Eindhoven University of Technology

MASTER

Multi-echelon spare parts management in Europe at FEI company

Thijssen, I.C.M.

Award date:
2007

Multi-Echelon Spare Parts Management in Europe at FEI Company

Ivo C. M. Thijssen
May 24, 2007

FEI COMPANY™
TOOLS FOR NANOTECH

Multi-Echelon Spare Parts Management in Europe at FEI Company

Master's Thesis
Final Report

Master of Science degree by:
Ivo Thijssen
Eindhoven University of Technology
Department of Technology Management
Program in Industrial Engineering and Management Science
Sub-department of Operations, Planning, Accounting and Control

Supervised by:

Tarkan Tan	Primary supervisor TU/e
Gudrun Kiesmüller	Supervisor TU/e
Loek Halmans	Primary supervisor FEI Company
Arjen den Boer	Supervisor FEI Company

TU/e technische universiteit eindhoven

FEI COMPANY™

I. ABSTRACT

This MSc. thesis describes the development of models and solutions for multi-echelon spare parts management in Europe for FEI Company. This includes a decision model for the location of spare parts warehouses in Europe, and two-echelon models to calculate item stock levels in these warehouses. Multi-item and single-item models are compared, and a heuristic solution is used to calculate the reorder point and order quantity in the central warehouse and order up to levels at the local warehouses.

II. PREFACE

In front of you is the thesis for the Master of Science degree in Industrial Engineering and Management Science from Eindhoven University of Technology by Ivo Thijssen. To complete this study a student must do a project in a company related to his specialization.

My project takes place at FEI Company, a manufacturer of tools for nanotechnology. The project is focused on service logistics in this company. In this project I developed a model to decide which warehouse locations in Europe are needed to provide service to customers. Given these warehouse locations I developed models to obtain order-up-to-levels for the local warehouses and the reorder point and reorder quantity at the central warehouse. These models are included in a tool that will be implemented at FEI Company.

I could not have done this project without the help of some people, whom I would like to thank:

First of all I would like to thank Tarkan Tan, my primary supervisor at Eindhoven University of Technology, who set the goals high for me and made me reach beyond the limits I expected for this project. His ever helpful suggestions and commentary were very useful to make this project a success.
I would also like to thank Gudrun Kiesmüller for her objective look on my models, which helped me in structuring these problems.
The third person from the university that I would like to thank is Koos Huibers. He has been a great help with programming my stock keeping models in Delphi.

At FEI Company I would like to thank Loek Halmans, who as my primary supervisor there helped me in finding my way in FEI Company (both in pinpointing the people to talk to, and guiding my way through the ERP system). I would like to thank Arjen den Boer for being critical on the proposed directions; he thereby guided the project and made it more exciting. Further I would like to thank my colleagues at FEI Company for the nice working environment.

Finally I would like to thank my family and friends for their support during my studies and this project in particular.

Ivo Thijssen
Eindhoven, May 2007

III. MANAGEMENT SUMMARY

FEI Company is a leading supplier of advanced tools for nanotechnology to a broad range of nanotechnology markets. Nanotechnology is the science of characterizing, analyzing and fabricating things smaller than 100 nanometers (a nanometer is one billionth of a meter).
FEI sells service contracts to customers using their tools. To provide this service to customers FEI operates a worldwide network of service engineers and regional and local warehouses.
This thesis will deal with service in Europe, where FEI currently operates one central warehouse located in Eindhoven, the Netherlands and three local warehouses for specific customers (local warehouses are located in Londonderry in Northern Ireland; Dresden in Germany and Crolles in France). The central warehouse is used for production stocks and supplies spare parts produced in the Netherlands throughout the world. The local warehouses are managed locally, though no formal stock keeping policies exist.
FEI believes there are improvement opportunities in the warehouse locations that deliver service to customers, and in the stocking policies of parts stocked in the warehouses.

FEI initially stated the problem as follows:

> *FEI Company perceives the current logistics infrastructure not as optimal. As a result FEI wants to know what is the most efficient way to deliver service to the end customers. FEI is most interested in knowing the best logistics structure in Europe, and in knowing which SKUs (Stock Keeping Units) to stock in these warehouses.*

This initial problem statement has been translated into a hierarchical approach of the problem. First a model is built to decide on the locations for local warehouses in Europe, and then models are developed to obtain proper stock levels in this multi echelon system. This is depicted in Figure 1. CW stands for central warehouse in this figure.

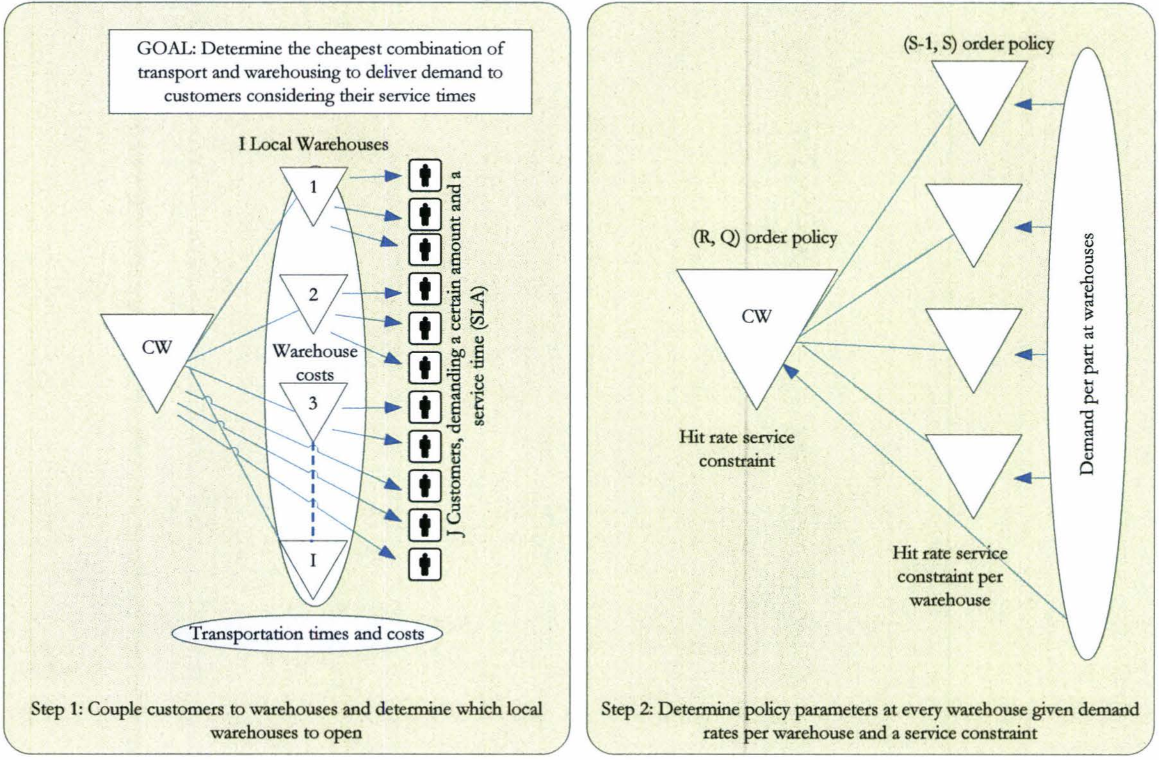


Figure 1: Overview project approach

The research assignment is stated similarly:

> *Analyze the current logistics infrastructure and confront it with literature. Develop models for improvement of spare parts management in Europe with a focus on control on the local warehouses. Specifically:*
>
> 1. *Develop a model for decision support for warehouse locations in Europe; which warehouse locations are needed to deliver service to customers at the lowest cost*
> 2. *Develop a model for spare parts stock keeping, to improve spare parts inventories in Europe.*
>
> *Integral costs of warehousing, distribution and inventory should be the goal for the developed models*

During this project a discrete location model was developed to decide on which warehouse locations in Europe are needed for service to specific customers. This model can be solved with Mixed Integer Linear Programming (MILP). *Discrete* means that only predefined locations for warehouses are considered. This model is used as input to the stock keeping model.

For stock keeping, different models have been developed. Two different types of models are the multi-item and single-item model. The *multi-item* model takes all items together and obtains an aggregated service level over all items. The *single-item* model uses a service constraint per item. Because the multi-item model optimizes stock levels for all items together it has lower overall costs; it decides to keep less expensive parts and more cheaper parts while still delivering the same aggregated service as the single-item model.

All developed models are *two-echelon* models; they obtain an integral solution for the central warehouse and local warehouses that are served by this central warehouse.

The local warehouses in these models use *base stock (S-1, S)* order policies. This means that whenever an order occurs at the local warehouse, this amount is immediately ordered at the central warehouse to keep the inventory position at level S.

The central warehouse uses *(R, Q)* order policies. Whenever reorder point R is reached an order of size Q is placed at the supplier. Different models are tested to compare performance of the central warehouse and the local warehouses:

- A Q=1 multi-item model is tested; in this case the central warehouse also uses (S-1, S) order policies; this model is often used in spare parts literature.
- An EOQ multi-item model is tested; the central warehouse uses the EOQ formula for the order quantity. EOQ is the deterministic Economic Order Quantity.
- An (R, Q) multi-item model is tested that uses a heuristic to calculate the stochastic economic order quantity at the central warehouse. (R, Q) stands for Reorder point and order Quantity.
- A single-item model is tested that uses a heuristic to calculate the stochastic order quantity at the central warehouse.

The following conclusions can be drawn:

Based on the location model:

- A warehouse in the south of Italy must be opened to deliver service to customers there. All current local warehouses must stay open.
- Delivery from the central warehouse is always cheapest. If delivery within 24 hours is appropriate for the customer, this customer must be served by the central warehouse since almost all locations in Europe can be reached from Eindhoven within 24 hours.

Based on the stock keeping model:

- All multi-item models outperform the single-item model. FEI should switch to a multi-item approach.

- The (R, Q) model outperforms the other models for all occasions. FEI should start using this model.
- Service levels for critical items can be overruled by using the appropriate order up to level and reorder point and order quantity from the single-item model.
- Currently many items are stocked in a wrong way at the central warehouse. FEI should carefully analyze the outcomes of the proposed model and adjust its stocking policy accordingly. These incorrectly stocked items include:
    - € 4,000,000 non moving items
    - € 4,400,000 items with too high inventory levels (overstock)
    - € 2,300,000 items stocked at too low inventory levels (understock)
- If the proposed model is used in Europe a total inventory of approximately € 6,000,000 would be enough for a 95% service level to all customers. Currently the central warehouse in Eindhoven alone has approximately € 12,000,000 inventory on stock.

Considering the outcomes of this project FEI is advised to open a warehouse in Italy and to start using the multi item (R, Q) model that has been proposed. Careful review of the outcomes of this model for critical items and changes in demand should be done when starting to use this model.
A plan has been written to help FEI achieve a good and effective implementation of this model into the organization.

INDEX **PAGE**

1 FEI COMPANY

FEI Company is a leading supplier of advanced tools for nanotechnology to a broad range of nanotechnology markets. Nanotechnology is the science of characterizing, analyzing and fabricating things smaller than 100 nanometers (a nanometer is one billionth of a meter).

FEI was founded in 1971 as Field Emission Inc. and began trading shares on the Nasdaq in 1995. In 1997 FEI merged with Dutch Philips Electron Optics into a company called FEI Company. FEI Company acquired American Micrion Technologies in 1999, Atomika Instruments in 2002 and Revise Inc. in 2003.

FEI operates in markets subject to rapid technological development which leads to a focus on research and development activities. FEI has research and development centers in North America and Europe and sales and service operations in more than 50 countries around the world. The vision and mission of FEI are shown below.

Vision

To be the leader in providing tools for nanotechnology which enable our customers to change the world for the better.

Mission

To be a profitable growth company committed to our customers' success by providing world-class solutions to challenges at the nanoscale. We are devoted to bringing leading technologies to markets with the highest quality products and services.

Manufacturing of FEI is located in Hillsboro, Oregon USA, Eindhoven, The Netherlands and Brno, Czech Republic. Manufacturing consists largely of assembly and testing of finished products.

FEI employs approximately 1600 people and revenues were $427,5 million in 2005 and $479 million in 2006.

