Preface

This Master Thesis is the result of cooperation between the Division of Packaging Logistics, Faculty of Engineering at Lund University and Microsoft Development Center in Copenhagen.

We would like to thank our supervisors Philippe Jacobsen and Thomas Jensen at Microsoft Development Centre in Copenhagen and our tutor Ola Johansson at the Division of Packaging Logistics, Faculty of Engineering at Lund University for constructive feedback and support during the project.

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Abstract

Title: Warehousing strategies – A simulation study

Division: Division of Packaging Logistics, Department of Design Science, Faculty of Engineering at Lund University.

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Key words: warehousing, picking methods, simulation, slotting, customer order profile

Purpose: Examine the effects of different warehousing strategies.

Problem: What effects can be seen through the use of different warehousing strategies based on different customer behavior?

Method: The simulation methodology used was based on Banks' line of action. The methodology regarding design of experiment was based on Montgomery's recommendations.

Objective: Quantify the picking efficiency gains associated to different warehousing strategies in a generic warehouse.

Conclusion: Customer behavior, as represented through customer order profiles, was more or less insignificant. Both slotting and viewing several customer orders at a time had major effects on both lead time, total pick time and total traveled distance.

Sammanfattning

Titel: Lagerstrategier – En simuleringsstudie

Avdelning: Avdelningen för Förpackningslogistik, Institutionen för Designvetenskaper, Lunds Tekniska Högskola.

Författare: Markus Hilmansson och Fredrik Johnsen.

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Företagshandledare: Philippe Jacobsen och Thomas Jensen, Microsoft Development Centre i Köpenhamn.

Nyckelord: lagerhantering, plockmetoder, simulering, inplacering, kundorder profiler

Syfte: Utvärdera effekterna av olika lagerhållningsstrategier.

Problem: Vilka effekter uppstår genom användandet av olika lagerstrategier baserat på olika kunduppföranden?

Metod: Simuleringsmetodiken baserades på Banks tillvägagångssätt. Metodiken relaterad till design of experiment baserades på Montgomerys rekommendationer.

Mål: Kvantifiera vinsterna, i form av plockeffektivisering, associerade till olika lagerhållningsstrategier i ett generiskt lager.

Slutsats: Kunduppförande, representerat genom kundorderprofiler, var mer eller mindre insignifikant. Både inplacering och valet att se på flera kundordrar samtidigt hade stora effekter på både ledtid, total plocktid och total tillryggalagd sträcka.

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1 Introduction

"Warehousing is expensive – making up between two and five percent of the cost of sales of a corporation. With renewed corporate emphasis on return-on-assets, minimizing the cost of warehousing has become an important business issue. At the same time, continued emphasis on customer services places most warehouse managers between the rock and a hard place – looking for ways to trim costs and improve customer services at the same time." [1]

"Never before has it been so critical for the warehouse to work efficiently, quickly and error free." [2]

1.1 Background

The project at hand is a cooperation between Microsoft Development Center in Copenhagen (MDCC) and Lund University, Faculty of Engineering, Department of Design Sciences, Division of Packaging Logistics. The focus of this project is to clarify and quantify when and where different warehousing strategies are useful. The choices of strategies have been set through discussions with tutor and supervisors.

1.2 Microsoft

Microsoft was founded in 1975 and is the worldwide leader in software, services and solutions that help people and business realize their full potential.[3]

Microsoft is divided into three core business to serve their customers[4], Microsoft Development Center Copenhagen is a part of the Business division, 750 employees makes the site to Microsoft's biggest development center in Europe[5].

MDCC have grown to become Microsoft's global Supply Chain Center of Excellence and develop, test and optimize ERP solutions for both small businesses and mega conglomerates. The primary products are Microsoft Dynamics AX and Microsoft Dynamics NAV.[6]

1.3 Purpose

The purpose of this master thesis is to examine the effect on picking efficiency when using different warehousing strategies in a generic warehouse. The strategies that are

[1] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 3
[2] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 5
[3] Microsoft Homepage: Press, 2009-01-27
[4] Microsoft Homepage: Business, 2008-10-02
[5] Microsoft Homepage: Proud Pioneers, 2008-10-02
[6] Microsoft Homepage: Bringing the Power, 2008-10-02

to be evaluated are number of viewed customer orders at a time and a selection of slotting methods. The strategies are also to be compared to different customer order profiles.

1.4 Problem definition

How do the chosen strategies really function in a warehouse and with what kind of order profile the different strategies are advisable respectively inadvisable? What combination of strategies are advisable respectively inadvisable in combination with different customer order profiles?

1.5 Focus and demarcations

The focus of the project is to analyze the picking efficiency in a generic warehouse. The basic warehouse activities, receiving and putaway are excluded, meaning that no focus will be given to the study and analysis of inventory levels or order quantities. Further delimitations will be that only a chosen set of picking methods will be studied. The warehouse is perfect in the aspects of inventory accuracy, pick accuracy and shipping accuracy, in other words error free. Due to the nature of a generalization, the model will not be exactly the same as a real warehouse. Finally all model input data is, in the aspect of route planning, heuristically optimized.

1.6 Target group

The target group for this master thesis is students at Lund University, Faculty of Engineering and concerned supervisors at the department and at Microsoft Development Center Copenhagen.

2 Methodology

Since the major part of this master thesis is based on simulation, the methodology used is therefore related to that. However a certain portion of the master thesis revolves around design of experiment and data analysis why suitable methodology regarding this have been used.

2.1 Line of action – Simulation[7]

When making a simulation study it is common to use a step by step method. The method used in this report is the one promoted by Banks. The steps can be seen in Figure 1 Steps in a simulation study.

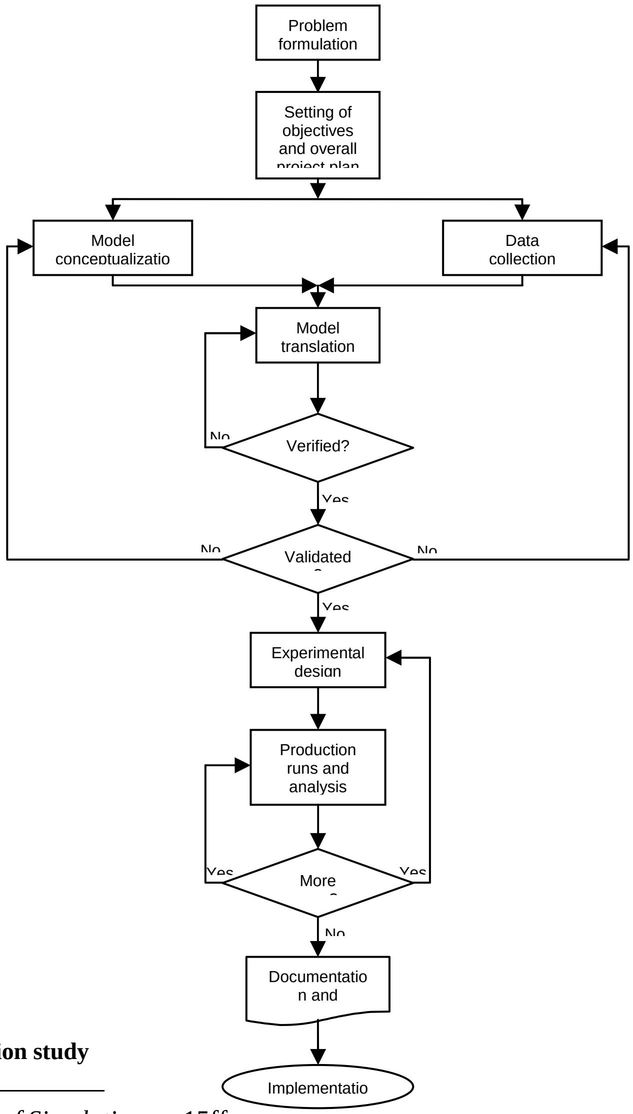

Figure 1 Steps in a simulation study

[7] Banks, 1998, *Handbook of Simulation*, p. 15ff

2.1.1 Problem formulation

A simulation study starts with stating the problem. It is important that everyone involved understand and agree on the formulation.

2.1.2 Setting of objectives and overall project plan

In this step it is determined whether or not the problem is suitable to solve through simulation. The objectives are the concrete questions that the study hopefully will answer to. If a simulation approach is decided upon, then the project plan should also include alternative systems to be considered and a method for evaluating them. The project plan is also to contain information on how much personnel involved, the total cost of the study and a time plan with specified goals at the end of every step.

2.1.3 Model conceptualization

The building of a model stars with an attempt to abstract the most essential characteristics of reality. From that basis details are added to the model one at a time until an acceptable and useful approximation results. Consequently it is best to start simple and add until desired complexity is reached. The model needs only to have a complexity equal to the requirements. Greater complexity only adds to the project costs. To increase the confidence of the model users they should be involved in the model conceptualization, in addition this will boost the quality of the resulting model.

2.1.4 Data collection

During the construction of a model there is a constant relationship between building it and gathering data for it. As the model grows in size and complexity it is likely that the required data also changes. Since collection of data makes up a large part of the project time it is important to initiate it early in the process. In large the data needed is connected to the project’s objectives.

2.1.5 Model translation

This step contains the important action of transferring the conceptual model into a digital one. The choice between hard coding and the use of simulation software is to be made. Though if it is possible to use simulation software the time required for model development is greatly reduced.

2.1.6 Verified?

At this point the model behavior and its results are compared to real data to see how well the model depicts reality.

2.1.7 Validated?

Validation is when the model is viewed upon as an acceptable image of the real system. To get there the model is tweaked and calibrated through an iterative process. The acceptance is to be gained from a person or group of people with great insight in the real system.

2.1.8 Experimental design

At this step the different alternatives that are to be simulated are decided upon. The decisions on which alternatives are to be run are often based on a small number of analyzed trial runs. The number of runs, simulation length and initialization time are all important issues to also decide upon.

2.1.9 Production runs and analysis

The runs and the following analysis are basis for the estimation of measures of performance.

2.1.10 More runs?

With the finished runs and corresponding analysis as a base the analyst decides whether or not more runs are needed. Also how these runs should be designed.

2.1.11 Documentation and reporting

Two types of documentation exist, which are program and process. The program documentation is an important step in the understanding of the program, for present users but also for future ones. Thorough program documentation vouches for quicker reusability, modification and understanding of the program.

