot location is on the left, average speed inside/outside aisles is 0.7 m/s, additional time to change aisles 2 s, average number of lines/order 15, administration time/order 60 s, time to pick a line 8 s, for the first experiment storage strategy is random, while in the second an ABC-1 method is selected.

The variable in which is based the analysis is the average travel time, representing the travel time spent by the picker to collect the items of the order list. The final result given by the simulation tool is averaged over 1000 simulation runs.

Results simulation 1

After creating a 256 x 5 matrix for the factorial design and obtaining the travel time from the tool simulation, the results of the general full factorial design are the following:

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
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<td>Model</td>
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<td>40012201</td>
<td>229955</td>
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<td>Linear</td>
<td>12</td>
<td>35402795</td>
<td>2950233</td>
<td>5621,80</td>
<td>0,000</td>
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Using a α-level of 0.05 as a reference we can determinate that the four main effects are statically significant in the model. The p-value of all four is less than 0.05. As it could be assumed, not only the main effects are significant in the
model, but also the interactions do. All the two and three way interactions are significant. The $p$-value for the four way interaction could not be calculated due to the lack of degrees of freedom for the error.

The main effects of the response are represented in figure number twelve. Logically, between the travel time and the factor aisle length there is a linear relationship. The larger the aisle is, the more the picker has to travel. With regard to the number of aisles its graph follows a parabolic pattern. And as it was commented in the theoretical part, increasing the number of cross aisles benefits the reduction of travel distance. Finally, in this graph we can see clearly that the optimal strategy is the one that provides the shortest route by far. While the average travel distance for the S-shape is 1011,7 m, for the Largest Gap 898,5 m, for the Combined 900,8 m and for the Optimal is only 448,0 m, that means that these strategies ranges from 125,83% and 101,07% over the optimal.

The following graph shows the interaction between the routing strategy and the number of cross aisles. First, one of the considerations more important to take into account is the clear decrease of the travel distance while the number of cross aisles increases. Therefore, the increase of cross aisles in a warehouse benefits the saving in terms of travel distance for all the routing strategies analysed. And second, there is a clear interaction effect between the Largest Gap and Combined strategies.
The graph below shows the interaction between the routing strategy and the number of aisles in a warehouse. As it could be assumed, when the number of aisles increases the mean travel distance also does. One point that deserves to pay attention is the slope of the curves. The slope for the optimal strategy tends to be zero, while the slope of the other strategies follows a parabolic pattern. That means that the effectiveness of the heuristic strategies (S-shape, largest gap and combined) decrease respect the optimal strategy when the number of aisles increases. As in the previous case of interaction, here there is also interaction between the Largest Gap and the Combined strategies.

Although it could be interesting to investigate with more number of aisles in order to see the tendency between the Largest Gap and Combined, the simulation tool only works with a number of aisles between 2 and 20.
Results simulation 2

A second simulation is carried out in order to compare the performance of an ABC (also known as Class-based) and a Random storage strategy. The parameters fixed for this simulation are the following: Size of zones: 15% A, 20% B and Percentage of picks: 85% A, 8% B.

All factors, its levels and other initial conditions (depot location, average speed inside/outside aisles, etc.) are exactly the same than in the previously simulation.
After proceeding in the same way that in simulation 1, creating a matrix for a $4^4$ factorial design, and obtaining the data from the simulation tool the results obtained with Minitab are the following:

On the one hand, the ANOVA (Analysis of Variance) results are similar to simulation 1, all the main, two and three interaction effects are significant. Their $p$-value is less than 0.05.

On the other hand, the mean travel distance has decreased notably for all the main effects. For instance, for the routing strategies it has decreased between 25.7% and 21.03%. The pattern that follows the graphs of each main effect is very similar to the first simulation; however, the range has become narrower. Therefore, the difference between each situation has decreased too. It seems that ABC storage benefits all sort of situations. In this situation optimal strategy also provides the shortest route, having to travel only 353.8 m (on average), while the longest route is provided by the S-shape, travelling 751.7 m.