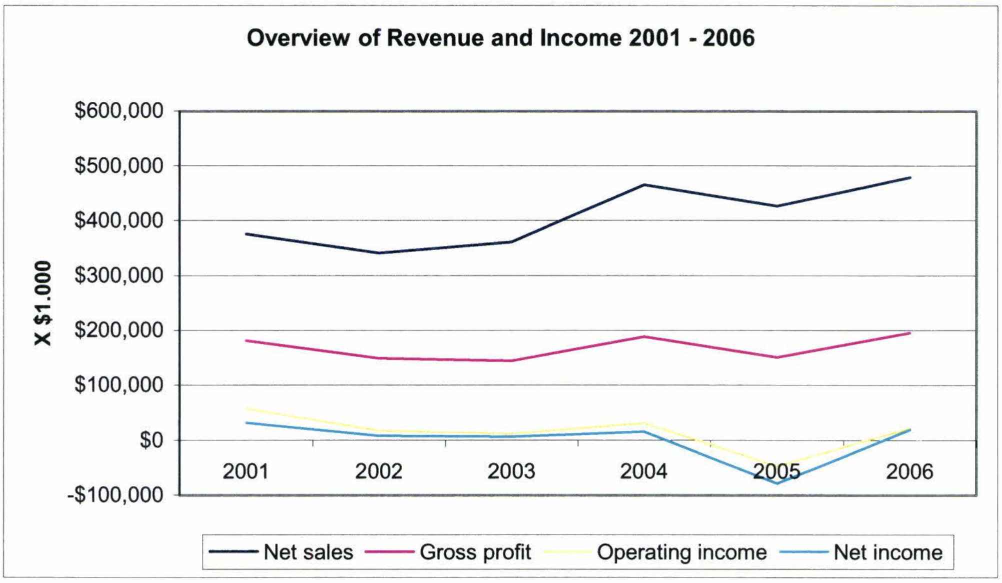


Figure 2: Historical revenue and income

1.1 PRODUCTS AND CORE TECHNOLOGIES

FEI arranges its products and services in four segments:

- Microelectronics (accounting for approximately 38.5% of net sales in 2005):
  - Focused Ion Beam systems (FIBs)
  - Dualbeam systems
  - Computer aided design navigation
  - Yield management software
- Electron Optics (accounting for approximately 36% of net sales in 2005):
  - Scanning Electron Microscopes (SEMs)
  - Transition Electron Microscopes (TEMs)
- Service (accounting for approximately 23.8% of net sales in 2005), performed on the installed base of products
- Components (accounting for approximately 1.7% of net sales in 2005), including electron and ion emitters and focusing ion columns

Core technologies to deliver these products include:

- Focused ion beams, which allow modification of structures in sub-micron geometries
- Focused electron beams, which allow imaging, analysis and measurement of structures at sub-micron and even atomic levels
- Beam gas chemistries, which increase the effectiveness of ion and electron beam and allow etching and deposition of materials on structures at sub-micron levels
- System automation and sample management tools, which profice faster access to data and improved ease of use for operators of the systems

1.2 MARKETS

In 2005 FEI reorganized its market focus into three major markets:

- NanoElectronics, driven by semiconductor capital equipment spending. Another important part of this market is a niche in the data storage market. (50% of net sales in 2005)
- NanoResearch and Industry, consists mainly of customers in materials research and development. Mainly institutions and universities. (39% of net sales in 2005)
- NanoBiology, includes research institutes, universities, hospitals and pharmaceutical companies. This is currently a relatively small market but with growth expectations. (11% of net sales in 2005)

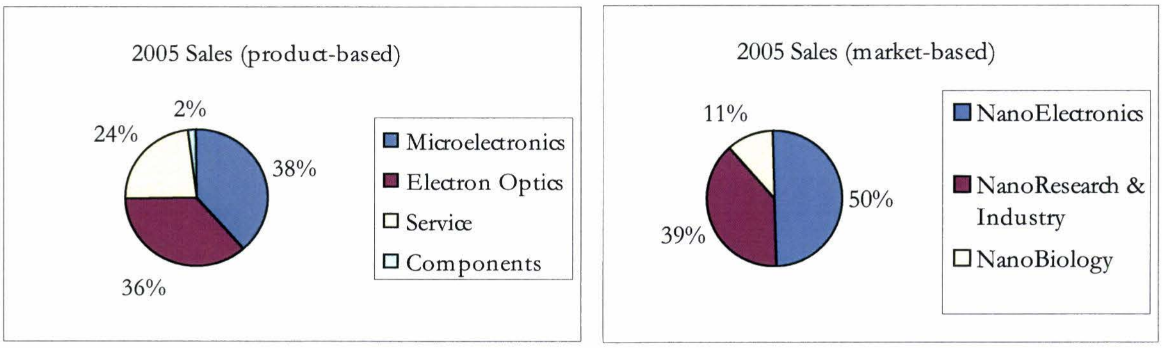


Figure 3: Sales segmentation

1.3 SERVICE AND LOGISTICS

Service is important for the business of FEI because it determines up-times of systems. The sales and service divisions of FEI is organized in Sales and Service Departments (SSDs) in three regions:

North America, Europe and the Asia-Pacific region. The SSDs are responsible for distribution of available products and spare parts of FEI. The FEI service business faces little to no competition from third-parties. This is due to the highly specialized nature of FEI products and technology and because of the critical mass which is needed to support a world-wide dispersed installed base. FEI installed base is currently about 6500 systems. Some of the older and less sophisticated systems are serviced by independent field engineers in competition with FEI.

The Europe SSD is located in Eindhoven. Service and Logistics are organized in the FEI Europe BV Customer Service Logistics department (CS Logistics) that has been part of the European SSD since November 2002 (Halmans, 2005). It was divided into CS Helpdesk (customer relations) and CS Materials (material planning / logistics). Currently the materials planning department is part of logistics and only has functional reports to the SSD in America, and no reports to the helpdesk in Europe. The direct reports are to the logistics department. An organization chart is shown in Appendix II. The main responsibility of CS Logistics is the availability of spare parts. More than 12.000 spare parts can be distinguished here. These parts can be divided into two main groups based on the production site: EOPD spare parts (produced in Acht, The Netherlands); FPD spare parts (produced in Hillsboro, USA). All parts are sourced from the respective production facility and its suppliers.

For products produced in the facility in Eindhoven there is one central warehouse in Eindhoven, one regional warehouse in Singapore, one regional warehouse in America (Hillsboro) and several local warehouses. Local warehouses are located in Europe (3), America (6) and Taiwan, Japan, Malaysia and Hong Kong.

For products produced in America the same warehouses exist, the warehouse in America being the central warehouse and the warehouse in Eindhoven being the regional warehouse that supplies to the local warehouses in Europe.

Besides these warehouses some stocks exist at smaller locations and at customer locations due to specific contracts.

FEI systems are sold with installation included and standard warranty on products of 15 months. Once the warranty period expires, customers are offered the possibility to purchase a service contract to cover planned maintenance and repair of the system. FEI commits itself to a predetermined service period and service level. Logistics service is discussed in more detail in section 2.

2 CURRENT SPARE PARTS MANAGEMENT

To get an overview of the current practice of spare parts management at FEI the present situation has been analyzed. First the characteristics of spare parts at FEI are analyzed. In the following subsection the structure of the FEI service logistics distribution network is explained. Thirdly the definition of customer service and the installed base is of importance. Finally the performance measures currently in use are analyzed.

2.1 PARTS CHARACTERISTICS

About 12,000 spare parts have been defined at FEI. For the sourcing site in Eindhoven only 5,000 parts can be characterized as active, which means they were ordered at least once in the period of January 2003 till November 2006. Some characteristics are provided in the table below.

Table 1: Spare part characteristics

spare parts characteristics	Consumable	Repairable
revenues per year	€ 6,097,195	€ 15,147,409
quantity per year	21957	2812
% revenues per year	28.70%	71.30%
% quantity per year	88.65%	11.35%
# items	4302	604
Min of Standard COGS	€ 0.01	€ 59.70
Max of Standard COGS	€ 28,016.29	€ 157,276.95

The table provides the insight that though the majority of spare parts orders are not repairable (88%) they only provide 28% of the revenues. The rest of the revenues is provided through repairable parts. Revenue here is actually the standard cost price of items for FEI since that is the value to which it is accounted. Margins have not been investigated because prices to customers depend on situations, contracts, warranty etc.

It is also remarkable that only observing the repairable items already leads to a more than Pareto rule; the 11% of repairable orders accounts for 71% of the revenues. The overall value analysis is shown in Figure 4. Less than 10% of the items accounts for 90% of the value of demanded spare parts.

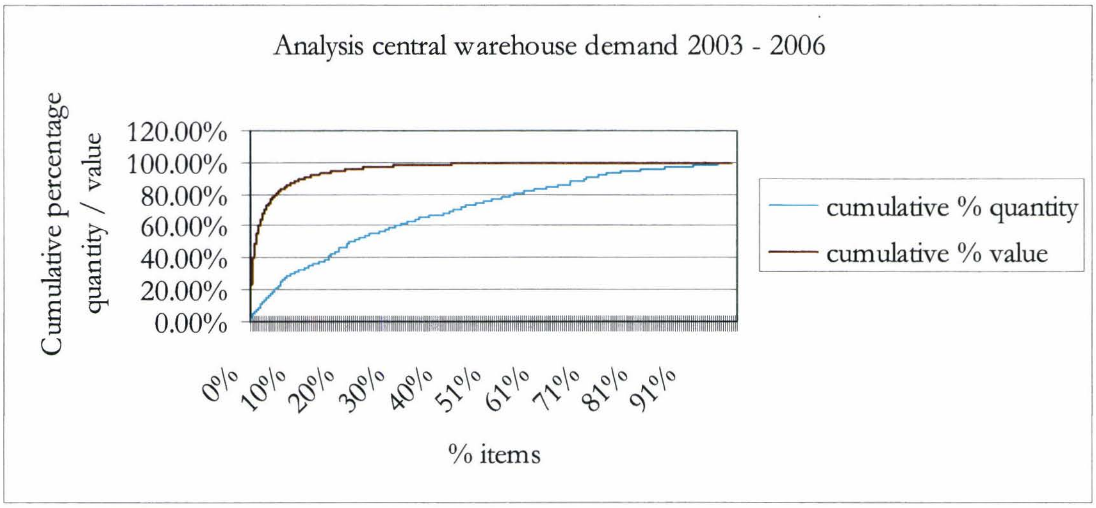


Figure 4: Central warehouse demand analysis

2.2 SERVICE LOGISTICS

The logistics infrastructure of FEI consists of the network structure and policies and methods that are in use in practice. The following is a simple characterization of the service process:

1. When a system at a customer breaks down a service engineer is contacted.
2. The service engineer visits the customer and investigates the system; he places an order for a specific spare part at the proper warehouse.
3. When the part arrives the service engineer repairs the system; if the replaced part is repairable the old part is sent to the central warehouse.

The next subsections provide more detail on parts of this process, like the distribution network, transportation, order policies and the service engineers involved.

2.2.1 DISTRIBUTION NETWORK

The network of FEI is shown in Figure 5 below:

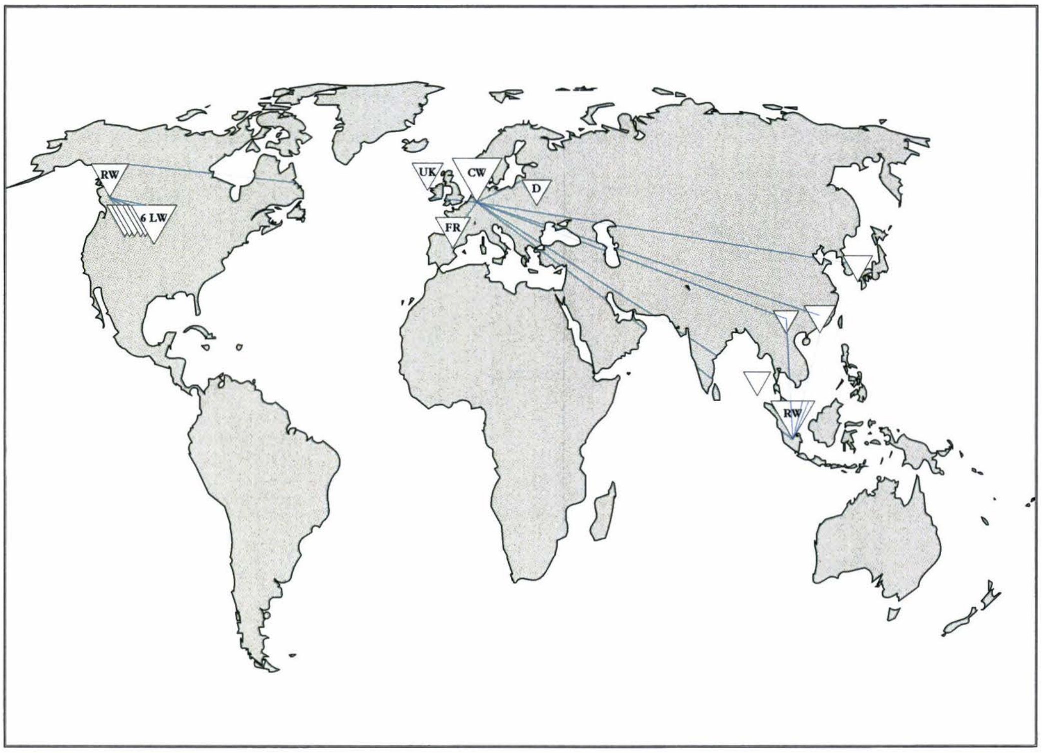


Figure 5: Logistics network FEI Company

In Europe there are 3 important local warehouses:

- Crolles in France,
- Dresden in Germany
- Londonderry in the United Kingdom.