It is also important with written progress reports to make up a history of the project. These reports can be of great value in the sense of keeping the project going in the right direction.

Reports should as well be forwarded to all the affected individuals, of the project. By doing this increases the awareness and enhances the successful completion of the project through useful input as early as possible.

In addition to the reports it is advisable to set up milestones along the way of the project. At these steps small presentations of the conceptual model, visual prototype etc. are to be shown to even further incorporate future operators and concerned personnel.

2.1.12 Implementation

The level of success in this phase is determined by how well the previous steps have been carried out. The success level is especially dependent on the involvement of the final model user, from start to end of the project.

2.2 Design and analysis of experiment[8]

When planning an experiment, a scientific approach must be employed. Statistical design of experiment has the goal of presenting valid and objective conclusions. The work of experimental design is based on collection of appropriate data that can be analyzed through statistical methods. It is important that a statistical approach is used so that meaningful conclusions can be drawn from the experiment. When data includes experimental errors, the way of statistic methodology is the only objective way of action. Consequently an experiment is always made up by both the design of the experiment and the statistical analysis of the data.

It is of great importance that everyone connected to the experiment have an idea of what is to be studied. Also how the data collection is to be performed and analyzed.

Guidelines for the recommended procedure are stated below.

1. **Recognition of and statement of the problem** – All ideas about the objectives of the experiment are necessary to be developed. It is important to get information from all involved parties, such as engineers, quality assurance, manufacturing, marketing, management, customers and operating personnel.
   To gain better understanding of the phenomenon studied a clear statement of the problem is often important.

2. **Choice of factors, levels and range** –The experimenter is to consider what factors that may be important for the performance of the system. The factors are classified as potential design factors or nuisance factors. Potential design factors are factors that may be varied in the experiment while nuisance factors may have large effects on the system but are uninteresting to analyze. When the design factors have been selected, the experimenter must choose the ranges over which these factors are to be varied. Also the specific levels at which runs are to be made. It is important to contemplate how these factors are to be measured and controlled.

3. **Selection of the response variable** – When selecting the response variable, or variables, it should be certain that the variable can grant useful data about the system. Often the average and, or, standard deviation of the measurements will be the response variable.

4. **Choice of experimental design** – This step involves the choice of number of runs and choice of run order. It is vital to keep the experimental objectives in

[8] Montgomery, 2001, *Design and Analysis of Experiment*, p. 11ff

mind when selecting the design. In many experiments it is already known that some of the factors will result in different responses. However it may be an objective to see which factors cause the difference and also in what magnitudes.

5. **Performing the experiment** – During an experiment it is important to observe the system carefully so that everything performs as planned. Errors in this phase can destroy the validity of the experiment.

6. **Statistical analysis of the data** – As stated before statistical methods are to be used when analyzing the data to grant objectiveness to conclusions and results. Often simple graphical methods are important in data analysis and interpretation. Hypothesis-testing and confidence interval estimation procedures are very useful when analyzing data from a designed experiment. In addition an empirical model, an equation derived from model data, can be very useful when presenting the results to show the relation between design factors and responses. Statistical methods cannot prove that a factor has a particular effect, but it can grant a level of reliability and validity to the results.

7. **Conclusions and recommendations** – When the analyses have been conducted it is up to the experimenter to draw practical conclusions about the results and conclude recommendations.

2.2.1 Statistical techniques in experimentation

Much research is empirical and uses experimentation. For the experimenter to make proper use of statistical techniques it is important that the following points are kept in mind:

1. **Use your nonstatistical knowledge of the problem** – Experimenters should be knowledgeable in the researched field. Nonstatistical knowledge is invaluable when choosing factors, levels, numbers of replications and interpreting results. Using statistics is no substitute for thinking about the problem.

2. **Keep the design and analysis as simple as possible-** Do not use too complex statistical techniques. Simple design and analysis methods are often best.

3. **Recognize the difference between practical and statistical significance** – Even if an experiment produce statistically significant responses it is not

necessary that they are practically significant. Meaning that the implementation cost might be to high compared to the gain.

4. **Experiments are usually iterative** – In most situations it is advisable to use an iterative approach when designing experiments.

2.3 Statistical analysis

2.3.1 Line of action[9]

Schematically the line of action can be described as below.

- Problem formulation
- Problem formulation conversion to hypothesis
- Sampling from population. Numerical calculation
- The null hypothesis is accepted or rejected

Acceptance or rejection is not the same as research finished. A study can spawn new problem formulations indefinitely.

2.3.2 Model analysis[10]

Normally it is of interests to test the significance of the model, that is to say if there exists a significant relationship between the resulting variable and the chosen set of input variables.

The null hypothesis states that there is no relationship between the resulting variable and the chosen set of input variables. The alternative hypothesis states that the relationship exists.

2.3.3 Hypothesis testing with p-value[11]

Depending on the nature of the problem formulated different levels of significance can be used.

The p-value, probability value, is determined for the null hypothesis. The p-value represents the likelihood of obtaining a result at least as large as the difference between the sample value and the null hypothesis value. If the p-value is little the null hypothesis can be rejected and the smaller it is the more support is granted to the alternative hypothesis.

[9] Körner et. al., 2000, *Statistisk Dataanalys*, p. 189
[10] Körner et. al., 2000, *Statistisk Dataanalys*, p. 359
[11] Körner et. al., 2000, *Statistisk Dataanalys*, p. 199ff

The level of significance based on p-value can be represented symbolically, as described below.

- P-value < 0.1% = ***
- P-value < 1.0% = **
- P-value < 5.0% = *
- P-value > 5.0% = no significance

3 Theoretical framework

3.1 Simulation theory[12]

Simulation is an imitation of a real-world process or system over time. It involves the generation of an artificial history to draw inferences concerning the operating characteristics of the real system that is represented. Simulation can describe and analyze the behavior of a system, ask what-if questions about the real system, and support the design of real systems.[13]

A model is a representation of an actual system, it should be complex enough to answer the raised questions but not too complex. There are different types of simulation, in this case discrete-event simulation will be used, a discrete-event model attempts to represent the components of a system and their interactions to such a level that objectives of the study are met. This type of model includes a detailed representation of the actual internals and is dynamic, which means that the passage of time plays an important role.[14]

Simulation enables the study of, and experimentation with, the internal actions of a complex system, or of a subsystem within a complex system, different kind of changes can be simulated and the effect of these alternations of the model's behavior can be observed. The knowledge gained in the model may be of great value toward suggesting improvement in the system under investigation. By changing the input to the simulation model and observing the resulting outputs valuable insights may be obtained. Insights explaining what variables are most important and how they interact.

There are several purposes with simulation; it can be used as a pedagogical device to reinforce analytic solution methodologies and to experiment with new designs or policies prior to implementation, so as to prepare for what may happen and to verify analytic solutions. By simulating different capabilities for a machine, requirements can be determined; it can also help in training without the cost and disruption of on-the-job learning.

Visualization is possible through animated simulation models, this helps when big modern systems such as factories and service organizations are simulated because they can be so complex that the interactions only can be treated through simulation.

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[12] Banks et. al., 2001, *Discrete-Event System Simulation,* p. 4ff
[13] Banks, 1998, *Handbook of Simulation*, p. 6
[14] Banks, 1998, *Handbook of Simulation*, p. 6

There are times when simulation is not appropriate; it should not be used when the problem can be solved using common sense or when it can be solved analytically or if it is easier to perform direct experiments.

It should neither be used if the simulation project costs exceed the savings or if the resources or time are not available.

Simulation takes data, sometimes lots of data, if no data is available, not even estimates, simulation is not advised. If there is no ability to verify and validate the model simulation is not appropriate.

3.2 Basic warehouse functions

Warehouse functions includes several activities, the most basic ones are described below.

3.2.1 Receiving[15]

Receiving is the setup for all other warehouse activities; if units are not properly received it will be very difficult to handle it properly in put-away, storage, order picking and shipping. And if damaged or inaccurate deliveries are allowed then it is likely that damaged or inaccurate units will be shipped.

3.2.2 Putaway[16]

Putaway is the action of transporting units from receiving area to the storage area. Putaway is order picking in reverse.

3.2.3 Storage[17]

Storage is the activity that provides a unit, with a warehouse location, from where it later on can be accessed and picked to an order.

3.2.4 Order Picking[18]

An employee is required to manage the order-pick activity. The responsibility of the employee, picker, is to pick the correct articles in the correct quantities as specified on an order. The order-pick activities include: listing order-lines, travelling to pick-up points, removing units from the pick-up points, verify the inventory reduction and transporting the units to stage or shipping area.

[15] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 74
[16] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 80
[17] Mulcahy, 1994, *Warehouse Distributions & Operations Handbook*, p. 2.4
[18] Mulcahy, 1994, *Warehouse Distributions & Operations Handbook*, p. 2.4

Order picking operating rates differ depending on aid; a picker using a cart performs somewhere between 25-60lines/hour and a picker using a powered pallet jack is able to pick 30-80lines/hour.[19]

3.2.5 Shipping[20]

The objective of the shipping function is to make sure that order-picks have been correctly performed, in the aspects of articles and quantities. Activities carried out here include scheduling of delivery trucks, sorting, consolidation, packing, addressing manifesting and loading.

3.3 Slotting[21]

Slotting is the work of determining, for each article in a warehouse, appropriate storage mode, appropriate allocation of space in its appropriate storage mode and appropriate storage location in its appropriate storage mode.