![Figure 16](image)

**Figure 16** Main effects comparison between simulation one and two.

The following graph shows the interaction between the number of cross aisles and the routing strategy selected for ABC storage. Like in the random storage when the number of cross aisles increases the travel distance decreases, especially for the optimal strategy. For the heuristic strategies the variation between the different number of cross aisles is less than in a random storage strategy because of the ABC storage, here the products with highest turnover...
rate are placed in the same place, therefore the picker has to travel less, and the number of cross aisles becomes “less important”. Like in the first simulation there is an interaction between the Largest Gap and Combined strategies.

Figure 17 Interaction between number of cross aisles and routing strategies. 2.

Figure number 17 shows the interaction between the number of aisles in a warehouse and the routing strategy under ABC storage strategy. In contrast to random storage whose curves follow parabolic patterns, here all the curves are linear. If all the curves were parallel there would not be interaction between any factor, but the curves of the Largest Gap and Combined strategy cross, therefore, there is interaction between these two factors again.

Figure 18 Interaction between number of aisles and routing strategies. 2.
4.2 Correlational study between some factors and the travelled time

The goal of the correlational study is to determine the strength and relationship between some variables, like the number of cross aisles or the number of aisles/picker, and the response, which in this case is the time that picker has to travel to retrieve the order.

Two variables are correlated when the value of one of them change systematically with regard to the homonyms values of the other. For instance, if there are two variables (A and B) exist correlation if increasing the values of A the values of B also increase, and vice versa.

The statistic used here is the coefficient of determination ($R^2$), it gives information about the goodness of fit of a model, and is always between 0 and 100%. An $R^2$ of 1 indicates that the regression line perfectly fits the data. Therefore, the higher the $R^2$, the better the model fits the data.

In order to obtain the travel times the same simulation tool as in the comparison of different routing methods and situations was used.

Three factors were analysed for each routing method, the objective is to quantify their correlation with the response, the travel time. The factors analysed were: number of cross aisles, number of aisles/picker and average number of lines/order. Other factors were not analysed because it seems quite logical that factors such as the aisle length or the centre distance between aisles will keep a linear (or very similar) relationship with the response. However, to prove it, an analysis for the aisle length under an optimal strategy and a random storage were carried out, and it shows what was supposed before, coefficient of determination is exactly one ($R^2 = 1$). See figure below.
All the simulations carried out are gathered in the first column of the following table. This table shows the coefficients of determination of each simulation.

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<tr>
<th>$R^2$</th>
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<th>Number of aisles/picker</th>
<th>Average number of lines/order</th>
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<td>Optimal: ABC-1 storage</td>
<td>0.8350</td>
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<td>0.8839</td>
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<td>Largest Gap: Random storage</td>
<td>0.8534</td>
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<td>Combined: Random storage</td>
<td>0.9721</td>
<td>0.9612</td>
<td>0.8628</td>
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</tbody>
</table>

Table 3 Coefficient of determination for every simulation

ABC storage method only was simulated once because I realised that results are very similar to Random storage, therefore I thought that it was not worth to do the double of simulations each time.

Almost all the coefficients of determination are closer to one, which means that the correlation between the factor and the response is high. When the value of one of these factors changes, the value of the response also changes.

Below, the analysis for the optimal routing strategy and random storage method is presented.

In the figures we can find different components. The first component is the main graph, where the response is displayed on the y-axis and the variable is on the x-axis. Inside the graph there is a regression line, if this line fits the data it means that there is correlation. In all the cases the regression line fits quite well.

![Fitted Line Plot](image)

Figure 19 Linear regression for the number of cross aisles vs response.
On the top there is an equation derived from the statistical software, which establish the numerical relationship between the variable and the response, this equation is used for predicting.

![Fitted Line Plot](image)

**Figure 20** Linear regression for the number of aisles/picker vs response.

Finally, on the right we can find the coefficient of determination and the coefficient of determination adjusted ($R^2_{adj}$). $R^2_{adj}$ plays the same role that $R^2$ but it is adjuster for the number of predictors in the model. We can also see the standard error of the regression ($S$) which is used to assess how well the regression equation predicts the response. The lower the value of $S$, the better the model predicts the response.