These warehouses are supplied by the central warehouse in Eindhoven, The Netherlands.
This central warehouse also acts as a local warehouse for customers in Europe with no specific local warehouse.

In Asia there is one regional warehouse in Singapore. There are also four local warehouses located in Japan, Taiwan, Penang (Malaysia) and Hong Kong. These local warehouses are supplied either directly from Eindhoven or through the Singapore warehouse.

Within Asia there is not a regular fixed operating infrastructure. This is due to a lack of management; new people are being attracted there. Also multiple databases of MFGPRO are used in the Asia region which makes centralized control over the warehouses difficult. MFGPRO is the ERP system used by FEI.

In America there is one central warehouse and 6 regional warehouses. These are all managed by FEI America.

2.2.2 TRANSPORT

Transport within Europe from the central warehouse to the local warehouses is done by logistics service providers or transportation companies. Express mail and road transport is commonly used here. Delivery is usually overnight, so within 24 hours, though faster delivery by courier is possible. Rates for express mail range from €5.45 for 0.5 kg to €63.43 for 75 kg in the countries these warehouses are located. An estimation of 5 kg on average leads to an average cost of €13.11 per shipment.

Local transport from the warehouses to the customer site is arranged by the Service Engineer.

Express delivery from the central warehouse to a customer site in Europe is also possible. A taxi or express courier could be used to take a part anywhere in Europe quickly. Transportation times are highly dependent on the location of the customer, but will vary from minutes (in the Eindhoven region) to many hours for destinations across Europe. Van den Boogaard Express Service charges FEI €0,34 per kilometer for a round trip, so approximately €0,68 per kilometer distance between Eindhoven and the location.

2.2.3 ORDER POLICIES

In Eindhoven a forecast and planning tool is used on a daily basis to support the planning and forecasting process (Halmans 2005). This tool uses multiple forecasting models on SKU (Stock Keeping Unit) level to calculate reorder point (s) and order-up-to-level (S). This tool uses ordinary inventory and forecasting models (like single exponential smoothing and linear exponential smoothing). Global demand data as received by the central Eindhoven warehouse is used as input. This means both real customer demands and replenishment orders from the regional warehouses are used. These data have been recorded since April 2000.

Local warehouses are expected to use (implicitly) an (S-1,S) replenishment model, so every time an item is consumed an order is placed. Stock keeping at local level however has never been formalized. Stocks have grown over the years and there is no model or forecasting method that optimizes stocks at local levels. In Asia there is no control or management in the warehouses, with the exception of Japan. Currently there are a lot of escalations because of this and most time in Asia is spent on these emergency orders.

The regional warehouse in America does its own planning. Replenishment orders are received, no customer demand data is available directly; how replenishment orders are calculated is also unknown.

2.2.4 SERVICE ENGINEERS

In general every service engineer serves a specific geographic or a specific customer account; this specifies at which warehouse the service engineer orders the part.

All warehouses directly serve service engineers (and thus customers) in their region. Furthermore the warehouse in Singapore serves as a regional warehouse for that region and also supplies to the local warehouses in Asia. In Europe the majority of orders is placed at the central warehouse in Eindhoven and parts are delivered directly to the customer site.

2.3 INSTALLED BASE

The installed base of FEI consists of all systems that have ever been delivered and installed by FEI across the globe and that are still operational. Some systems are more than 25 years old already. The total number of installed systems of FEI Company is 6482 systems (on September 29, 2006).

Figure 6 shows the systems per region. This is actually in which regional database the customer is located. Hong Kong also includes all customers in China; Singapore also includes customers in the rest of Asia, like Malaysia and The Philippines.

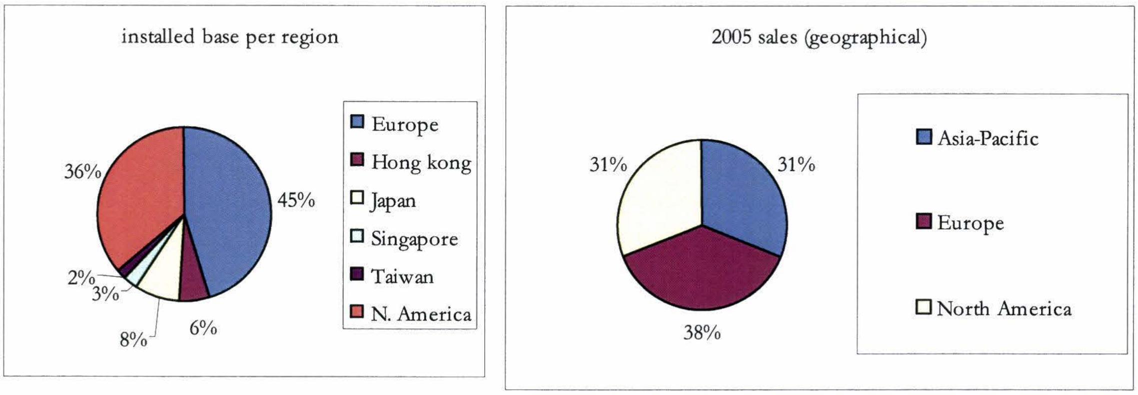


Figure 6: Installed base and sales per region

The figure shows that Europe is clearly the largest market for FEI at the moment, but Asia is a growth market since it is now only 21% and sales in 2005 were 31%. This shows the importance of improving not only the current situation but keeping in mind the growth opportunities for the future, especially in Asia.

2.3.1 IMPORTANT CUSTOMERS

Contracts only specify service engineer response times and never specify specific spare part availability. Therefore FEI management has been asked to provide a list of important customers. This list contained 15 locations in Europe with a maximum of 4 hours of response time. This list has been taken as leading in the remainder of the report. The relation between contracts and spare part availability is shown in Appendix V, data on the installed base in Europe and important customers in Europe can be found in Appendix IV.

2.4 LOGISTICS PERFORMANCE

The performance of the service logistics department is measured in the delivered service to customers and in the generated profits.

One of the key performance indicators is the hit rate in FEI warehouses. The hit rate is the number of times a spare part can be delivered directly from stock in the warehouse. Hit rate is thus the same as the fill rate, type 2 or β service level as defined in literature (see for example Silver et al. 1998). At FEI hit rate is measured by same day shipments, this is actually comparable to the definition in literature.
Hit rate in FEI warehouses around the world in general is low. The central warehouse in Eindhoven manages a hit rate of about 80% and is one of the best performing warehouses (the target is 90%). With this hit rate Eindhoven manages inventory turns of 1.8, with 2 as the target, it also scores below target. More details on hit rate, inventory turns and the economic performance of FEI can be found in Appendix VI.

3 PROBLEM DEFINITION AND RESEARCH ASSIGNMENT

FEI Company develops, produces, markets and services Tools for Nanotechnology.
This project is aimed at the Service Logistics division of FEI Europe.
Delivery of spare parts to FEI field service engineers is crucial for obtaining service to customers. To be able to deliver these spare parts FEI owns several warehouses. Currently there is one central warehouse in Eindhoven and there are three local warehouses in Europe: Londonderry in the UK, Dresden in Germany and Crolles in France.

3.1 PROBLEM DEFINITION

FEI faces difficulties to deliver the agreed service levels to the customer. FEI believes the current infrastructure of warehouses and transportation needs reviewing because it might be the cause of failing to deliver service. Currently no formal way of stock control exists in the warehouses except for the central warehouse in Eindhoven. As a result a lot of escalations happen and the performance of the warehouses is lower than the target in both hit rate and inventory turns.
The lack of management for the warehouses also needs to be resolved since the European headquarters are responsible for all service in Europe.

The problems above lead to the following initial problem statement:

Initial problem statement:

FEI Company perceives the current logistics infrastructure not as optimal. As a result FEI wants to know what is the most efficient way to deliver service to the end customers. FEI is most interested in knowing the best logistics structure in Europe, and in knowing which SKUs to stock in these warehouses.

In literature no integral solution for deciding on warehouse locations, transportation and specific stocking policies per Stock Keeping Unit (SKU) exists. This is quite logical because warehouse location determination usually is a more strategic decision, and the stocking policy and reorder point of individual SKUs are a more tactical decision. Therefore the problem above has been split into two problems that can be approached hierarchically.

1. The first problem is to improve the warehouse locations and transport structure in Europe. The goal is to decide on the best infrastructure for service to specific customers; where to stock goods, how to transport them, against a constraint on spare part delivery time for the customers.
2. The second problem is to decide what to stock at the warehouse locations decided upon in the first problem. In the second problem the reorder point and order quantity at the central warehouse and the order up to level in the local warehouses must be decided on, considering a service level per warehouse.

These steps are shown graphically in Figure 7. These problems are translated into the research question.

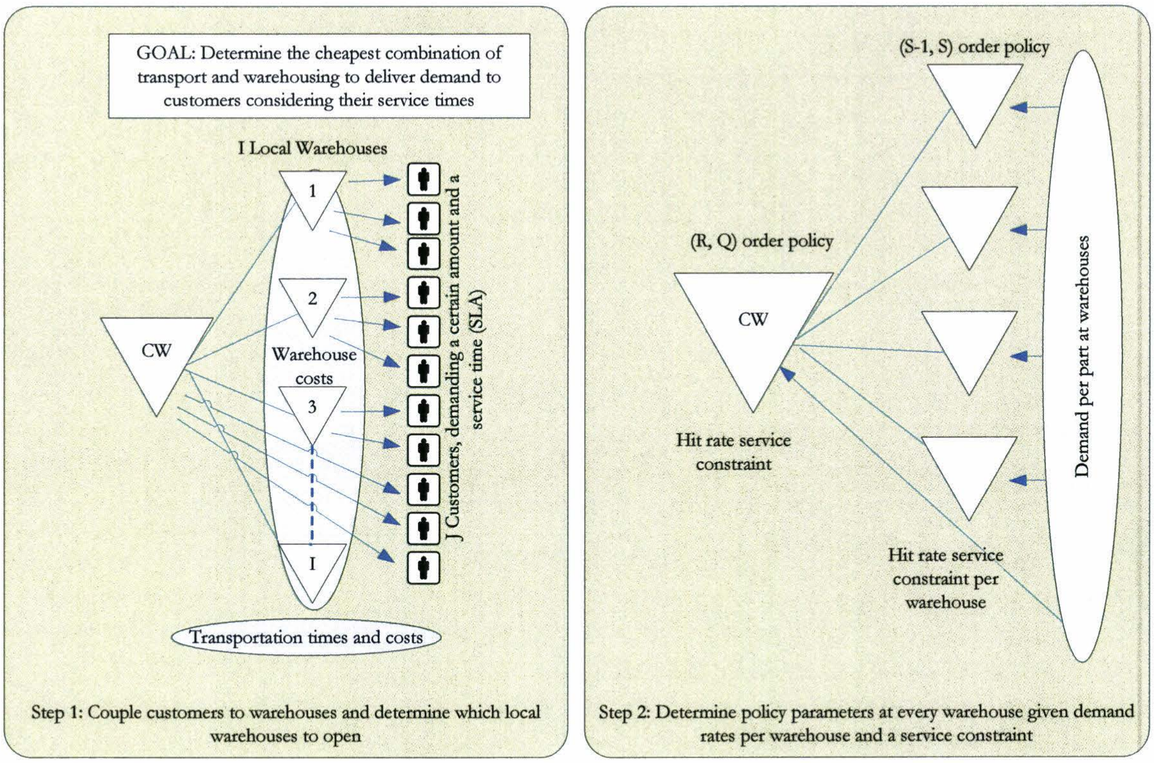


Figure 7: Overview project approach

3.2 RESEARCH QUESTION

The problem above is an interconnected problem which consists of a location problem and a stock keeping problem. The problem is as follows; FEI has some warehouses in Europe, but these locations might not be optimal. FEI wants to improve logistics performance by replacing some of these stock points if this leads to lower costs or better service to customers. On the other hand management of these stock points is not done properly and the wrong products are stocked at the wrong locations. This explains the in general low hit rate in the warehouses. FEI also wants to improve this. Therefore the following research question has been defined:

Research question:

Analyze the current logistics infrastructure and confront it with literature. Develop models for improvement of spare parts management in Europe with a focus on control on the local warehouses. Specifically:

1.` *Develop a model for decision support for warehouse locations in Europe, which warehouse locations are needed to deliver service to customers at the lowest cost*
2. *Develop a model for spare parts stock keeping, to improve spare parts inventories in Europe*

Integral costs of warehousing, distribution and inventory should be the goal for the developed models

Boundaries

In the remainder of this report only Europe is considered. The focus is on service to customers in Europe, and the service delivered from warehouses in Europe. The central warehouse in Eindhoven (Acht) is not subject to location changes. It must remain in Acht.

3.3 METHODOLOGY

This research project is approached through the model of Van Aken, Van der Bij and Berends (2003) which is suited for MSc. projects in Industrial Engineering and Management Science. This methodology suggests that a master's thesis project consists of two different types of research: diagnostic research and design oriented research.