3.3.1 Profiling

With profiling means the work of maintaining order profiles, item activity profiles and planning profiles to identify root causes of process impediments and breakthrough opportunities for improvement.[22]

To carry out the work of slotting it is important to generate item activity profiles, so that decisions can be based on hard facts.[23]

Pareto Principle

The Pareto principle is named after the Italian national economist, Vilfredo Pareto (1848-1923), who said that roughly 20% of the population stands for approximately 80% of the wealth in a state. Due to this, the principle is also called the rule of 80/20.[24]

The principle can be transferred to a range of areas, among them warehousing. In warehousing, for example, the principle can be used to show that a minority of articles make up for the majority of the turnover.[25]

The more popular an item is the more accessible warehouse location it should placed in, close to the door and close to the floor[26]. The three zones of Pareto's law are

[19] Sisko et. al., 2003, *Rules of Thumb*, p. 17
[20] Mulcahy, 1994, *Warehouse Distributions & Operations Handbook*, p. 4.1
[21] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 168
[22] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 6
[23] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 30
[24] Nationalencyklopedin Homepage Keyword: Pareto, 2008-09-17
[25] Lumsden, 2006, *Logistikens Grunder*, p. 460ff
[26] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 30

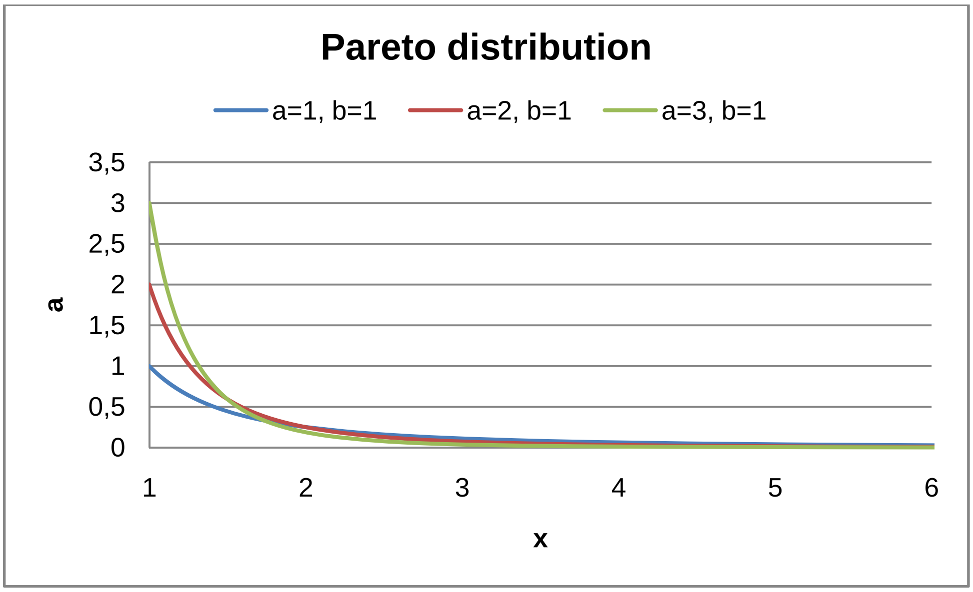
named A, B, and C. The A-zone contains the most fast moving items, B-zone the little less popular items and C-zone the least popular items.[27] This is why the Pareto distribution is also called ABC-curve or popularity distribution[28].

The probability density function for a Pareto curve can be seen in the Equation 1 Pareto density function below and illustrated in Chart 1 Pareto distributed density function.

$$P(x) = \frac{(a * b^a)}{x^{a+1}}, x \geq b$$

Equation 1 Pareto density function[29]

Chart 1 Pareto distributed density function[30]



Family grouping principle

This principle states that similar items, in terms of, needs and co-ordering should be placed as a group or family in the warehouse.[31]

[27] Mulcahy, 1994, *Warehouse Distributions & Operations Handbook*, p. 3.14
[28] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 30
[29] Wolfram MathWorld Homepage, 2009-01-16
[30] Authors' processing of Wolfram MathWorld Homepage, 2009-01-16
[31] Mulcahy, 1994, *Warehouse Distributions & Operations Handbook*, p. 3.19

Order pattern principle

This principle states that similar items, in terms of, co-ordering and popularity should be placed as a group or family in the warehouse.[32]

3.4 Picking strategies[33]

Picking strategies in a warehouse can be defined by the combination of the number of orders being picked together and how large part of the warehouse being picked from at the same time. There are four fundamental combinations that all modern picking strategies can be derived from. These can be seen in Figure 2 Picking methods.

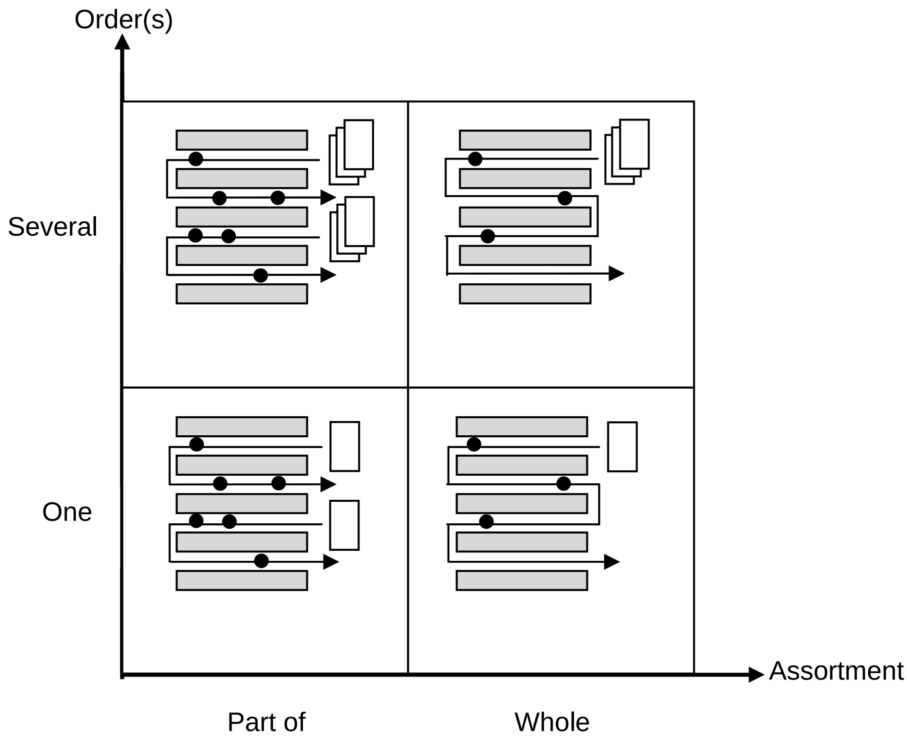


Figure 2 Picking methods

3.4.1 Zone picking (One order-Part of assortment)

This method splits an order into several orders answering to the zoning of the warehouse. The pickers work in a given area, zone, and pick their portion of articles. Then the next picker picks their share, and so on.

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[32] Mulcahy, 1994, *Warehouse Distributions & Operations Handbook*, p. 3.19

[33] Lumsden, 2006, *Logistikens Grunder*, p. 474ff

The size of a zone is determined by the amount of goods being picked in the area and speed of picking relative to storage method. The advantage of this method is that distance per order row is decreased. The downside is that extra sorting is needed.

3.4.2 Single order picking (One order-Whole assortment)

This strategy is characterized by that one picker is responsible for the completion of a full order. The drawback of this strategy is the low picking effectivity due to the long distances the picker must travel. The gain is that errors are reduced since orders are kept separately and no area, or personnel, is needed for sorting.

3.4.3 Progressive order assembly (Several orders-Part of assortment)

Pickers in an organization using progressive order assembly are accountable for picking parts of several orders at the same time. The strategy is often implemented in systems using mechanized conveyors. The major benefits from using this method is that greater volumes and order sizes can be managed and that an order can be completed faster, since a number of persons are picking at the same time.

3.4.4 Batch picking (Several orders-Whole assortment)

When using this method pickers are responsible for completing several orders at a time. Sorting of the goods can either be done during picking or afterwards. The primary benefit of this strategy is the reduction of movement per order row. The downside is the added equipment, area and personnel needed for sorting.

3.5 Route planning

A route planning problem can be defined as how to serve a certain amount of customers with different demands as efficient as possible. Gathering/picking starts from one or several terminals that are trafficked by one or more trucks/pickers. The routes are built so that all customers' needs are satisfied without the maximum capacities of the pickers being exceeded.[34]

In reality route planning problems are very complex, which is why simplified mathematical models are used.[35]

A route planning problem where certain relaxations have been made is called a classical route planning problem. The prerequisites are that the distances between terminal and pick-up points are known and compiled in a distance table. In addition the pickers capacities are considered homogenous, that is to say that all pickers have the same capacity. Every picker is only allowed to traffic one route and all routes start and end at the terminal. This can be seen as a classical optimization problem of

[34] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 5ff
[35] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 5ff

mathematical character. In a system of unknowns, who correlate with each other, the best solution with certain delimitations is searched for.[36]

3.5.1 Savings methods

Route planning methods of savings type are built upon a savings function. It emanates from the principle that from every change of the present solution an improvement regarding total cost (cost or distance) is to be made.[37]

The most famous savings method is the one that was presented by Clark and Wright 1964. The method has an initial state where every individual pick-up point is visited by an individual picker. The initial solution is often forbidden since it uses more pickers than available.[38]

When the initial state is defined the goal is to successively decrease the total transportation cost and at the same time eliminate the non-existing pickers from the solution. This goal is to be reached by connecting the routes in couples. A connection means that a picker serves all pick-up points on the linked route without the picker capacity being exceeded. It should be added that the final solution might not be optimal, since the number of combinations is so large and therefore to time consuming to evaluate.[39]

One drawback of the Clark and Wright method is that preferentially connects pick-up points in the periphery.[40]

An example of the Clark and Wright method can be seen in Appendix A: The Clark and Wright method.

3.5.2 Other route planning methods[41]

One of the simplest route planning methods is the S-shape method. The S-shape method means that any aisle that contains at least one item is traversed entirely; aisles without items are not entered. From the last visited aisle the picker returns to the stage area.

Another simple method is the return method where the picker enters and leaves each aisle from the same end. Only aisles with items to pick are entered.

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[36] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 7
[37] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 16
[38] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 16ff
[39] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 16ff
[40] Lundgren et. al., 1993, *Handbok i Ruttplanering*, p. 20
[41] de Koster et. al., 2007, *Design and Control of Warehouse Order Picking: A Literature Review*, p. 481ff

The midpoint method divides the warehouse into two areas. Items in the front half are accessed from the front cross aisle and picks in the back half are accessed from the back cross aisle. The picker traverses to the back half by either the last or the first aisle to be visited.

All of these methods can be modified and combined.

3.6 Fixed and floating placement[42]

In a system using fixed placement, every article has its pre-defined placement. The size of the warehouse is the sum of all articles safety stock and order quantities.

The opposite of fixed placement is floating placement. When using this method, the items can be placed anywhere in the warehouse. This means that the warehouse can be used more efficiently and that the needed warehouse size is reduced. The placement of an item is determined, through system supported optimization, when arriving to the warehouse. When making withdrawals from the warehouse, some kind of system support is also needed.

Combinations of fixed and floating placement are obviously also possible[43].