![Fitted Line Plot](image)

**Figure 21** Linear regression for the average number of lines/order vs response.
Conclusions

From the data obtained from the simulation tool and after the analysis it can concluded that the optimal strategy, as its own name indicates, is the best routing strategy for every situation. Then there are the Combined and Largest Gap, whose performance is very similar between them. And finally the S-shape, which is the worst by far.

As it was commented in the theoretical part, cross aisles facilitate moving around the warehouse; in figure (16) we can see that on average, increasing the number of cross aisles can decrease the travel time, but what is true is that only optimal strategy results benefited from any number of aisles. Thanks to the correlational analysis we could realise that heuristic strategies do not benefit as much as optimal does with any number of aisles. It seems that for a large number of cross aisles the travel time increases for heuristic routings, it may be due to the increase in distance travelled.

The use of ABC storage method benefits notably all the routing strategies. The data analysed shows that some routing strategies results more benefited than others, but it may be due to the data obtained.

With regard to the correlation study, there is a clear and strong relationship between the travel distance and the variables analysed, the value of the response will change when one of the factors studied change.

To sum up, the performance of a warehouse can increase notably if some of the methods studied before are applied. For instance, through the previous policies we could achieve the highest performance in a warehouse applying an optimal routing method, although the picking sequence can seem not logical the performance of this routing method is by far the best one, it was proved in the previous analysis, and implementing a storage method, because the benefits outweigh the disadvantages. These two implementations could lead to a significant decrease of the travel time, therefore a decrease in the travel costs.
Future research

Obtain data that could not be obtained with the simulation tool used, in order to have a more accurate and exhaustive study. In other words, enlarge the range of the study. For instance, explore what happens for warehouses with more than twenty cross aisles or aisles with a length larger than 200 m.

Analyse more routing strategies that could not be analysed because of the simulation tool, such as return, midpoint or composite strategies.

Due to the lack of information, it could be interesting analyse new storage methods that take into account factors such as consumer purchase. I am talking about Intelligent storage methods, like The cloud or Product group affinity, which in my opinion will be very used in the near future.

Develop an Excel sheet or some application able to calculate the travel time or the distance that a picker has to do in order to collect an order following some routing strategy.

Study and analyse picking operations that take place in a warehouse of a real company, in order to put into practice all the knowledge acquired along this thesis.
APPENDIX A

S-shape

1. The route starts by going from the depot to the front of the left most pick aisle that contains at least one pick location (which is called *left pick aisle*) (a).
2. Traverse the left pick aisle up to the front cross aisle of the farthest block (b).
3. Go to the right through the front cross aisle of the farthest block until a subaisle with a pick is reached (c). If this is the only subaisle in this block with pick locations then pick all items and return to the front cross aisle of this block. If there are two or more subaisles with picks in this block, then entirely traverse the subaisle (d).
4. At this point, the picker is in the back cross aisle of a block, and there are two possibilities:
   a. There are picks remaining in the current block. Determine the distance from the current position to the left most subaisle and the right most subaisle of this block with picks. Go to the closer of these two (e). Entirely traverse this subaisle (f) and continue with step 5.
   b. There are no items left in the current block that have to be picked. Therefore, continue in the same pick aisle to get to the next cross aisle and continue with step 7.
5. If there are items left in the current block that have to be picked, then traverse the cross aisle towards the next subaisle with a pick location (g) and entirely traverse that subaisle (h). Repeat this step until there is exactly one subaisle left with pick locations in the current block.
6. Go to the last subaisle with pick locations of the current block (i). Retrieve the items from the last subaisle and go to the front cross aisle of the current block (j). This step can actually result in two ways of traveling through the subaisle (a) entirely traversing the subaisle or (b) enter and leave the subaisle from the same side.
7. If the block closest to the depot has not yet been examined, then return to step 5.
8. Finally, return to the depot (k). [10]
Largest gap

1. Determine the left-most pick aisle that contains at least one pick location and determine the block farthest from the depot containing at least one pick location.