Diagnostic research is aimed at focusing on what the real problem to be tackled is, and is the first phase of a master's thesis. On the right hand side of the model for the diagnostic research phase (Figure 8) the goal of this phase is given. This goal is reached by confronting the current situation with an evaluation method obtained from theory and interviews; which is shown on the left hand side of the model. The goal is a diagnosis and identification of the problem to be tackled.

Most of the analysis done according to this diagnostic model has already been dealt with in Section 2. Other parts of the analysis can be found in Appendix III till Appendix VII.

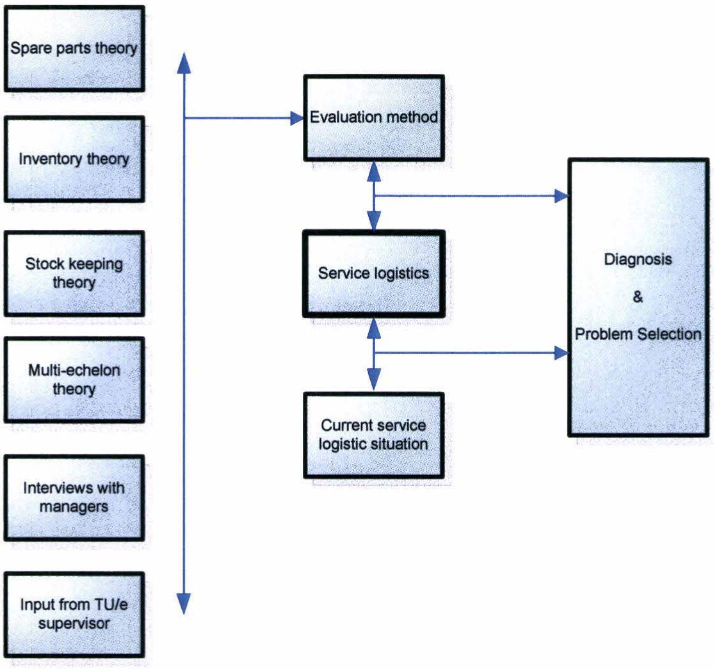


Figure 8: Research model for diagnostic research

After this diagnostic phase is finished and the problem to be tackled is selected, a model for design of the solution can be obtained (Figure 9). This model can be read similar as the previous one; the goal, a design and implementation plan, is shown on the right. Investigations and literature to obtain the design guidelines and constraints are shown on the left. The middle section shows the confrontation that must lead to the goal.

This model shows the approach taken in section 4 and 5 that deal with the developed models.

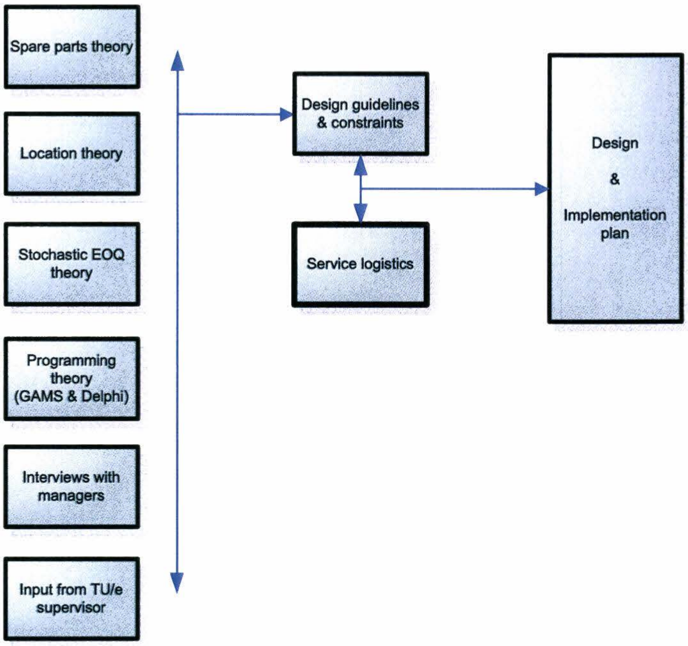


Figure 9: Model for design oriented research

3.4 STRUCTURE OF THE REMAINDER OF THIS REPORT

The remainder of this report is structured as follows:
Section 4 discusses the location problem and model that results in a decision which warehouse locations in Europe are needed to serve certain customers.
Then section 5 deals with the stock keeping models developed for the locations decided upon in section 4. Multiple models, both single-item and multi-item, are developed here.
Section 6 continues with the results of these stock keeping models and section 7 provides the conclusions and recommendations based on these results. Finally section 8 provides an implementation plan for the models and policies described in this thesis.

4 LOCATION DETERMINATION

The problem analysis showed that warehouse locations directly influence spare part delivery times and the service that can be delivered to customers. FEI is also convinced that these locations need review. Therefore the warehouse locations have been investigated with a discrete location model. A discrete location model means that only predetermined locations are evaluated. This is largely due to the nature of transport cost for FEI, which only depends on the country to ship to for a certain item. The left part of Figure 7 (on page 10) is a graphical overview of the model. The decision is how to ship demand to customers within their specified service time. Shipments are either directly to the customer from the central warehouse, or through a local warehouse. These shipments can be emergency shipments with a courier, or through express mail.
This section starts with a brief description of the most important parts of the analysis. In section 4.1 the model is explained and the last section contains the most important conclusions and recommendations on the location determination.

Literature on facility location (Drezner and Hamacher 2001) and decision analysis (Eiselt and Sandblom 2004) was reviewed as well as some articles to get an idea of the possibilities in modeling locations of warehouses for FEI.
The model that has been developed is a discrete location model. The locations of customers (the respective cities) are chosen as options for warehouses. This is done because transport costs only depend on the country shipped from and the country shipped to, and premium service (better than from the central warehouse) is only possible by using couriers from a local warehouse to the customer. Because courier costs are very high compared to normal transportation; and a site in between 2 customers leads to extra courier costs and is thus not better. However if the model selects two (or more) customers who make use of the same warehouse it is useful to look in detail into the warehouse options there because then a site close to all customers might be beneficial and local specific cost differences could matter. This could then be added as an extra scenario (local warehouse) to the model.
In Appendix VII the analysis on cost drivers and parameters for this model can be found. Here only the main conclusions will be restated:

1. Transportation from Eindhoven is always cheaper than from anywhere else in Europe
2. Transport from Eindhoven has the best service times for express post compared to other locations in Europe; almost all locations in Europe can be reached within 24 hours.
3. The average customer does not need service within 24 hours, only the important customers are candidates for local warehouses and the rest can be supplied through the cheaper central warehouse.
4. Only by courier or taxi is it possible to provide improved service, better than overnight express post, against considerable cost. Courier tariffs are based on contracts in Eindhoven.

4.1 LOCATION MODEL

A Mixed Integer Linear Programming model was constructed to answer the provide an answer on an aggregate level to the question which warehouses are needed in Europe. This model contains two decision variables, Y_{ij} the decision to ship demand for customer j through local warehouse i which is binary and X_i the decision to open warehouse i. These decision variables are binary which makes it possible to select different scenarios in the model (a warehouse is either open or closed, and a customer is served through a certain warehouse or not).

In the model the important valued customers are modeled separately per customer location (city). These customers are modeled separately to make sure they receive the proper service their SLA

(Service Level Agreement) requires. As aggregation measure for all other customers a country has been chosen, because transportation costs depend on the country a shipment is sent from and the country it is sent to. Shipments are sent directly to the customer overnight.

For warehouse locations areas near the important customers are chosen. The specific site is not selected but it is required that it is less than 1 hour from the customer(s). This is done because the assumption is that a warehouse is located somewhere to serve a specific customer. For customers that are located near each other also courier delivery is modeled against the guessed kilometer tariff. This tariff is based on the tariffs in Eindhoven.

4.1.1 ASSUMPTIONS

For ease of reference all assumptions and decisions for this model are stated here:

- Every customer j is connected to only one warehouse, which delivers all demand of this customer from stock.
- Demand is a number of items, every item is a single shipment, and shipments are never consolidated. This is to a large extent similar to the current situation.
- Every demand instance and shipment is similar in size and weight (5 kg).
- All shipments from the central warehouse are made through UPS Express because this is the cheapest option.
- Demand sizes in the model are based on the expected total year demand over 2006.
- A penalty cost is considered for every hour the customer is located further away from a warehouse than the SLA specifies.
- No variations in delivery times or different confidence levels of delivery times are considered. Delivery with UPS Express is for example guaranteed before a certain time whereas delivery times with a courier will vary much more. This difference is not considered.
- Courier delivery times are based on an ideal situation of immediate access to the stock and calculations with a route planner.
- Only one option is considered for the central warehouse. This location is fixed because:
    - The warehouse is used for more than just service logistics in Europe, relocation cannot be based on just that.
    - Very good transportation contracts exist for the current location (Philips contracts) this might not be true if the warehouse is relocated.
    - With these contracts it is much cheaper to ship from Eindhoven than from anywhere else in Europe, in a lot of cases it will be cheaper to ship from Eindhoven to a customer in a country than from another location in that country to the same customer.
    - Eindhoven is located near the hubs of UPS, FedEx and DHL and because of that has among the best shipping options and delivery times throughout Europe.
    - The warehouse is located near the factory which makes management easy and cheap, it is visited at least twice a week.
    - Given the above cost structure the model would lead to the current location anyway, let alone that the possibilities for improvement are very small, considering service logistics in Europe.

The location model is shown below:

Set i: *Warehouse locations*

Set j: *Customer locations*

Y_{ij}: *Binary decision variable to ship demand for customer j from local warehouse i*

X_i: *Binary decision variable to open local warehouse i*

S_j: *Positive decision variable, slack on service level agreement of customer j (hours)*

λ_j: *Lagrange Multiplier per customer j (Euro per hour)*

w_j: *Weight (demand) of customer j (number of items)*

C_i^{loc}: *Cost of opening local warehouse i (Euro per warehouse)*

C_i^{inv}: *Cost of handling inventory at location i (Euro per shipment)*

C_{ij}: *Cost of serving customer j through warehouse i (transportation cost) (Euro per transport)*

SLA_j: *Service level agreement customer j (hours)*

T_{ij}: *Time from warehouse i to customer j (hours)*

$$Min\ Z = \left\langle \sum_i C_i^{inv} \sum_j Y_{ij} w_j + \sum_i C_i^{loc} X_i + \sum_{i,j} w_j C_{ij} Y_{ij} + \sum_j \lambda_j S_j \right\rangle$$

s.t.

1. $Y_{ij} \in \{0,1\} \forall i \in I, j \in J$
2. $X_i \geq Y_{ij} \forall i \in I, j \in J$
3. $\sum_i Y_{ij} = 1 \forall j \in J$
4. $\sum_i Y_{ij} T_{ij} \leq SLA_j + S_j \forall j \in J$
5. $S_j \geq 0 \forall j \in J$
6. $X_0 = 1$

Constraint 1 makes sure Y_{ij} is an integer, binary variable
Constraint 2 makes sure that X_i is opened if shipments are made through i ; X_i is binary because the objective is to minimize and X_i is larger than Y_{ij} for every i.
Constraint 3 makes sure only one local warehouse i is selected for every customer j
Constraint 4 makes sure the delivery times are smaller than the SLA for every customer j and that a slack constraint is added for every hour that the delivery time is more than the constraint
Constraint 5 makes sure the slack constraint S_j is nonnegative and only delivery slower than the SLA is penalized and delivery faster than the SLA does not lead to an extra profit
Constraint 6 makes sure the central warehouse is always open. With the current cost structure this constraint is not really necessary because delivery from the central warehouse is always the cheapest option.

4.1.2 LAGRANGIAN RELAXATION

Because there is uncertainty at FEI what service level constraints should be set for which customers, the mixed integer linear programming model uses Lagrangian relaxation for the constraint that delivery times must be less than or equal to the Service Level Agreement (SLA). Lagrangian relaxation means that one of the constraints of a linear model is rewritten in the objective function with a multiplier (λ_j).

λ_j, the Lagrange multiplier can be considered as the cost of not meeting the service level agreement to that specific customer. By guessing the cost of not meeting this constraint the model can optimize the locations while taking into account the penalty cost of not meeting the delivery time to this customer. The total cost of the model results in the 'real' cost including a penalty cost for not meeting the service to the customer and weighs this against the cost of delivering to this customer using a warehouse. The estimate for λ_j has been made together with FEI management. For all customer locations except the locations currently served by a warehouse it is estimated to be €1,000.-. per hour For the current warehouse locations (Crolles, Dresden, Londonderry) the estimate is €10,000.- per hour. This is based on the size and activities of the service sites. These costs will be incurred because of taxi costs and other escalation costs if FEI does not fulfill their SLA.
Alternatively, if the penalty costs are unknown, λ_j can be considered a decision variable. In that case a breakeven point can be calculated to obtain 'good' values of λ_j. More details about this can be found in Appendix VII.