3.7 Lines per order distribution[44]

The lines per order distributions can vary greatly. In certain industries, such as the mail order industry, single or few lines per order is common, whereas in the retail industry the lines per order distribution is characterized by several lines per order. It is important to consider the operation strategies that take advantage of the present order profile.

[42] Lumsden, 2006, *Logistikens Grunder*, p. 456
[43] Lundin, 2008, *Kurskompendium i Materialhandling*, p. 18
[44] Frazelle, 2002, *World-Class Warehousing and Material Handling*, p. 28ff

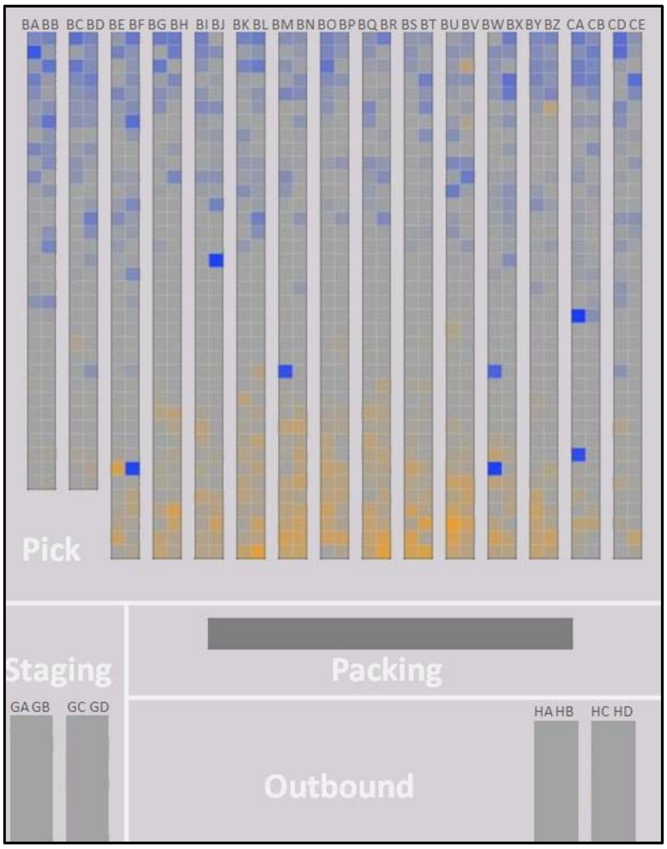
4 Empirics

4.1 Simulation model

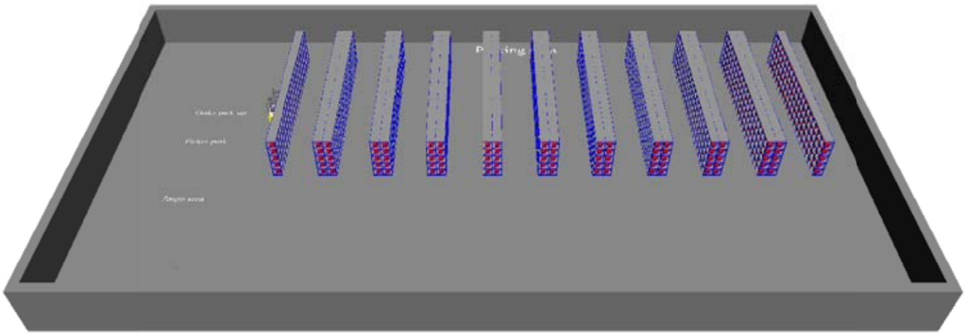
The simulation model is built in AutoMod. AutoMod is a simulation tool with 3D-visualisation possibilities with certain modules that facilitates simulations of this nature.

4.1.1 Layout

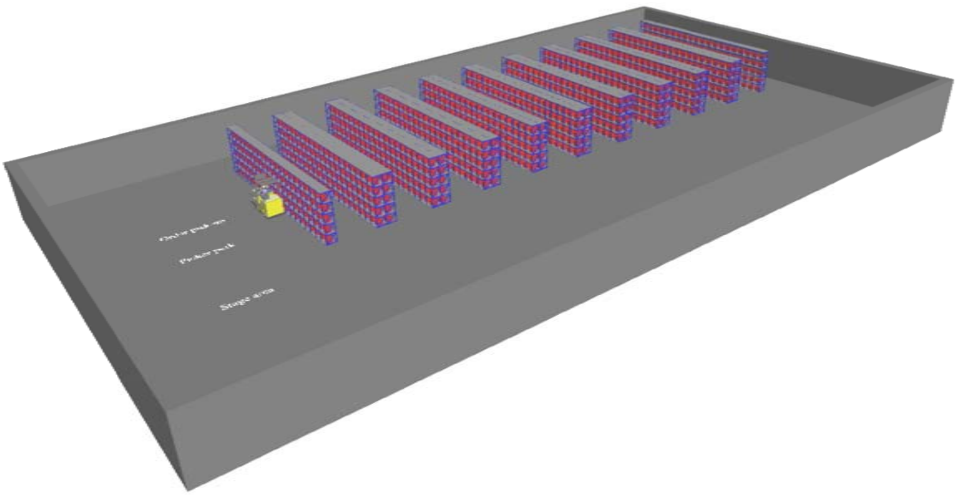
The warehouse layout it based on a demo layout provided by Microsoft Development Center in Copenhagen. This can be seen in Picture 1 Warehouse demo layout below. The simulated warehouse consists of ten aisles. Each aisle contains of two sides, where each side has 20 racks and five tiers. The whole warehouse has a width of 60 meters and a length of 20 meters. One aisle is consequently four meters wide and 20 meters long. Each rack is one meter wide and each tier is one meter high. The layout is illustrated in Picture 2 View of warehouse, Picture 3 View of warehouse and Picture 4 View of warehouse.



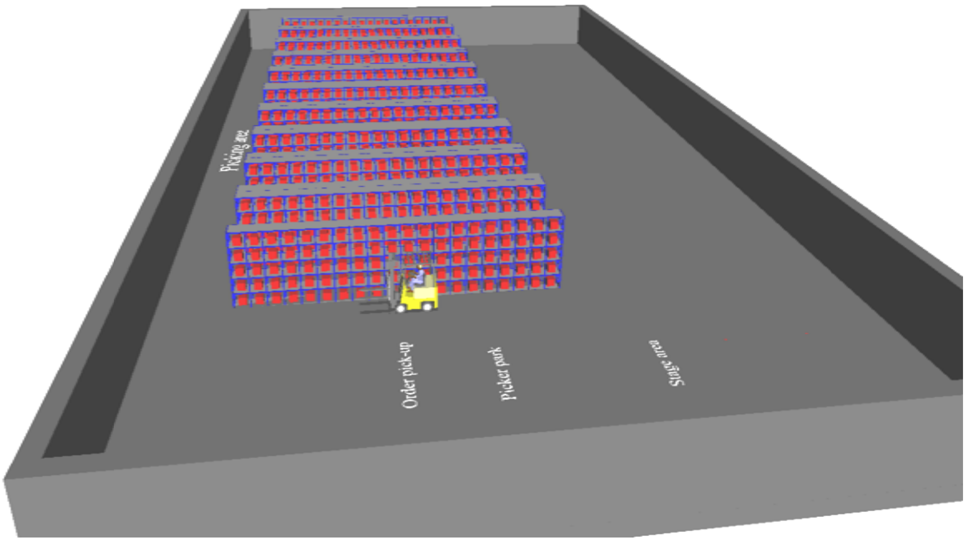
Picture 1 Warehouse demo layout



Picture 2 View of warehouse



Picture 3 View of warehouse



Picture 4 View of warehouse

The model uses three different, fixed, slotting principles. The first is based on the frequency of an items demand. With this method the most popular item, item one, is placed at the nearest position and the least popular item, item 2000, at the position most far away. When using the second slotting principle all units are placed randomly in the warehouse. The third principle places all units in three different zones, A, B and C. The most popular units are randomly placed in the A-zone, the least popular units randomly placed in the C-zone and all the remaining units are randomly placed in the B-zone. There are three alternative settings of the zone principle, one where the size of the A-zone is 5%, the B-zone is 60% and the C-zone is 35%. In the second alternative is the size of the A-zone is 20%, the B-zone is 50% and the C-zone is 30%. In the third alternative the size of the A-zone is 35%, the B-zone is 40% and the C-zone is 25%.

4.1.2 Picker specifications

There are six pickers in the model, all of them have the same specifications. The specifications are assessments based on the data stated in Gross & Associates, “Rules of Thumb”[45]. The velocity of a picker is 1 meter per second. To avoid a collision when two pickers meet one of them is forced to decelerate and stop to let the other one pass. Afterwards it can accelerate and continue at normal velocity. The picker has a maximum capacity of 120 units.

When a picker picks up an order it is done more or less on the run, therefore the order pick up time is two seconds. When a unit is being picked the action takes five

[45] Sisko et. al., 2003, *Rules of Thumb*, p. 17

seconds. If there is a demand for several units from the same position the time is multiplied with the number of units. Depending on which tier the unit is placed on it takes a different amount of time, for every tier two seconds are added.

This means, if three units are to be picked from the fourth tier the time consumed is made up by the following: two seconds times four, depending on the tier, and then an additional five seconds times three, depending on how many units that are picked. Therefore the total time will be 23 seconds.

When a picker unloads a unit at the stage area it takes 2 seconds.

4.1.3 Logic

When the simulation starts all pickers are waiting at the park area and all orders are waiting to be picked. An order appears at the pick-up point and thereby activates a picker who travels to pick it up. The picker travels to the position where the item on the first order line is placed. Depending on the amount of units demanded the picker stays at the pick-up position until all units are picked. If an item from the same position is needed by another picker that picker waits until the first picker has finished and the position is available. When all units are picked the picker travels to gather the item on the next order line and repeats the picking procedure.

When the last order line is picked, and the order is finished, the picker travels to the stage area and unloads all units. There can only be one picker occupying the stage area at a time. If the stage area is already occupied the other pickers waits in line for their turn.

When all units are unloaded the picker checks if there are any orders left at the order pick up point. If so the picker travels there to pick up an order, otherwise it travels to the park area and waits until an order appears at the order pick-up point. When the picker has left the stage area auxiliary personnel consolidates and packs the customer order for one minute.

When a customer order has been fulfilled it is shipped.