2. The route starts by going from the depot to the front of the left pick aisle (a).

3. Traverse the left pick aisle up to the front cross aisle of the farthest block (b).

4. Go to the right through the front cross aisle of the farthest block until a subaisle with a pick is reached (c). If this is the only subaisle in this block with pick locations then pick all items and return to the front cross aisle of this block. If there are two or more subaisles with picks in this block, then entirely traverse the subaisle (d).

5. The order picker is in the back cross aisle of a block, called the current block. Now there are two possibilities:
   a. There are picks remaining in the current block. Determine the subaisle of the current block with pick locations that is farthest from the current position. Call this subaisle the last subaisle of the current block. Continue with step 6.
   b. There are no items left in the current block that have to be picked. Continue in the same pick aisle to get to the next cross aisle and continue with step 9.

6. Follow the shortest path through the back cross aisle starting at the current position, visiting all subaisles that have to be entered from the back (e) and ending at the last subaisle of the current block (f). Each subaisle that is passed has to be entered up to the largest gap.

7. Entirely traverse the last subaisle of the current block to get to the front cross aisle (g).

8. Start at the last subaisle of the current block and move past all subaisles of the current block that have picks left. Enter these subaisles up to the largest gap to pick the items (h).

9. If the block closest to the depot has no yet been examined, then return to step 5.

10. Finally, return to the depot (k). [10]
APPENDIX B

Descriptive Statistics: Time. Simulation 1 - Random storage

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Analysis of Variance Simulation 2

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Descriptive Statistics: Time. Simulation 2 - ABC Storage

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<td>0</td>
<td>353.8</td>
<td>22.5</td>
<td>180.2</td>
<td>109.9</td>
<td>220.0</td>
<td>295.3</td>
<td>432.6</td>
<td>884.6</td>
</tr>
</tbody>
</table>
APPENDIX C

Optimal-ABC1 analysis

Fitted Line Plot
Time = 138.9 - 7.399 Cross Aisles

Fitted Line Plot
Time_1 = 49.32 + 7.862 Number of aisles/picker

Fitted Line Plot
Time_2 = 97.35 + 2.162 Average number of lines/order
S-shape-Random analysis

Fitted Line Plot
Time_3 = 262.8 + 8.804 Cross Aisles_1

Fitted Line Plot
Time_4 = 48.68 + 16.48 Number of aisles/picker_1

Fitted Line Plot
Time_5 = 170.9 + 2.864 Average number of lines/order_1
Largest Gap-Random analysis

**Fitted Line Plot**

**Time\textsubscript{6} = 247,0 + 15,24 Cross Aisles\textsubscript{2}**

\[ S = 22.0875 \]
\[ R-Sq = 85.3\% \]
\[ R-Sq(adj) = 83.7\% \]

**Fitted Line Plot**

**Time\textsubscript{7} = 59,49 + 11,84 Number of aisles/picker\textsubscript{2}**

\[ S = 16.9143 \]
\[ R-Sq = 95.3\% \]
\[ R-Sq(adj) = 94.7\% \]

**Fitted Line Plot**

**Time\textsubscript{8} = 123,9 + 4,026 Average number of lines/order\textsubscript{2}**

\[ S = 13.5903 \]
\[ R-Sq = 95.0\% \]
\[ R-Sq(adj) = 94.2\% \]
Combined-Random analysis

Fitted Line Plot
Time_9 = 224,8 + 13,48 Cross Aisles_3

Fitted Line Plot
Time_10 = 55,01 + 13,50 Number of aisles/picker_3

Fitted Line Plot
Time_11 = 144,6 + 3,238 Average number of lines/order_3
References


[8]: Rubenstein. L (2006), Intelligent Product Placement Strategies for Amazon.com’s Worldwide Fulfillment Centers, Master’s Thesis of Business Administration and Science in Engineering, Massachusetts Institute of Technology, United States.