The model has been implemented in modeling language GAMS (General Algebraic Modeling Language). GAMS was selected because modeling in this language is largely similar to the way a model is described in normal algebra and because of the extensive feedback on errors which made starting using the language very easy. The GAMS model is shown in Appendix IX.

4.1.3 SENSITIVITY ANALYSIS

As indicated before, some uncertainties exist with regard to service level agreements. Therefore different scenarios are investigated and compared with regard to these service level agreements. Sensitivity analysis has been performed by varying parameters for all scenarios.

Service Level Agreement (SLA)
Scenario 1 is the current situation in which service levels agreements are set to the current service of a customer.
Scenario 2 is when all important customers requiring 4 hour response times according to management in America are considered to have this service level.
Scenario 3: In this case all customers are set to 24 hours of service time. This shows the cost of delivering only this basic service and can be used to compare the cost of other cases with.
Details of all scenarios are shown in Table 20 in Appendix XIII.

For all scenarios a base case and alterations in four parameters (transport cost, demand, warehouse cost and the Lagrange multiplier) have been investigated. For transport cost, demand and the Lagrange multiplier the following fluctuations were tested: 50%, 90%, 110% and 150%. This was done to check stability of the outcome on small changes and large changes. For warehouse cost fluctuations of 80% and 120% of warehouse cost were tested. The fluctuations for warehouse cost are lower because this is a decision variable that can only be adjusted by changing the service from a warehouse. If warehouse cost becomes much larger or smaller, it is reasonable to assume service will also change. In that case it is probably wise to also reconsider the penalty costs of the Lagrange multiplier. Appendix VII till Appendix XII contain all parameters used in this model.

Appendix XV shows the sensitivity analysis graph on total cost of all scenarios and details about what happens in every scenario. What is important to notice is:

- The total costs in the model increase almost in a linear manner when order costs, warehouse costs or transportation costs increase; although the optimal solution sometimes changes. Even when the optimal solution changes this only leads to very small improvements with respect to total costs compared to when the base solution is used.

- The model is in all cases almost as sensitive to changes in demand as to changes in transport costs
- Sensitivity to warehouse cost depends on the number of warehouses opened.
- The largest fluctuation (50% demand increase or decrease) leads to 19% to 30% total cost changes, so the model is not as sensitive as demand fluctuations but still flexible.
- Total costs are not as sensitive to fluctuations of the Lagrange multiplier as to the other parameters, but total costs do not behave in a linear manner when the Lagrange multiplier changes, because it directly influences decisions.

Table 2 shows the differences between the three scenarios and changes that occur due to sensitivity analysis. When a change occurs this is highlighted by a blue marking (change of service level to a customer, but no change in warehouse structure) or a yellow marking (change in warehouse structure). In case of a blue marking (other service level to customer) this means that for a certain customer the service level has changed (for example the customer in Rousset is served by the central warehouse instead of by courier from the warehouse in Crolles).

Appendix XIV shows a graphical representation of all candidate warehouse sites and in which scenario they must be opened. It also shows the demands that are allocated to these warehouses to evaluate the capacity and usefulness of these warehouses.

Table 2: Difference in scenarios location model

				Transport cost				**Warehouse cost**		**Demand**			
	Base Cost	**Base**	Changes	50%	90%	110%	150%	80%	120%	50%	90%	110%	150%
scenario 1	€ 430,845.19	**5**	# warehouses	5	5	5	5	5	5	5	5	5	5
scenario 2	€ 550,310.11	**5**	# warehouses	5	5	5	5	6	5	5	5	5	5
scenario 3	€ 313,649.64	**2**	# warehouses	2	2	2	2	2	2	2	2	2	2

Legend: changes compared to the base solution:
🟨 other warehouse
🟦 other service level to customer

4.2 CONCLUSIONS

Delivery from the central warehouse is cheapest

First it is important to remember from the analysis that lead to this model that delivery from the central warehouse is always cheaper than delivery from the local warehouses. Local warehouses can only add value (deliver faster than the central warehouse) if the customer is located very close to the local warehouse, in the same city or can be reached through courier delivery.

Open a warehouse in Italy and keep all current warehouses

It is very clear from the model that even for basic service to the important customers in Italy FEI needs one warehouse there. The location model shows that the best place for this warehouse is Catania, in the southern tip of Italy. This is because this customer has a larger demand than the customer in Avezzano and therefore courier costs are lower. The other customer, located in Agrate Brianza should be supplied from the central warehouse because it can be reached within 24 hours. Opening a warehouse should be investigated in more depth because then local opportunities and cost differences might make a difference. FEI could add these options to the model to determine the best option.

The model also shows that the current warehouses need to stay open.

Model performance and stability

In two of the three scenarios the outcome is stable with respect to which warehouses have to be opened for relatively large changes in parameters. This is the main decision to be made. Furthermore, in the current situation the same warehouses have to be opened when all customers would require service. Even when large changes in demand lead to other decisions this has very little influence on the total cost. At most 3% can be won by applying these changes compared to the base solution.

Though the model is very stable with respect to which warehouses have to be opened, changes do happen with respect to which customers are served by which warehouse. This depends to a very large extent on the demanded service level by the customer. It is still very important for FEI to choose the right service level for every customer because the stock in the local warehouses must be placed specifically for that customer, and therefore it must be clear for which customers the warehouse needs to be stocked.

To have some estimate on the importance of a customer it may be useful to look at the demand of this customer. The same goes for differences with respect to which customers must be served through a warehouse. In Appendix XIV the demand to be delivered through each warehouse is given for the base solution.

5 STOCK KEEPING MODEL

Now that warehouse locations have been identified in the location model of section 4, these locations are used as input for the stock keeping model. In the stock keeping model the central warehouse in Eindhoven (CW0) and four local warehouses will be modeled, namely Dresden (LW1), Londonderry (LW2), Crolles (LW3) and Italy (LW4); Italy being the new warehouse that needs to be opened according to the location model. The goal of the stock keeping model is to determine the order up to levels (S-1, S) at the local warehouses and the reorder point and order quantity (R, Q) at the central warehouse considering a service level (hit rate) per warehouse. A graphical representation of the model is shown in Figure 10.

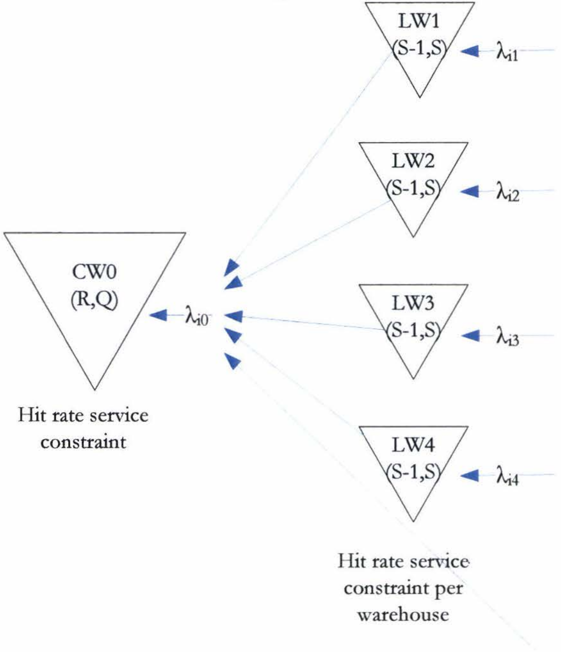


Figure 10: General stock keeping model

Single-item and multi-item

In literature a difference is made between two approaches, namely single-item and multi-item. These approaches differ in that a single item approach optimizes stock levels for every single stock keeping unit (SKU) separately whereas a multi-item approach optimizes the stock levels for all SKUs at the same time. A multi item approach is known to have a better performance in terms of total costs of the system because it weighs stocking more cheaper and fast moving goods against stocking fewer expensive and slow moving SKUs. Performance is evaluated for the system as a whole instead of per item. Both a multi item and a single item model have been developed for FEI because of the specific interest of FEI in comparing both approaches and the feeling that certain critical items need some extra control. The problem represented in Figure 10 fits both the single item as the multi item model; the difference is in how the objective function and service constraint is represented. For the multi item model the service constraint and objective function are aggregated over all items in a warehouse, whereas in the single item model the service constraint and objective is set per item.

Example:

Consider one warehouse with just two parts, A and B. In a single item model both A and B must be stocked so that a 95% hit rate is reached. Say this requires 20 items A and 1 item B. Using a multi item model, 95% hit rate can be achieved overall instead of per item. If demand of item A is 20 times the demand of item B it is possible to stock only item A (with a 100% hit rate) and 0 item B. For example 25 or 30 items A will be enough to cover all possible demand. If item A is much cheaper than item B this results in lower overall warehouse costs.

Service constraint per warehouse

The stock keeping models are developed to minimize the inventory cost of the warehouses while delivering a minimum service from these warehouses, measured in a hit rate of the warehouse. Hit rate (also called fill rate or β service level in theory) is selected as the service measure for the warehouses because that is what the service logistics department at FEI is accounted for in the end. Hit rate is measured as the number of times an order can be delivered from stock. A constraint is set per warehouse because FEI is accounted for the service per warehouse.

For the central warehouse this might not be a good measurement; focus should be on performance to the end customer and service levels should not be set in between, that is if information is shared over the echelons (Van Houtum et al. (1996)). On the other hand, the central warehouse also acts as a local warehouse for customers in Europe and other warehouses around the world, and therefore must be able to supply those orders directly from stock. For better control over the central warehouse the orders should be split in customer orders and replenishment orders as proposed by Kalchschmidt et al. (2003). This is investigated in section 6.4.

One aggregate constraint is not set because FEI wants to determine inventory levels, given a service constraint for all warehouses individually. Separate constraints lead to higher inventory levels because all warehouses have to deliver a certain service instead of an overall service that is provided from the most efficient warehouses. This is because FEI service logistics are accounted for the service level of each warehouse individually. FEI service logistics are also accounted for the inventory turns, the number of times the inventory is sold per year. Given a service constraint maximum inventory turns is achieved by minimizing inventory cost under this constraint.

The problem here is finding the optimal inventory levels for FEI. The local warehouses of FEI are managed using a (S-1, S) policy, which is common in spare parts literature (for an overview see for example Guide and Srivastava 1997). The central warehouse however is managed using a (R,Q) policy. Currently the order quantity at the central warehouse is obtained using a standard EOQ formula. In section 5.4 a heuristic is suggested that will take stochastic demand into consideration.

Lateral shipments and emergency shipments

In this model the local warehouses only receive goods from the central warehouse, which is supplied by infinite supply. Customers are served either directly by the central warehouse or by one of the local warehouses. Lateral shipments; shipments in between local warehouses are not modeled because delivery from the central warehouse is always cheaper (see section 4). In practice however it may be possible to have lateral shipments if the central warehouse has no stock available. Emergency shipments from the central warehouse are not modeled. Focus is on service delivered from a warehouse and if a local warehouse cannot deliver service this is considered a miss in the hit rate. All demand is backordered.

In both the single item and multi item model demand is considered to follow a Poisson process with parameter λ_{in} per item i and warehouse n. For sake of reference all assumptions are (re)stated below.

5.1 ASSUMPTIONS

- All local warehouses use (S-1,S) stocking policy
- The central warehouse uses (R,Q) order policies

- Every individual item demand at all warehouses follows an independent Poisson process with a fixed parameter λ
- All demand not delivered from stock is backordered
- The lead times to the central warehouse are independent and identically distributed random variables with mean T_{i0}
- Delivery times from the central to the local warehouses are deterministic
- Stock is paid for upon receipt
- Order costs are deterministic and the same for each item
- There is infinite supply to the central warehouse
- All warehouses have infinite capacity
- Repairable items are treated as consumables, they are ordered / repaired in quantity and have the same price as new items
- No lateral shipments or emergency shipments are modeled

The notations that will be used in the models are introduced here:

$index\ i : Item\ number\ \ i \in I$

$index\ n : Warehouse\ number\ \ n \in N$

$Z : Total\ cost\ function\ per\ year$

$Q_i : Order\ quantity\ at\ central\ warehouse\ for\ item\ i$

$R_{i0} : Reorderlevel\ at\ central\ warehouse\ for\ item\ i$

$S_{in} : Base\ stock\ level\ for\ item\ i\ at\ local\ warehouse\ n\ (n > 0)$

$C_i : Item\ costprice\ for\ all\ n \in N$

$E\left(I_{in}\right) : Expected\ inventory\ for\ item\ i\ at\ warehouse\ n\ in\ steady\ state$

$I_{in} :\ Physical\ stock\ of\ item\ i\ at\ warehouse\ n$

$\beta_{in} : Item\ hitrate\ at\ warehouse\ n$

$\beta_n : Aggregate\ hitrate\ at\ warehouse\ n\ for\ all\ items$

$\widehat{\beta_n} :\ Target\ aggregated\ hit\ rate\ for\ warehouse\ n$

$\widehat{\beta_{in}} :\ Target\ item\ hit\ rate\ for\ warehouse\ n(single\ item)$

$X_{in} : Pipeline\ stock\ for\ item\ i\ at\ warehouse\ n\ (total\ amount\ on\ order)$