4.1.4 Distance table

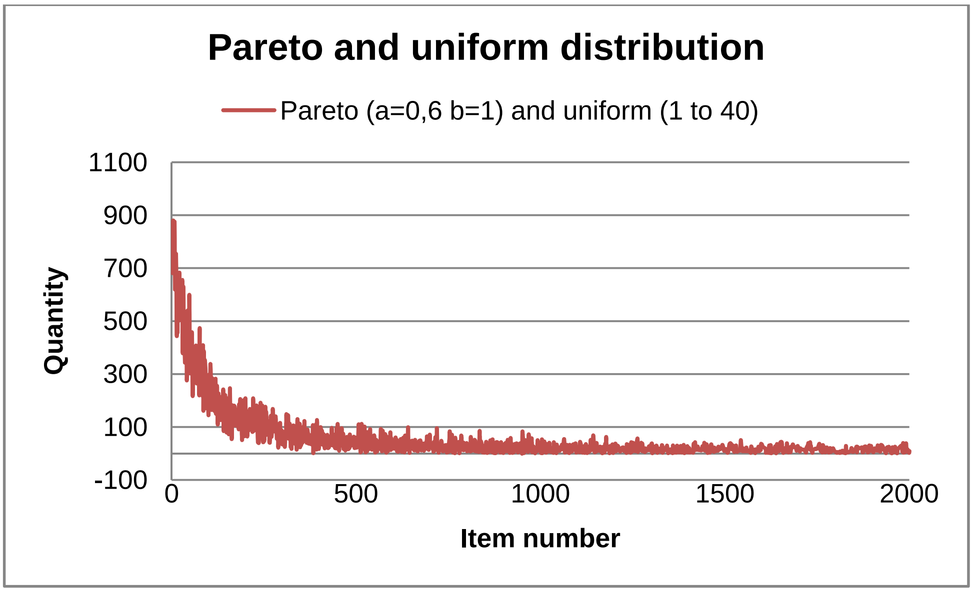
The distance table, which the route planning is based on, is built in the simulation model. In one run one picker travels from the order pick-up point to all positions in the warehouse and also between all positions in the warehouse. The picker always travels the shortest route, from A to B, and the distance is exported to an Excel sheet. The Excel sheet is used to calculate the savings values in the route planning.

4.2 Generation of raw order

Based on Frazelle's thoughts on lines per order distribution, discussions between supervisors, tutors and authors; the guidelines for raw order and order profiles were generated.

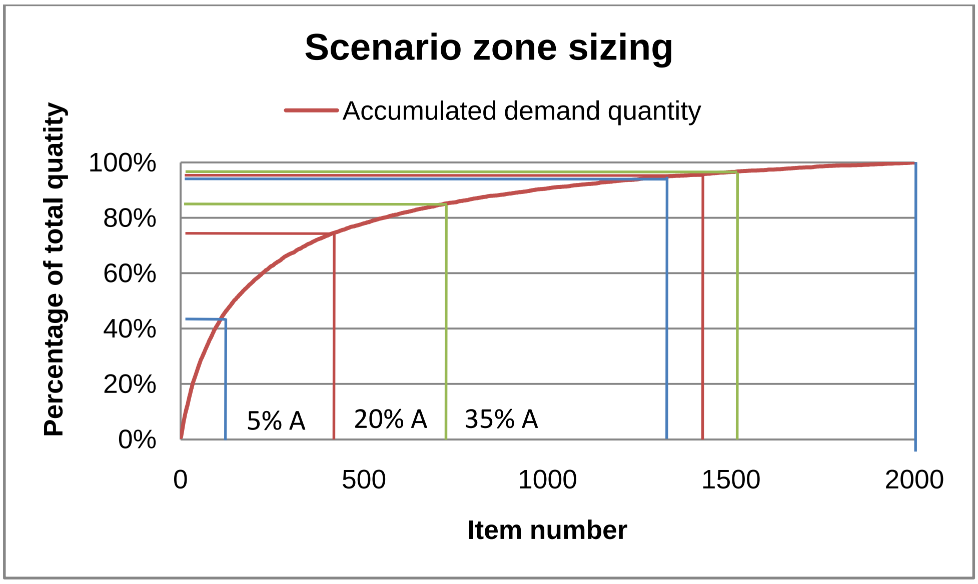
The raw order was generated based on the Pareto density function with the constants a=0.6 and b=1. 10000 order lines were generated containing 2000 unique items in different quantities. The quantities were derived from a uniform distribution between one and 40. The superposition of these distributions can be seen in Chart 2 Pareto and uniform distribution.

Chart 2 Pareto and uniform distribution



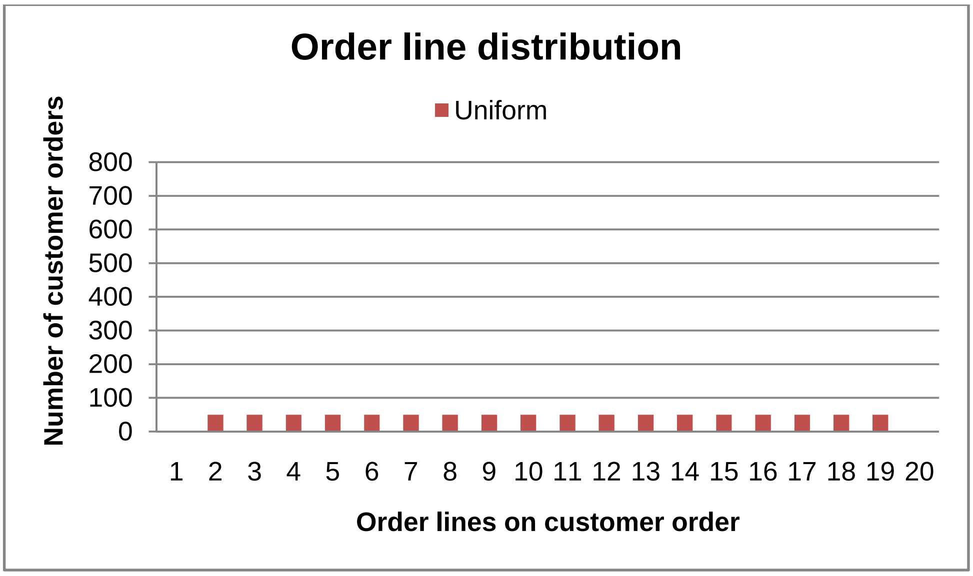
The three different zone sizing settings can be seen in Chart 3 Scenario zone sizing below.

Chart 3 Scenario zone sizing



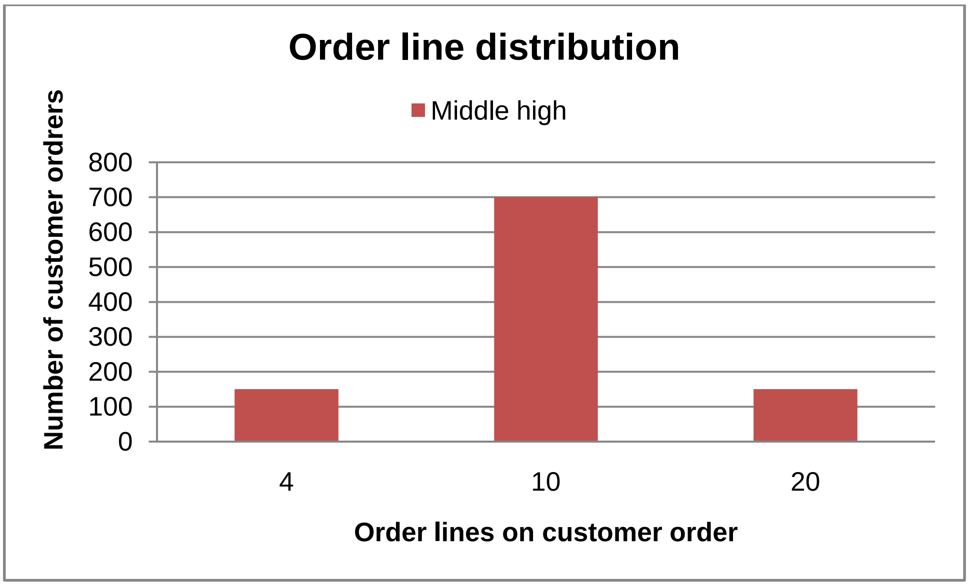
From the raw order three different order profiles were created.

Chart 4 Uniform order line distribution



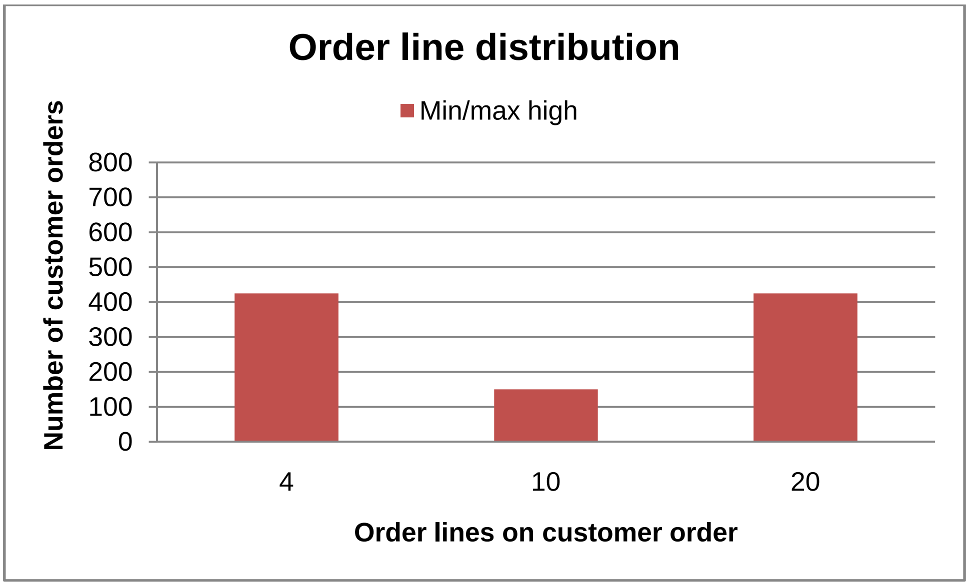
In the first profile the customer order lines were randomized between two and 19.

Chart 5 Middle high order line distribution



In the second profile the majority of the order lines, 70%, were portioned in tens.15% of the order lines were portioned in bundles of four and the remaining 15% in bundles of 20.

Chart 6 Min/max high order line distribution



In the third profile 42.5% the order lines were portioned in bundles of four. The other major part of the order lines, 42.5%, was portioned in bundles of 20. The remaining 15% was bundled in tens.

When the raw order was processed, into a profiled order, it was divided into raw customer orders. The customer orders were then concentrated so that all order lines were unique in the customer order. There was never more than one order line containing a specific item in a customer order. This means that the order profiles that were used in the simulation looked a little bit different even if the three profiles consisted of exactly the same items and quantities. The used order line distributions can be seen on the following charts.

When generating the order line distributions it is possible to get more than one order line, containing the same item, on the same customer order. When this happens the order lines are consolidated to one order line with a quantity equal to the sum of the individual order lines.

Chart 7 Uniform order line distribution

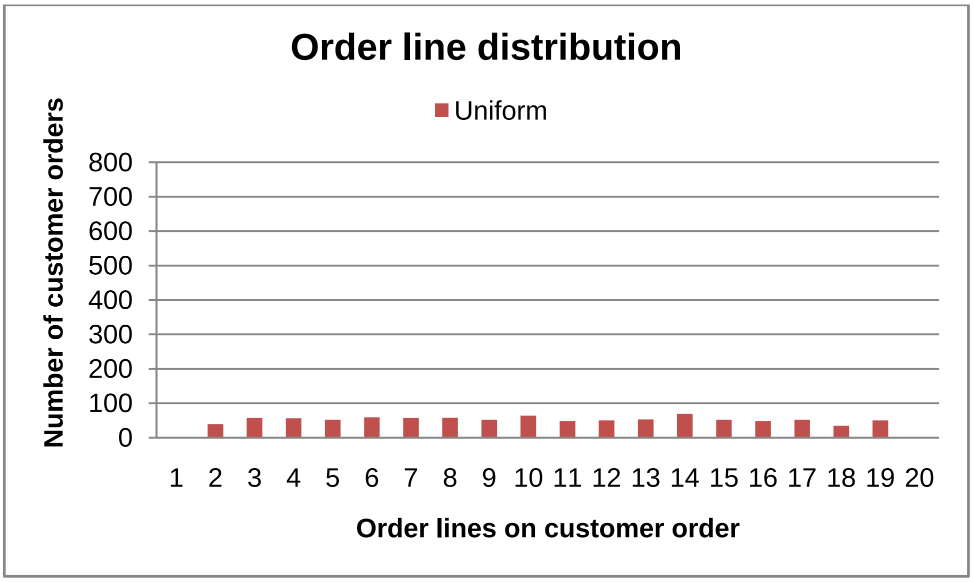


Chart 8 Middle high order line distribution

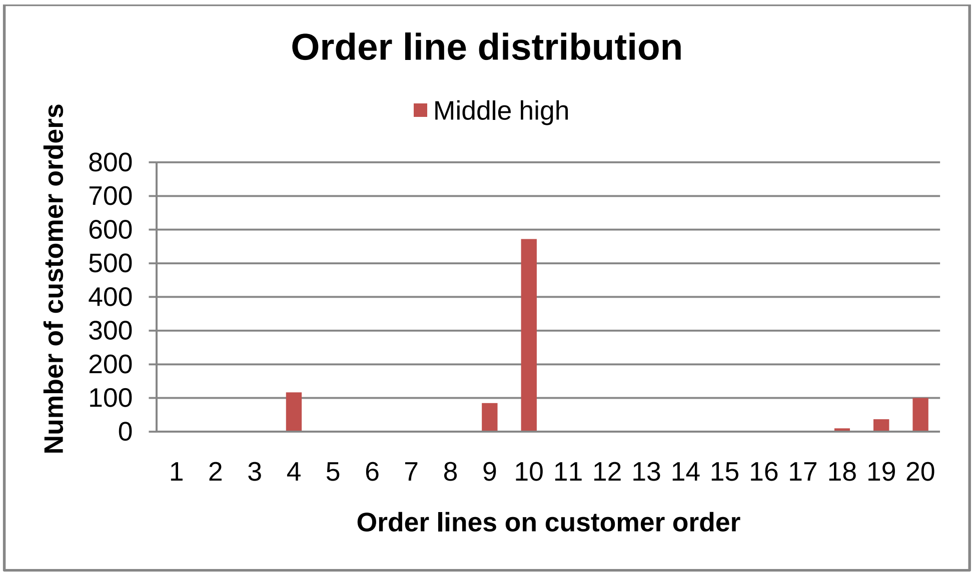
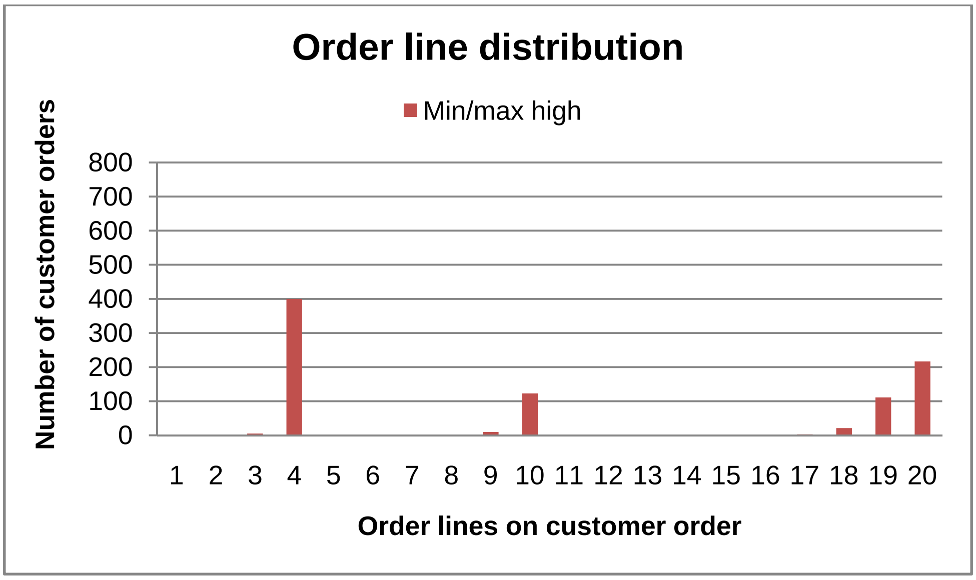


Chart 9 Min/max order line distribution



4.3 Route planning program

The route planning program is written in visual basic and outputted in an Excel sheet. The route planning method used in the study is built on the one proposed by Clarke and Wright. Since the method in its pure form is not directly implementable the authors were forced to modify and add to it.

The customer orders are analyzed individually or in bundles of ten depending on the specifications of the current optimization. The order lines that individually, or together with other order lines containing the same article, can fill up the capacity of a picker are removed until later since those order lines already are optimized.

The remaining articles on the order are then connected with each and every other article on the order so that the Clark and Wright savings value can be calculated. Then the couples are sorted among each other on which couples give the highest savings. If zoning is used the sorting is primarily done on zone belonging; A, B, C or mixed. The articles on a route are chosen in couples. The first couple decides what other couples are eligible to connect to the series. For every pick a capacity check is performed to see if the picker can handle the amount of articles in the picking route.

There is, as mentioned above, also a choice of zoning in the program. When using zones, all articles in a pick series are confined to one zone at a time. If only one more order line exists in a certain zone or in the present portion of customer orders an over capacity of up to 20% is tolerated and the last article may be picked to.

When all the picking series are done, in the present portion of customer orders, the series are consolidated with the full picks removed earlier and a matrix of sorted order information is created as input to the simulation model.

One after the other, all customer orders are optimized as described above.

4.3.1 Route planning output/Model input

The output from the route planning program is an Excel sheet containing order information. Every line contains the following information: “Pick order number”, “Item”, “Quantity”, “Identity of the customer order”, “Total item quantity on customer order”, “Total number of lines on pick order”.

Every line in the sheet belongs to a certain pick order. The pick order specifies what items are to be picked during a route. The items are identified by a number and have a certain quantity. The identity of the customer order exists to keep track of what item, in what quantities, belong to what customer order when optimizing routes for ten customer orders at a time. Total article quantity on customer order and total number of lines on pick order are information only created to help with tracking in the simulation model.

The order the pick order is arranged in is the output order from the route planning program.

4.4 Verification and validation

Since the simulated warehouse is a general warehouse, and that no hard, or measured, data exists it is not possible to verify it. The model is validated by the supervisors and the tutors through discussions and visualization in an iterative process where the picker specifications and whole system acts like it is supposed to, the picker travels to the right positions and picks the right items in the right order, and the system acts realistic.

4.5 Experimental design

There are 30 scenarios built up by, three different order profiles, five slotting types and four different picking methods. The scenario tree can be seen in Appendix B: Scenario tree. The model runs until all orders are picked. Since the runs have definite start and end points and all runs are compared to each other regarding all data, no warm up time is needed.

4.6 Measurements

The model measurements used are the following:

- Total distance traveled for all pickers per simulation run
- Total lead time
- Sum of all pick order times

The total distance traveled for all pickers per simulation is the measurement of how far all pickers together have traveled to complete the set of orders handed to them.

Total lead time is the measurement of how much time is consumed from the first pick order is activated until the last pick order is finished. This measurement is influenced by the number of available pickers.

Sum of all pick order times is the summation of how much time is needed to finish every individual pick order. This measurement is not influenced by the number of available pickers. At least not more than by the temporary clogging of aisles.

5 Analysis

The first step of the analysis was to do a statistical analysis using Minitab. Two different experiments were performed individually. The first experiment contained the data relating to random versus frequency-sorted slotting, 12 runs, and the second one was based on the data derived from runs with different zone size slotting, 18 runs. Two kinds of analyzes were performed. Firstly a Factorial fit was run on both experiments and secondly a Regression analysis was performed on the data of the second experiment since it was not explained by the Factorial fit.

The final influence on the result/response variable of the statistical analysis can be viewed in Appendix C: Results of statistical analysis. Only the factors that are significant have been kept. The level of significance is shown for each factor and interaction. The results explain how the different factors, and interactions, affect the warehouse’s performance.

The table below shows the effect of different settings of the number of viewed customer orders and the choice of slotting type for the analysis of random versus frequency-sorted slotting. The effect measurements of these settings are: Total lead time in hours, Total pick order time in hours and Total pick order distance in meters. The percentages are calculated compared to the worst possible setting, which is one order at a time and random slotting.