$Y_{in} : Demand\ during\ leadtime\ for\ item\ i\ at\ warehouse\ n$

$T_{in} :\ Leadtime\ of\ item\ i\ to\ warehouse\ n$

$B_{in} :\ Backorder\ level\ for\ item\ i\ at\ warehouse\ n$

$\lambda_{in} :\ Poisson\ demand\ parameter\ for\ item\ i\ at\ warehouse\ n\ per\ day$

$K :\ Order\ costs\ per\ order\ at\ central\ warehouse$

$r :\ Interest\ rate\ for\ invested\ inventory\ per\ day$

$ry : Interest\ rate\ for\ invested\ inventory\ per\ year$

The total cost function for the stock keeping model can then be written as follows, where n=0 stands for the central warehouse.

$$Z(S_{in},R_{i0},Q_i)=\sum_{i\in I}\left[\left(E\left[I_{i0}(R_{i0},Q_i)\right]+\sum_{n=1}^{|N|}E\left[I_{in}(S_{in},R_{i0},Q_i)\right]\right)*C_i*ry+\frac{365*\lambda_{i0}K}{Q_i}\right] \quad \text{(eq. 5.1)}$$

or more specifically:

$$Z(S_{in},R_{i0},Q_i)=\sum_{i\in I}\left[\left(\sum_{x=1}^{R_{i0}+Q_i}P\left(\left(I_{i0}(R_{i0},Q_i)\right)=x\right)*x+\sum_{n=1}^{|N|}\sum_{x=0}^{S_{in}-1}P\left(\left(X_{in}(R_{i0},Q_i)\right)=x\right)*(S_{in}-x)\right)*C_i*ry+\frac{365*\lambda_{i0}K}{Q_i}\right]$$

The total cost function above consists of two parts; the total order costs and the total inventory costs. The total order costs are only relevant for the central warehouse because there an order quantity Q is used which influences the total order costs. These total order costs will be determined by calculating the order quantity according to the heuristic of Gallego (1998) which is explained in section 5.4.

The exact models and constraints are discussed in section 5.2 for the multi item model and section 5.3 deals with the single item model because the constraints are different in these two models. Section 5.4 explains the heuristic used for the stochastic economic order quantity. Finally section 5.5 deals with important item characteristics used in the model.

5.2 MULTI ITEM STOCK KEEPING MODEL

As a preparation to this master's thesis a literature review on spare parts literature has been done (Thijssen 2006). Already in this literature review the paper of Wong et al. (2005b) seemed to resemble the situation at FEI very much. Wong et al. (2005b) have developed heuristics for a multi item spare parts stock keeping model that give close to optimal solutions while significantly reducing computation times for real life size problems. Their greedy approach heuristic is the most promising since it has much lower computation times than their lagranian relaxation based heuristic while results are still close to optimal, especially when it is combined with a local search algorithm. Computation time is very important since the spare parts system under investigation consists of approximately 5,000 active spare parts and 5 different warehouses.

Another pro for the greedy heuristic of Wong et al. (2005b) is that it has been used in two other master's thesis projects already (Bours 2007, Corbijn van Willenswaard 2006) where it was possible to implement this heuristic in a real life size problem and achieving workable computation times.

The model of Wong et al. (2005b) uses base stock (S-1, S) policies for the local warehouses and the central warehouse. The central warehouse is only used for the replenishment of the local warehouses. In the case of FEI the largest demand is actually served by the central warehouse, and the local warehouses are only used for service to specific customers or a group of customers. The central warehouse uses (R,Q) order policies, and the local warehouses use (S-1, S) policies. Therefore these two parameters (R and Q) have to be built into the stock keeping model. These adjustments have already been made in another master's thesis (Bours 2007). Bours investigates a situation with one central and one local warehouse where the central warehouse replenishes the local warehouse every period. In that case the central warehouse uses (R,Q) policies with a given order quantity Q and the local warehouse uses (S-1, S) policies

This model differs from the model of Bours in the following:

1. A stochastic approximation for the economic order quantity Q is used instead of a given order quantity.
2. More than one local warehouse is modeled, which leads to another objective function for the greedy heuristic and other choices in the programming code.
3. The number of items is ten times the number of items of the model of Bours which leads to a newly developed and more efficient optimization procedure.

Objective:

$$Min\ Z(R_{i0},Q_i,S_{in}) = \sum_{i\in I}\left[\left(E\left[I_{i0}\left(R_{i0},Q_i\right)\right] + \sum_{n=1}^{|N|} E\left[I_{in}\left(S_{in},R_{i0},Q_i\right)\right]\right) * C_i * ry + \frac{365 * \lambda_{i0} K}{Q_i}\right]$$

$s.t.$ (eq. 5.2)

$$\beta_n \geq \widehat{\beta_n} \quad \forall\, n \in N$$

$$R_{i0} \geq -1,\ S_{in} \geq 0, .Q_i \geq 1 \ and\ INT$$

Hit rate constraint:

The model objective function is subject to a hit rate constraint per warehouse. The aggregated hit rate per warehouse is calculated as a weighted average over the hit rates per item. An item with a high demand ratio has more influence on the hit rate of the warehouse than an item with a relatively low demand rate.

$$\beta_n = \sum_{i\in I} \frac{\lambda_{in}}{\sum_{k\in I} \lambda_{kn}} \beta_{in} \qquad \text{(eq. 5.3)}$$

To obtain the hit rate for a single item in a warehouse the formulas in (eq. 5.4) are needed. For pure Poisson demand the hit rate is equal to the ready rate (see Axsäter 2006), the chance on positive stock on hand. Using that relationship the following formulas are obtained for the hit rate.

$$\beta_{i0} = 1 - \frac{E(B_{i0})}{Q_i} = P(I_{i0} > 0) = \sum_{x=1}^{R_{i0}+Q_i} P(I_{i0} = x) \qquad (central\ warehouse)$$

$$\beta_{in} = 1 - E(B_{in}) = P(I_{in} > 0) = \sum_{x=0}^{S_{in}-1} P\left[X_{in}\left(R_{i0}\right) = x\right] \qquad (local\ warehouse)$$

(eq. 5.4)

The objective of this model (eq. 5.2) is a solution over three variables. Therefore a sequential procedure has been developed to solve this model. First this solution procedure will be introduced in section 5.2.1, then in section 5.2.2 the math to evaluate the warehouses is introduced, finally section 5.2.3 explains how the greedy heuristic works. Because heuristics are used, no real optimal solution is reached so the obtained solution is a feasible solution that is at best close to optimal.

5.2.1 MULTI ITEM MODEL SOLUTION PROCEDURE

The following part describes the solution procedure that was developed. Because no heuristic or optimal solution is known that optimizes all three parameters (R_{i0}, Q_i, S_{in}) at the same time in a multi item system under a service constraint this approach has been developed. The logic is that the greedy heuristic can solve the multi item model with respect to R and S without considering order costs which determine Q (if order costs are not considered the lowest outcome depends only on inventory costs and is found for Q=1). This leads to the best item hit rates. Then a heuristic solution for Q can be calculated based on the ideal part hit rates that were obtained using Q=1. Using this order quantity the greedy heuristic can again calculate the solution for the multi item model.

Solution procedure

The difficulty in the multi item problem is that the item hit rate is needed to calculate the heuristic for Q. However the item hit rate is not known beforehand because an aggregated target is set instead of a target per item.

The greedy algorithm provides the reorder points (R and S) and hit rates, given the target aggregate hit rates per warehouse and the order quantity Q. The following solution is proposed:

1. Solve the multi item model with the greedy heuristic (with respect to R , S) for Q=1
2. Use the obtained part hit rates to calculate Q. This value of Q is calculated using the heuristic of Gallego (1998) for the stochastic order quantity, explained in section 5.4
3. Solve the multi item model with the greedy heuristic (with respect to R and S) for this value of Q

The objective functions of each step are:

$$1.Min\ Z1(R_{i0}, S_{in} \mid Q_i = 1) = \sum_{i=1}^{I}\left[\left(E\left[I_{i0}\left(R_{i0}\right)\right] + \sum_{n=1}^{N} E\left[I_{in}\left(S_{in}, R_{i0}\right)\right]\right)C_i * ry\right]$$

$$2.Min\ Z2\left(Q_i \mid \left(\beta_{i0} \mid Z1\right)\right) \approx E\left[I_{i0}\left(R_{i0}\right)\right] * C_i * ry + \frac{365 * \lambda_{i0} K}{Q_i}$$

$$3.Min\ Z3\left[R_{i0}, S_{in} \mid \left(Q_i \mid Z2\right)\right] \approx \sum_{i=1}^{I}\left[\left(E\left[I_{i0}\left(R_{i0}\right)\right] + \sum_{n=1}^{N} E\left[I_{in}\left(S_{in}, R_{i0}\right)\right]\right)C_i * ry + \frac{365 * \lambda_{i0} K}{Q_i}\right]$$

This will lead to a suitable solution because of the following:
Step 1 minimizes inventory cost only and leads to the cheapest inventory investment subject to the service constraint. These are the optimal hit rates per item.
These optimal hit rates are used to calculate the stochastic economic order quantity (using the heuristic of Gallego (1998) in section 5.4). This will lead to the best possible solution, even if hit rates change because of this order quantity since that is a change from the optimum.

- The hit rate of an item with a deliberately low hit rate might be higher after calculation with Q > 1 because of this larger Q. Adjusting this Q again because the hit rate is now higher does not lead to a better solution because it only moves further away from the optimal hit rate.
- The hit rate of an item with a deliberately high hit rate might be lower because the optimal solution is now achieved at a lower hit rate for this item because other items are stocked more due to order quantities (see point above). Adjusting the heuristic Q for this item will lead to a lower Q than in the ideal situation because now the high hit rate is not achieved. This leads to a move further away from the optimum hit rate.

Choosing the Q based on (S-1,S) policies thus leads to the best solution. Order quantities are chosen in such a way that they reflect the choice that is made for that item (stock a lot or stock few). Adjusting Q afterwards only leads to all Q moving more towards the average and further away from the decision namely to keep items on stock or not.

5.2.2 MULTI ITEM EVALUATION PROCEDURE

Evaluation is used to calculate the performance of the system with certain parameter settings. It is used to calculate the hit rate and expected inventory given values for R_{i0}, Q_i and S_{in}. Note that in this part of the evaluation Q_i is assumed to be known and not part of the evaluation process. Therefore for ease of notation it is not mentioned. Alternatively for example (eq. 5.5) could have been written as $P\left[I_{i0}\left(R_{i0} \mid Q_i\right) = x\right]$ instead of $P\left[I_{i0}\left(R_{i0}\right) = x\right]$.

According to Wong et al. (2005b) for the central warehouse it holds that the total amount on order at the central warehouse in a steady state $X_{i0} = Y_{i0}$; the amount in the pipeline equals the demand during the leadtime (which is Poisson distributed) in a base stock (S-1,S) model.

Axsäter (2006) shows that in a continuous review (R,Q) policy with Poisson demand the inventory position has a uniform distribution on the integers R+1, ... R+Q.
This leads to the following distribution for the inventory level and the backorder position in a steady state:

$$P\left[I_{i0}\left(R_{i0}\right)=x\right]=\begin{cases}\dfrac{1}{Q_i}\displaystyle\sum_{k=\max(R_i+1,x)}^{R_{i0}+Q_i} P\left(Y_{i0}=k-x\right) & 1\leq x\leq R_{i0}+Q_i \\ 1-\displaystyle\sum_{x=1}^{R_{i0}+Q_i} P\left[I_{i0}\left(R_{i0}\right)=x\right] & x=0\end{cases} \qquad \text{(eq. 5.5)}$$

$$P\left[B_{i0}\left(R_{i0}\right)=x\right]=\begin{cases}\dfrac{1}{Q_i}\displaystyle\sum_{k=1}^{Q_i} P\left(Y_{i0}=R_{i0}+k+x\right) & 1\leq x\leq R_{i0}+Q_i \\ 1-\displaystyle\sum_{x=1}^{Q_i} P\left[B_{i0}\left(R_{i0}\right)=x\right] & x=0\end{cases} \qquad \text{(eq. 5.6)}$$

The formulae for x=0 are obtained by the fact that the sum of all probabilities is equal to one.

With the distribution of inventory above, the expected inventory at the central warehouse can easily be calculated:

$$E\left[I_{i0}\left(R_{i0}\right)\right]=\sum_{x=1}^{R_{i0}+Q_i} P\left[I_{i0}\left(R_{i0}\right)=x\right]*x \qquad \text{(eq. 5.7)}$$

Local warehouses evaluation:

The backorders in the local warehouse can be calculated by the fraction of backorders at the central warehouse that are originated from the local warehouse given the chance on backorders at the central warehouse using a binominal distribution. This is the conditional probability that backorders at the local warehouse are equal to x if the backorders at the central warehouse are equal to y.

$$P\left[B_{in}\left(R_{i0}\right)=x\right]=\sum_{y=x}^{\infty}\begin{bmatrix}y\\x\end{bmatrix}\left[\frac{\lambda_{in}}{\lambda_{i0}}\right]^{x}\left[1-\frac{\lambda_{in}}{\lambda_{i0}}\right]^{y-x} P\left[B_{i0}\left(R_{i0}\right)=y\right] \qquad \text{(eq. 5.8)}$$

The pipeline stock of the local warehouses is then given by the demand during lead time and backorders at the local warehouse, according to Wong et al. (2005b).

$$X_{in}\left(R_{i0}\right)=B_{in}\left(R_{i0}\right)+Y_{in} \qquad \text{(eq. 5.9)}$$

Therefore the probabilities are given by the following formula.

$$P\left[X_{in}\left(R_{i0}\right)=x\right]=\sum_{j=0}^{x} P\left(Y_{in}=j\right)*P\left[B_{in}\left(R_{i0}\right)=x-j\right] \qquad \text{(eq. 5.10)}$$

The inventory is calculated by the following formula.

$$P\left[I_{in}\left(R_{i0}\right)=x\right]=P\left[X_{in}\left(R_{i0}\right)=S_{in}-x\right] \qquad \text{(eq. 5.11)}$$

Equation (eq. 5.11) can be derived directly from (eq. 5.9) and is explicitly stated in Axsäter 2006. The expected inventory (eq. 5.12) can be derived from that.

$$E\left[I_{in}\left(R_{i0},S_{in}\right)\right]=\sum_{x=0}^{S_{in}-1} P\left[X_{in}\left(R_{i0}\right)=x\right]*\left(S_{in}-x\right) \qquad \text{(eq. 5.12)}$$

The part hit rate is given by the probability that on hand inventory is larger than zero. The on hand inventory is given by the distribution of pipeline inventory (X_{in}) (eq. 5.11).

$$P(I_{in}=x)\equiv P\left[X_{in}\left(R_{i0}\right)=S_{in}-x\right]$$

$$P(I_{in}>0)=\sum_{x=0}^{S_{in}-1}P\left[X_{in}\left(R_{i0}\right)=x\right]$$

This explains the part hit rate for the local warehouses in (eq. 5.4).

5.2.3 MULTI ITEM OPTIMIZATION WITH THE GREEDY ALGORITHM

The greedy algorithm of Wong et al. (2005b) uses a so called greedy approach to obtain a close to optimal solution. The basic idea is to increase the order up to level for local warehouses, or the reorder point of the central warehouse step by step, till a feasible solution is reached. For every step the algorithm chooses the largest increase in service relative to the costs. The algorithm uses the evaluation procedure presented in section 5.2.2 to calculate these improvements in every step for every combination of i and n.

The greedy heuristic calculates for every combination of part and warehouse the improvement ratio (eq. 5.13). This ratio is calculated by computing for every location and item combination the improvement in overall hit rate compared to the target hit rate (eq. 5.15) relative to the cost of increasing this inventory position. So the improvement ratio for every part-stock combination is:

$$r_{in}=\frac{\Delta\beta_{in}}{\Delta Z_{in}} \qquad \text{(eq. 5.13)}$$

The difference in total cost is given by the cost of the item that will be put on stock. For calculation of a ratio the interest rate does not need to be included because it is the same for all items and will not change which ratio is best.

$$\Delta Z_{in}=C_i \quad \forall\, n\in N \qquad \text{(eq. 5.14)}$$

The difference in hit rate is given by (eq. 5.15), this difference in hit rate is the improvement compared to the target hit rate $\widehat{\beta_n}$. Once the current hit rate approaches the target, a relatively small and cheap increase in hit rate may be enough to reach the target whereas a more expensive big step might have a higher ratio if the target is not considered in this objective function. $\beta_m\left(i,n\right)$ is obtained by calculating the aggregated hit rate (eq. 5.3) for an increase in order up to level or reorder point for item i in warehouse n. This can be calculated using the item hit rates (eq. 5.4).

$$\Delta\beta_{in}=\sum_{m=0}^{|N|}\left[\left(\max\left(0,\widehat{\beta_m}-Old\beta_m\right)-\max\left(0,\widehat{\beta_m}-\beta_m\left(i,n\right)\right)\right)*\sum_{j\in I}\lambda_{jm}\right]$$

$$m\in N,\, j\in I \qquad \text{(eq. 5.15)}$$

$Old\beta_m$: *hit rate of warehouse m without adding item i to location m*

β_m : *hit rate of warehouse m, obtained by adding item i to location m*

It is clear from the above that the hit rate difference is evaluated as a weighted sum over all changes that happen. This is important because the demand at the local warehouses is much lower than the demand at the central warehouse. By multiplying the change in hit rate by the total size of the warehouse demand, their account on total performance is evaluated instead of just improving local performance.

There are three important observations:

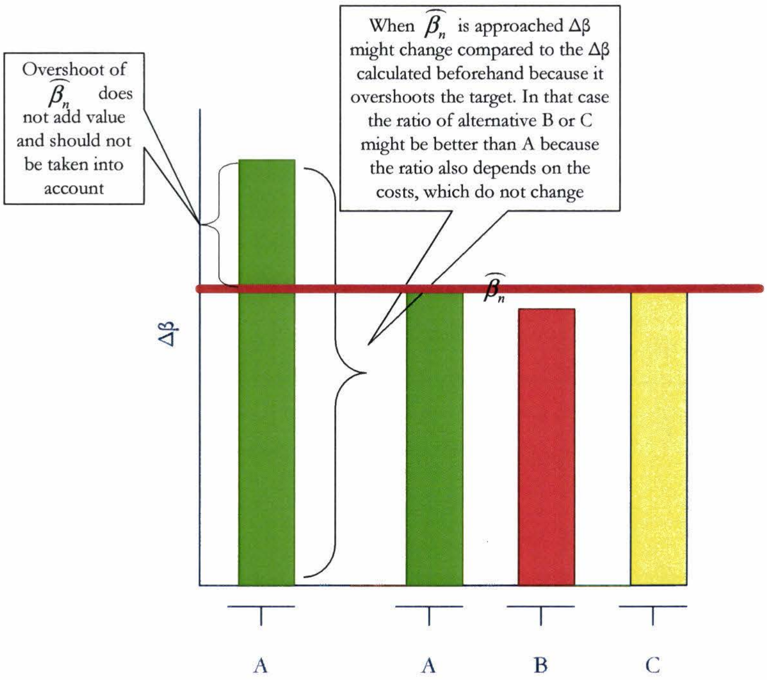
1. Adding one part to the central warehouse can influence the local warehouse hit rate because it reduces the chance on backorders at the local warehouse.
2. The local warehouse indirectly influences the central warehouse ratio because the impact of the central warehouse on the local changes when a part is added to the local warehouse.
3. Since the central warehouse serves the majority of the customers and the local warehouses, adding one part to the central warehouse usually has a smaller effect than adding a part to the local warehouse (adding a certain part to a local warehouse can increase the hit rate of that part in a local warehouse from 0 to 1). By evaluating a weighted sum instead of the absolute improvement this is corrected.

These observations are exploited in the greedy optimization algorithm.

The greedy algorithm follows the logic below:
Let $\underline{S}$ be the matrix with the base stock levels S_{in} for the local warehouses and reorder point R_{i0} for the central warehouse for all combinations of i and n.

1. Set initial values of matrix $\underline{S} = 0$ for all local warehouses and use start values or $R_{i0}=-1$ in $\underline{S}$ for the central warehouse. Set all ratios r_{in} to start value -1 (this commands the program to calculate this ratio in step 3).
2. Calculate values for β_n (current hit rate) and store this for comparison (this is Old β_n)
3. Select the largest ratio (r_{in} = MaxRatio) from all combinations of i and n. If $r_{in}= -1$ calculate r_{in}.
    a. If $\widehat{\beta}_n \geq \beta_n$ → only calculate ratios with value -1. This means that after the first run you only calculate r_{in} for item i, that was selected in 4.
    b. If $\widehat{\beta}_n < \beta_n$ → recalculate ratio of item i and location n
        i. If ratio (item i location n from b.) is still the largest ratio: (r_{in} = MaxRatio) then add item i to location n in $\underline{S}$ and set all ratios of warehouse n with $\widehat{\beta}_n < \beta_n$ to 0. (this warehouse is finished)
        ii. Else continue
4. If MaxRatio $\neq 0$ then increment $\underline{S}$ with one for the maximum ratio with parameters i and n, reset ratios to start values (-1) for item i that changed (for all warehouses n where the ratio is not 0). else END
5. Go to 2

This algorithm exploits the fact that if the target service level is not yet reached only the ratio of the item that is chosen as the best ratio changes. By storing all ratios the highest ratio can be picked by a simple comparison of stored values.
Once an item with a ratio is selected that leads to a higher hit rate than the target hit rate, this ratio has to be recalculated with the current values of $\widehat{\beta}_n$ because this ratio might have changed since the ratio was calculated. This is because only the part of improvement till the target service level adds value to the ratio, the overshoot is not taken into consideration. If this item still has the largest ratio it is selected and all calculations for the warehouse that has reached the target are stopped. If it is not the largest ratio anymore the program continues with that largest ratio. How these ratios change is shown in Figure 11. Once all warehouses have reached their target the program stops.



Overshoot of $\widehat{\beta}_n$ does not add value and should not be taken into account

When $\widehat{\beta}_n$ is approached Δβ might change compared to the Δβ calculated beforehand because it overshoots the target. In that case the ratio of alternative B or C might be better than A because the ratio also depends on the costs, which do not change

Figure 11: Calculation of ratios when the target is reached

5.3 SINGLE ITEM STOCK KEEPING MODEL

Besides the multi-item model also a single item model has been developed because of specific interest of FEI Company in comparison of performance. The single item model uses the same evaluation procedures as the multi item model (described in section 5.2.2 Multi item evaluation procedure) but has a different objective function and optimization procedure. The objective function is:

$$Min\ Z(R_{i0},Q_i,S_{in}) = \left(E\left[I_{i0}\left(R_{i0},Q_i\right)\right] + \sum_{n=1}^{|N|} E\left[I_{in}\left(S_{in},R_{i0},Q_i\right)\right] \right) * C_i * ry + \frac{365 * \lambda_{i0} K}{Q_i}$$

$s.t.$ (eq. 5.16)

$$\beta_{in} \geq \widehat{\beta_{in}} \quad \forall\ n \in N, \forall i \in I$$

$$R_{i0} \geq -1,\ S_{in} \geq 0,\ Q_i \geq 1\ and\ INT$$

Note that this objective function only differs from the multi item objective function in that the objective function and constraint is now for every individual item instead of per warehouse.
The single item model evaluates the hit rate of every part separately and then ensures that targets are met for every warehouse. For the single item model the target hit rate can be set for every warehouse and specific for a group of parts, defined by their ABC classification. That ensures that A items can have a higher hit rate than less important C items.

This single item model can be used to override hit rates for critical items, to ensure availability against an increased cost. This might be necessary because the multi item model only optimizes the aggregate hit rate against minimal cost whereas for some items it might not be accepted that the customer has to wait.

5.3.1 SINGLE ITEM MODEL SOLUTION PROCEDURE

Since stocks at the central warehouse influence the local warehouse performance, but local warehouse performance has no influence on the central warehouse performance, or performance of the other local warehouses, the problem is solved for the central warehouse first. Because the model is now per item it can be split into an (R,Q) problem for the central warehouse with a hit rate constraint followed by a problem per single warehouse because there is no interaction between the warehouses. This must be solved for every single item.

The objective function for the central warehouse is:

$$1.\ Min\ Z(R_{i0},Q_i)=E\left[I_{i0}\left(R_{i0},Q_i\right)\right]C_i*ry+\frac{365*\lambda_{i0}K}{Q_i}$$

$s.t.$

$$\beta_{i0}\geq\widehat{\beta_{i0}}\quad\forall i\in I$$

The central warehouse problem with R and Q is solved for Q first by the heuristic of Gallego (1998) (like in the multi item model) using the target hit rates. This is solved in two steps:

$$1.1\ Q_i=Q_i^g=\min\left(\sqrt{2},\sqrt[4]{1+\left(\frac{(C_i*r+p_i)T_{in}}{2K}\right)^2}\right)EOQ$$

$$1.2\ \ Min\ Z(R_{i0}\mid Q_i)=E\left[I_{i0}\left(R_{i0}\mid Q_i\right)\right]C_i*ry+\frac{365*\lambda_{i0}K}{Q_i}$$

$s.t.$

$$\beta_{i0}\geq\widehat{\beta_{i0}}\quad\forall i\in I$$

Then the local warehouse objective becomes:

$$2.\ \ MinZ\left(S_{in}\right)=E\left[I_{in}\left(S_{in}\mid R_{i0},Q_i\right)\right]$$

$s.t.$

$$\beta_{in}\geq\widehat{\beta_{in}}\quad\forall\ n\in N-\{0\}\quad\forall i\in I$$

This is solved for every warehouse individually. This procedure must be repeated for every item.