Table 1 Number of viewed customer orders versus slotting method

			Number of viewed customer orders			
			1		10	
Slotting method	Random	Total lead time (h)	67.99	0.0%	64.19	-5.6%
		Total pick order time (h)	398.39	0.0%	378.10	-5.1%
		Total pick order distance (m)	299 274.74	0.0%	269 411.55	-10.0%
	Frequenced	Total lead time (h)	63.71	-6.3%	61.04	-10.2%
		Total pick order time (h)	372.80	-6.4%	359.25	-9.8%
		Total pick order distance (m)	192 635.97	-35.6%	102 089.73	-65.9%

The reason why the gain in total pick order distance is so great compared to total pick order time when using frequenced slotting is because the travel speed of a picker is high compared to the time it takes to perform a pick at a pick-up point. The effect of more efficient picking routes is shadowed by long pick-up times.

In the next table the effect of different settings in the choice of zone size and the number of viewed customer orders for the Regression analysis of different zone size can be viewed. The effect measurements of these settings are: Total lead time in hours, Total pick order time in hours and Total pick order distance in meters. The percentages are calculated compared to the worst possible setting, one order at a time and a small A-zone.

Table 2 Number of viewed customer orders versus zone sizing

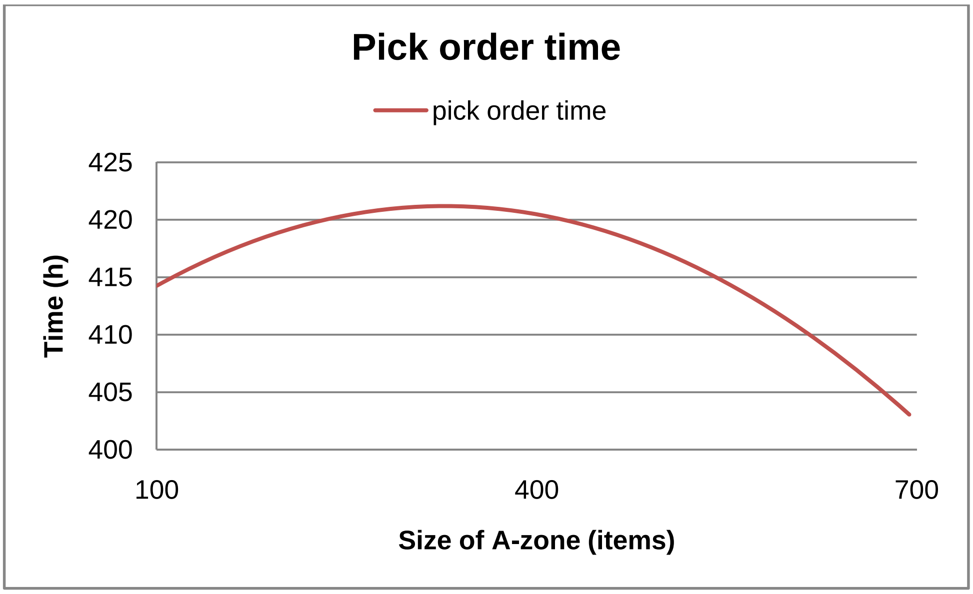
Zone sizing		Number of viewed customer orders: 1		10	
A:5%, B:60%, C:35%	Total lead time (h)	80.46	0.0%	70.29	-12.6%
	Total pick order time (h)	466.69	0.0%	414.20	-11.2%
	Total pick order distance (m)	506 046.65	0.0%	384 175.00	-24.1%
A:20%, B:50%, C:30%	Total lead time (h)	79.93	-0.7%	71.27	-11.4%
	Total pick order time (h)	463.59	-0.7%	419.96	-10.0%
	Total pick order distance (m)	500 175.66	-1.2%	384 539.83	-24.0%
A:35%, B:40%, C:25%	Total lead time (h)	74.91	-6.9%	68.50	-14.9%
	Total pick order time (h)	434.37	-6.9%	403.37	-13.6%
	Total pick order distance (m)	388 842.00	-23.2%	300 642.31	-40.6%

The reason why the results (distance and time measurements) are worse, when using zoning, is that a picker always sticks to the “rules” of zone picking/progressive assembly. Sometimes it would be better to consolidate three very small picks instead of having three different pick orders making each picker pick only a few units in their given zone.

The data analysis concluded that the distribution of order lines, customer order profiles, was not significant. It was not statistically significant in any analysis except one where the effect, although statistically significant, was minor. The exception was the analysis of Factorial fit of total pick order time. The significance was at a 95% level compared to most of the other significance levels that were at 99.9%.

All data that were analyzed could be explained, significantly, by linear functions. All but the data connected to how different zone sizes effects the results. This data was significantly explained, for all results, by a second degree equation. The characters of the functions were parabolic with a maximum at the point were the derivate is zero. One of the functions, that only contain data given by the above settings, can be seen in Chart 10 Pick order time.

Chart 10 Pick order time



6 Conclusions and recommendations

The data analysis concluded that the distribution of order lines was not significant, which means that no matter how the customer order profile looks like it is unimportant in the viewed aspects.

In the analysis of random versus frequency-sorted slotting the worst results, in all measurements, was contributed by the setting of random slotting and only viewing one order at a time. The best results were found when viewing several customer orders at a time with total frequency-slotting. The reasons why the best results differ so greatly from the worst is because by looking at several customer orders at a time the pick routes can be more efficiently planned, since more eligible connections are possible. It is also likely that a higher fill rate can be achieved. Obviously the choice of slotting has a major impact, the more popular an item is the closer to the floor and closer to the door it should be placed. To attain the largest benefits these two settings should be used together. In any given warehouse the slotting is very seldom totally randomized which would suggest that the gains from the analyzed settings are lower in practice.

It would be possible to view more than ten orders at a time to gain even more efficient routes, shorter total lead time and possibly gain a higher fill rate. However this would come at a cost. The cost being that time used for a single customer order to be fulfilled would increase (earlier activation and later finishing). This would lead to focus shifting from customer order fulfillment of a specific customer order to total lead time efficiency. The decision on the number of viewed customer orders should be based on how incoming orders are distributed and if any customers are prioritized.

In the regression analysis of using different sized zones the most beneficial setting was using a large A-zone and viewing several customer orders at a time. The worst setting was using a small A-zone and viewing only one customer order at a time. The reason being that with a larger A-zone the more optimal number of A-zone picks, but at the same time the B- and C-zones decrease in size and the B- and C-zone picks becomes less optimal. The negative effects caused by less optimal B- and C-zone picks are shadowed by the positive effect of more optimal A-zone picks.

The choice of number of viewed customer orders can be discussed in the same way as above. The results from the run scenarios shows that the larger A-zone the better. However, a larger A-zone is probably not always better. An optimum might be possible to find although this would require further scenario runs.

The choice of certain model variables, specifically the choice of picker travel speed and picker pick-up speed may have led to a shift of importance. In real life the effect of travelling time might be significantly larger than the modeled effect.

When using zoning in real life positive effects might be gained through the relaxation of certain discussed “rules”, of zoning, so that more efficient routes can be planned.

It is also important to once again point out that the analysis are based on a limited set of scenarios founded on a generic model and therefore the effects might differ when implementing the strategies in real life.

6.1 Future studies

As future studies the authors would like to propose that more scenarios covering different sized zones should be run. That study would supposedly result in a different regression function. It might also be possible to find an optimal sizing of zones based on certain item popularity.

It might also be beneficial to further analyze the combination of frequency-slotting and zoning.

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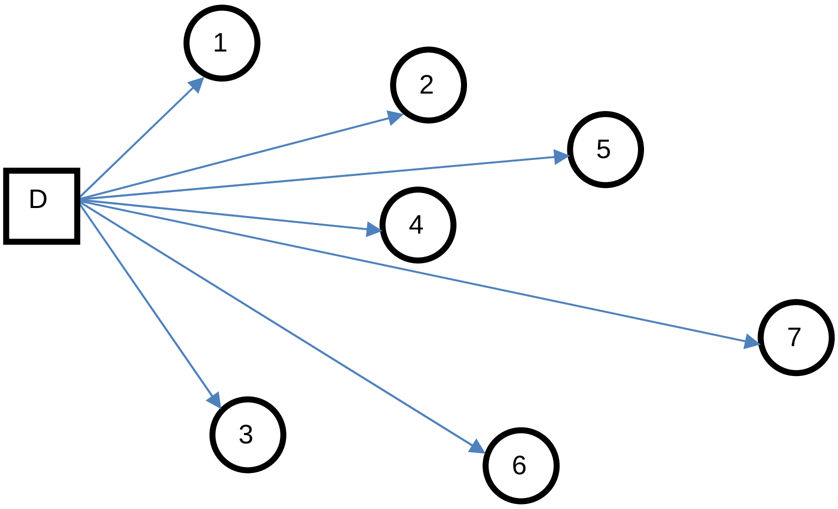
Appendix A: The Clark and Wright method[46]

Warehouse pickers need to gather articles from seven (n=7) different pick-up points in a warehouse. The warehouse has k employed pickers available with a specific capacity of C_k=17 units. All orders for the timeframe are known from the beginning. Pick-up points are named G_n. All pickers start and end at their depot D. The goal is now to minimize the number of pickers needed.

The following steps are performed in guidance of the above:

1. Identify pick-up points and quantities



n	1	2	3	4	5	6	7	SUM
Quantity for n=G_n	4	3	1	6	2	8	12	36

2. Generate a distance table (d=distance and D=depot).

	D	1	2	3	4	5	6	7
D	0	11	15	13	14	18	17	23
1	11	0	10	15	13	16	17	21
2	15	10	0	15	9	8	14	16
3	13	15	15	0	12	13	12	20

d(D,i)=d(i,D)

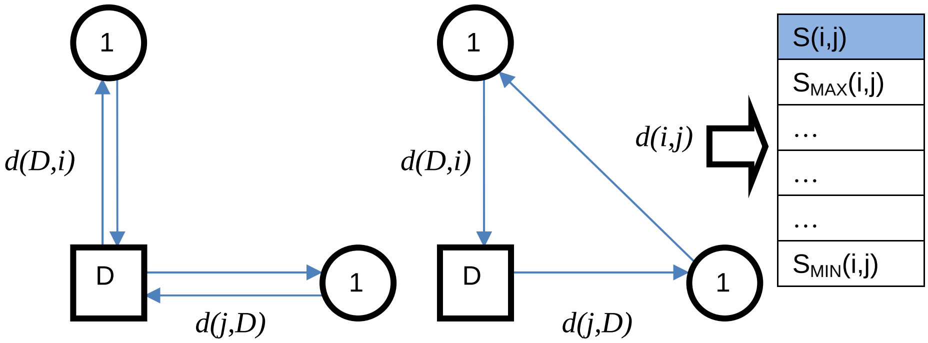
d(D,j)=d(j,D)

d(i,j)=d(j,i)

[46] Authors' processing of lecture given by Urciuoli, 2008-11-17

4	14	13	9	12	0	10	11	13
5	18	16	8	13	10	0	16	11
6	17	17	14	12	11	16	0	15
7	23	21	16	20	13	11	15	0

3. Calculate savings value(TL=total distance)



$TL_d=2d(D,i)+2d(D,j)$ $\quad$ $TL_s=d(D,i)+d(i,j)+d(D,j)$

$S(i,j)=TL_d\text{-}TL_s=2d(D,i)+2d(D,j)\text{-}[d(D,i)+d(i,j)+d(D,j)]=d(D,i)+d(D,j)\text{-}d(i,j)$

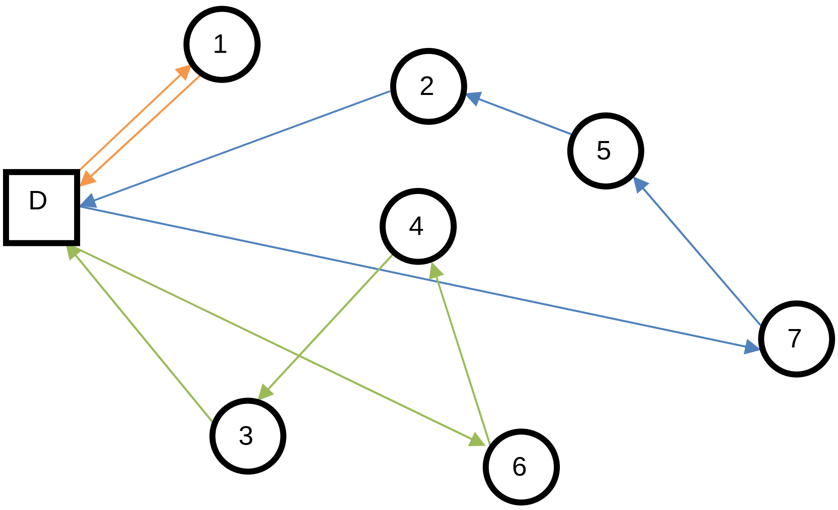
4. Sort savings values in descending order.

The rules that govern how pick-up points, variables i and j, are connected are the following:

- Create a new route if neither i nor j are already used in a route.
- Given S(i,j), savings value between i and j, include link (i,j) in the route if either i or j are already in the route and are not interior points.
- Do not include link (i,j) if both I and j are already in a route.
- Do not include link (i,j) if any of the restrictions you are considering will be violated.

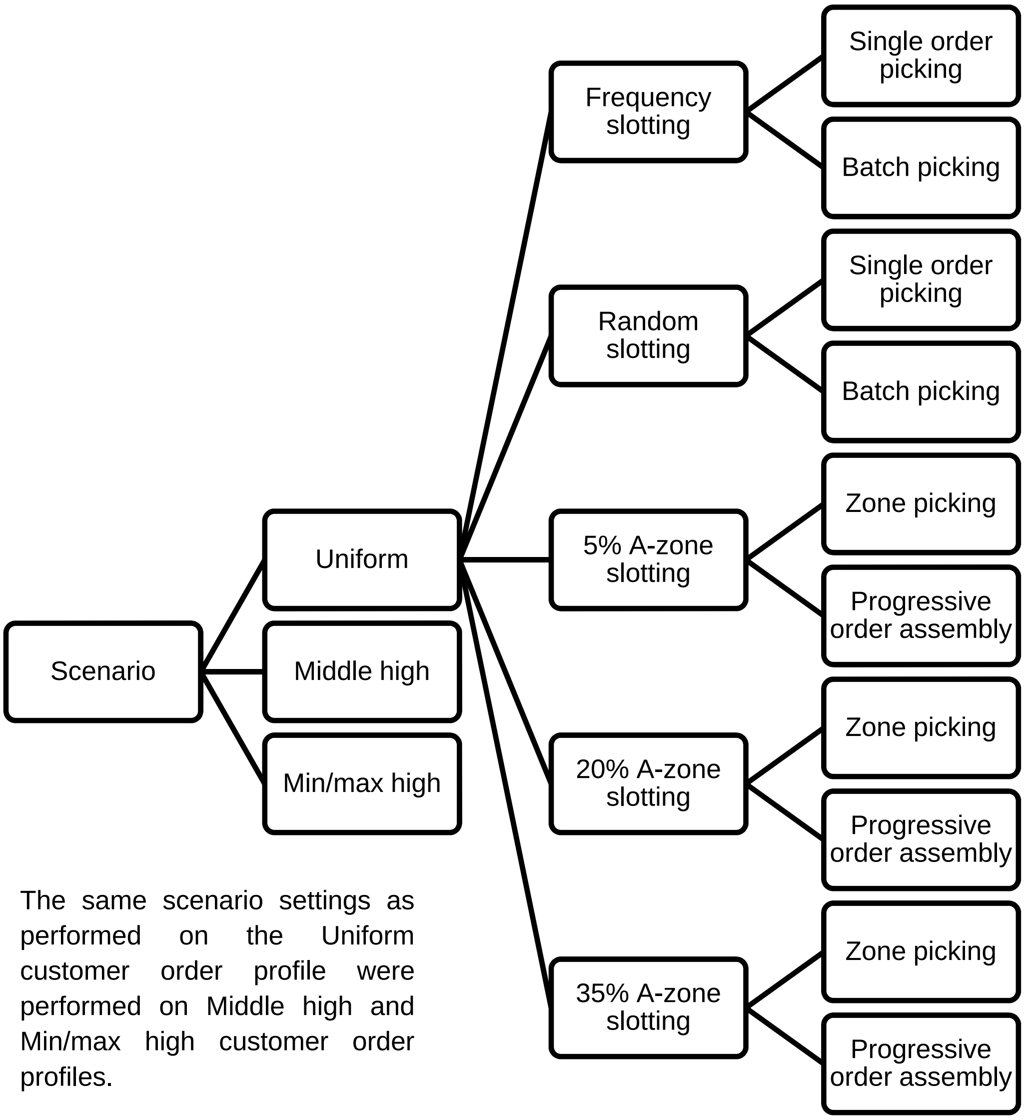
i	j	S(i,j)
7	5	30
5	2	25
7	6	25
7	4	24
7	2	22
5	4	22
4	2	20
6	4	20
6	5	19
6	2	18
5	3	18
6	3	18
2	1	16
7	3	16
4	3	15
5	1	13
7	1	13
3	2	13
4	1	12
6	1	11
3	1	9

5. Pick-up points are connected into routes. In this example the routes were: 7-5-2 with total quantity of 17, 6-4-3 with total quantity of 15 and 1 with total quantity of 4.



This example needed three routes requiring three pickers or at least one picker doing all three routes.
Since the total quantity of the picking routes is 36 and the maximum capacity of a picker is 17 the minimum number of picking routes is $\frac{36}{17} = 2{,}12 \approx 3$ which, in this case, gives the same result as the heuristically optimized solution.

Appendix B: Scenario tree



Appendix C: Results of statistical analysis

Key to levels of significance: ***>=99.99%, *>=95% and (*)>=93%

Analysis of Random versus Frequency-sorted placement

Table 3 Total lead time

Total lead time, Factorial fit			
Term (coded)	**Coefficient**	**Effect**	**Significant**
Constant	231 239.00	x	***
Customer orders (0=1, 1=10)	-5 833.00	-4.92%	***
Slotting (0=Frequenzed, 1=Random)	6 684.00	5.95%	***
R^2=93.25%			

Table 4 Total pick order time

Total pick order time, Factorial fit			
Term (coded)	**Coefficient**	**Effect**	**Significant**
Constant	1357690.00	x	***
Customer orders (0=1, 1=10)	-30458.00	-4.39%	***
Order profile (-1=Min/max high, 0=Uniform, 1=Middle high)	-9516.00	-1.39%	*
Slotting (0=Frequenzed, 1=Random)	40001.00	6.07%	***
Customer orders*Order profile	7732.00	1.15%	(*)
Customer orders*Slotting	-6067.00	-0.89%	(*)
R^2=98.41%			

Table 5 Total pick order distance

Total pick order distance, Factorial fit			
Term (coded)	**Coefficient**	**Effect**	**Significant**
Constant	215 853.00	x	***
Customer orders (0=1, 1=10)	-30 102.00	-24.48%	***
Slotting (0=Frequenzed, 1=Random)	68 490.00	92.95%	***
Customer orders*Slotting	15 171.00	15.12%	***
R^2=99.88%			

Analysis of Zone-picking

Table 6 Total lead time

Total lead time, Regression analysis			
	Coefficient	**Effect**	**Significant**
Constant	289 866.00	x	***
Customer orders (0=1, 1=10)	-37 048.00	-22.67%	***
Zone (Zone A size: 0=100, 1=400, 2=700)	4 868.00	3.42%	***
$(Zone)^2$	-7 426.00	-5.00%	*
Customer orders*Zone	6 765.00	4.78%	***
R^2=99.20%			

Table 7 Total pick order time

Total pick order time, Regression analysis			
	Coefficient	**Effect**	**Significant**
Constant	1 681 215.00	x	***
Customer orders (0=1, 1=10)	-191 215.00	-20.42%	***
Zone (Zone A size: 0=100, 1=400, 2=700)	29 076.00	3.52%	***
$(Zone)^2$	-43 629.00	-5.06%	*
Customer orders*Zone	38 681.00	4.71%	***
R^2=98.19%			

Table 8 Total pick order distance

Total pick order distance, Regression analysis			
	Coefficient	**Effect**	**Significant**
Constant	507 813.00	x	***
Customer orders (0=1, 1=10)	-125 405.00	-39.61%	***
Zone (Zone A size: 0=100, 1=400, 2=700)	36 260.00	15.38%	***
$(Zone)^2$	-47 431.00	-17.08%	***
Customer orders*Zone	16 836.00	6.86%	***
R^2=99.67%			