For the single item model the order quantity Q (in step 1.1) is calculated using the target hit rates per item class in the model and the heuristic from section 5.4 Order quantity. After the calculation of Q the optimization procedure shown in Figure 12 will be used.

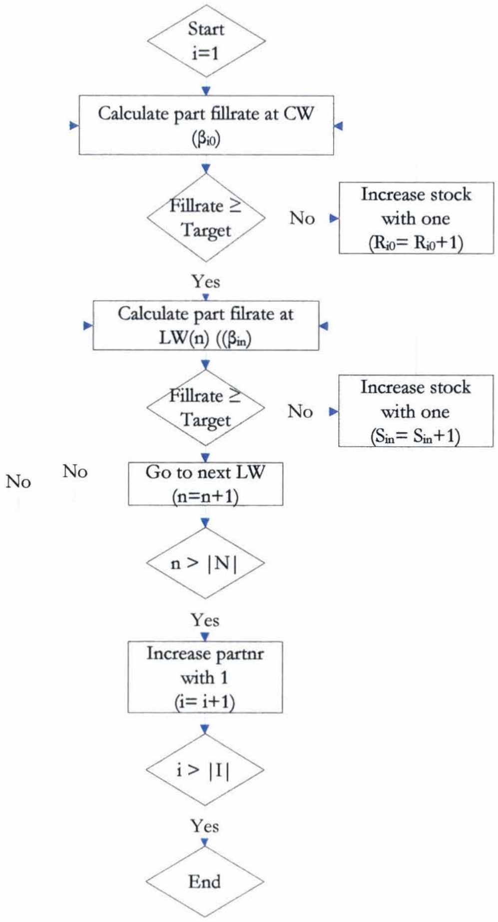


Figure 12: Algorithm for solving single item stock keeping model

5.4 ORDER QUANTITY Q_i

FEI Company uses an order quantity Q_i in the central warehouse instead of a stock level which is proposed in spare part literature. Currently an Economic Order Quantity (EOQ) formula is in use to determine this order quantity. The EOQ formula is a well known formula in literature (see for example Silver et al 1998) and is a deterministic approximation of the optimal order quantity in a stochastic model.

For this master's thesis the use of a heuristic stochastic solution for the order quantity Q is proposed, based on the article of Gallego (1998). Details about other literature and the use of this heuristic is shown in Appendix XVII.

The heuristic is:

$$Q_i^g = \min\left(\sqrt{2}, \sqrt[4]{1+\left(\frac{(C_i * r + p_i)T_{in}}{2K}\right)^2}\right) Q_i^d \qquad \text{(eq. 5.17)}$$

Penalty costs are calculated using the newsvendor ratio. This ratio links the time average probability of being out of stock to penalty and holding costs. The time average probability of being out of stock equals the hit rate if demand follows a Poisson process.

$$p_i = \frac{C_i * r * \beta_{i0}}{(1-\beta_{i0})} \qquad \text{(eq. 5.18)}$$

5.5 ITEM CHARACTERISTICS

This subsection deals with characteristics of the individual items (SKUs) in the model and how they have been obtained or determined. Some of this might be straightforward from the formulas but nevertheless it is convenient to state it explicitly here.

5.5.1 ITEM COST C_i

Prices used at all warehouses in the models are the standard cost prices of items at which they are valued within FEI. This has been chosen because it is the closest to the real cost FEI pays for its inventory. Customer prices have not been used because they vary widely between customers and orders because of warranties, special contracts and other specific deals for specific orders. Repairable items are also accounted against their standard cost because repair prices also vary widely and are not specified in contracts beforehand; a price offer must be obtained for every single repair.

5.5.2 LEAD TIME T_{in}

The lead time at the central warehouse is an item specific random variable with mean T_{i0}. The lead time to the local warehouses is deterministic and warehouse specific; not item specific because the same mode of transport is considered for all items. For the existing warehouses (Londonderry, Dresden and Crolles) the lead time is one day. For the new warehouse to be built in Italy the lead time is two days. This is based on the fastest possible delivery times with UPS. For repairable items the average lead time at the central warehouse is the maximum between the repair lead time and the order lead time. The most important part of the revenue comes from repairable items whereas this is only a minor part of all demanded items. Repairable items are dealt with just like consumable items. Their average lead time is adjusted to the maximum of the average repair lead time (standard 91 days according to Halmans 2005) and the lead time. This is done so because repair lead time is highly uncertain; FEI uses 91 days aa standard average lead time but real data on repair times are not generally available. In many cases it is not even known beforehand if the item can be repaired at all. Because these items are often crucial, and a large part of management time is spent on these items a conservative approach is used to provide FEI with the opportunity to always be able to purchase or repair the item within the lead time stated in the system.

5.5.3 DEMAND λ_{in}

Demand is assumed to follow a Poisson process, which is common in spare parts literature. A χ^2-goodness of fit test was performed to see if the number of demand occurrences per period (and not the inter arrival times) are Poisson distributed. The analysis shows that for demand observed per quarter for 80.2% of the tested items it cannot be rejected that the demand follows a Poisson distribution, if 99% certainty is needed to reject this. For local warehouses this percentage is between 60% and 68.8%. Appendix XVI shows all results of fitting a Poisson process to the demand data.
The expected demands are calculated as the average demand over the time that the item has been in existence from 01/01/2003 and onwards. So if an item only came into existence at 05/06/2005 this is taken as the start date to calculate the average demand, and if it already existed before 01/01/2003 this date is taken as the start date because the demand information is only available worldwide from then on. For the local warehouses the average demands are based on demand from specific customer sites that are served by this warehouse. For the central warehouse demand is based on worldwide orders originating from Eindhoven (products produced here) and total demand in Europe.
Only calls from customers for spare parts are taken into account, no replenishment orders.

5.5.4 START VALUES REORDER POINT R_{in}

The start value is not an item characteristic, but the start values are based on the demand and lead time at the central warehouse, which are item characteristics. Therefore it is treated here.

To make the model faster and to make sure a minimum level of service is delivered to all customers it is possible to use start values for the reorder point at the central warehouse. The optimization then starts with these reorder points. Demand during lead time – 1 is taken as a start value. Since the demand during lead time is necessary to provide a minimum service the stock level must be that when you reorder. Since the reorder point is S-1 the demand during lead time -1 is selected. This still provides the opportunity not to keep items on stock (if there is no demand during lead time, the reorder level is -1, which means an order is placed as soon as demand arrives and no sooner). This is especially useful for items with a lead time of 0, which is chosen on purpose because FEI does not want to keep those items on stock.

6 RESULTS

This subsection deals with results of different analyses. These results focus mostly on difference in total costs. Total costs have been taken as objective for comparison because these reflect changes in the central warehouse and all local warehouses. It must be noted that the central warehouse is much larger than all single local warehouses together and that also order costs are taken into account here. Therefore changes in the central warehouse have the largest influence on the total costs. Detailed costs for the standard solution of all models are shown in Appendix XVIII.
In this section four different models will be compared:

1. R,Q model; this is the proposed solution procedure that solves the multi-item, multi echelon problem with a stochastic heuristic for Q and uses the greedy heuristic to obtain numerical values for R and S.
2. EOQ model: this multi-item model uses the deterministic EOQ formula for Q and then uses the greedy heuristic to obtain R and S.
3. Q=1 model: this multi-item model uses base stock (S-1, S) policies for all warehouses.
4. Single item model: This model uses a single item approach and calculates the stochastic economic order quantity Q by the target item hit rates.

Section 6.1 deals with verification and validating the models and is especially focused on validating the proposed R, Q model solution. Section 6.2 comments on the differences between the single-item and multi-item solutions. Section 6.3 then continues with sensitivity analysis. Section 6.4 compares this model with a model without a service constraint for the central warehouse. In that case the model is changed so that only service constraints are set for customer demand and not for warehouse demands. Section 6.5 compares the proposed solution with the current inventory in the central warehouse. Finally section 6.6 provides a summary of these analyses.

6.1 VERIFICATION AND VALIDATION

The above models and solution procedure have been incorporated in a program in the programming language Delphi. To make sure the proposed solution process is correct the models have been verified and validated. Because the solution procedure for the R, Q model is new, part of the validation is aimed at validating this solution procedure.

Verification is defined as "ensuring that the computer program of the computerized model and its implementation are correct"; the process of checking if a program does what it is intended to do. To make sure calculations with the program are correct it has been debugged and calculations have been run step by step to make sure it works as intended.
Validation is defined as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Schlesinger et al. 1979 in Sargent 2005). It consists of conceptual model validation, data validity and operation validation.
Data validity is defined as ensuring that data necessary for building, evaluation and testing of the model are adequate and correct. This is done by obtaining all parameters directly from the ERP system of FEI, (if possible), data that could not be obtained directly from the ERP system have been checked by FEI management for correctness.
Conceptual model validity is defined as determining that the theories and assumptions underlying the conceptual model are correct and that the model representation of the problem entity is reasonable for the intended purpose. Therefore all assumptions have been listed and discussed with FEI management, before, during and after development of the model. Also a Poisson process is fitted to demand data in Appendix XVI. The Poisson demand process is the only process used in spare parts literature, though it is difficult to prove a good fit to this process there is no alternative.

Conceptual model validation (with respect to the proposed heuristic R, Q model solution procedure) has also been obtained by enumeration of all solutions (this shows how far from optimal the model solution is with respect to Q), and by sensitivity analysis with respect to the parameters r and K (this shows how the model behaves for various parameter settings).

Operational validation is defined as determining that the models output behavior has sufficient accuracy for the models intended purpose over the domain and intended applicability. Operation validity is obtained by comparing the model solution to real demand data.

6.1.1 ENUMERATION OF SOLUTIONS

The heuristic to optimize Q, R and S has been validated by checking its outcome in a small test bed against all possible values of Q. This is done by enumerating all possible options and calling the greedy optimization algorithm for all these options. As bounds for Q the deterministic EOQ and √2 * EOQ have been taken according to the bounds on the optimal order quantity as stated in Gallego (1998).

Since this procedure is strongly exponential for the number of items, and depends strongly on the range of Q to be investigated, this could only be done for very small test beds.

It must be noted that the performance of the greedy heuristic that is used in the solution improves when more items are considered. This is because then single decisions have less impact than when only a few items are considered. So to check the performance of the newly proposed heuristic sample sets of items are used that might not lead to the best performance of the solution procedure. The calculated optimum is thus not necessarily the real optimum since it is obtained by the greedy heuristic.

Items with large demand and large EOQ

One test bed consisted of five items (randomly selected) with fairly large demand and economic order quantities. Prices ranged from €429.93 to €1,752.81 and the deterministic EOQ ranged from 6 to 12. Demand at the central warehouse ranged from 0.20 to 0.77 on a daily basis. The total number of scenarios to be calculated was 1440. The heuristic solution was number 229 of all 1440 solutions considering total cost, but the deviation from the optimal cost was only 0.6%.

This analysis showed that the heuristic solution performed well. Only for one item the order quantity differed from the heuristic solution. This was probably because a slightly lower total cost was possible by approaching the target aggregate hit rate closer. In the optimal solution the achieved hit rate was 0.95002 whereas the model solution was 0.9511. Further analysis revealed that for this item the optimal Q was not consistent with literature. In literature it is usually assumed that the optimal order quantity is close to the EOQ for relatively expensive items (order costs are relatively low here) and the optimal order quantity is close to √2 * EOQ for relatively inexpensive items. This is also coupled to the penalty cost; if penalty costs are high (a high service is needed; high hit rate in this case) the optimal order quantity is also higher. In the optimal solution the order quantity of the cheapest item was close to the EOQ whereas the hit rate achieved by this item was 0.99 which indicates high penalty costs. (EOQ=11, Q*=12 Qg=15). Table 3 and Table 4 contain details of this analysis.

Table 3: Cost comparison order quantities – large demand items

		Costs		Δ% Optimal	Aggregate
	Inventory	Order	Total	Cost	Fillrate CW
Q optimal	€ 7,037.00	€ 1,391.96	€ 8,428.99	0.00%	0.95002
R,Q model	€ 7,128.80	€ 1,351.03	€ 8,479.84	0.60%	0.9511
EOQ	€ 6,776.70	€ 1,869.47	€ 8,646.19	2.58%	0.95058
Q=1	€ 6,339.30	€ 16,808.87	€ 23,148.20	174.63%	0.95015

Table 4: Part fill rates and order quantities – large demand items

			Part fillrate			Order quantity		
Price	Part number	Q=1	(R,Q) model	Q optimal	EOQ	(R, Q) model	Q optimal	EOQ
€ 1,752.81	4022 268 00433	0.88787	0.88275	0.88275	0.89271	8	8	6
€ 919.94	4022 268 00015	0.93942	0.93446	0.93446	0.93585	11	11	8
€ 535.14	19201	0.95300	0.96409	0.96409	0.95272	12	12	9
€ 1,188.68	23900	0.96299	0.96688	0.95863	0.96315	16	16	11
€ 428.97	330-000016	0.99447	0.99240	0.99050	0.99527	15	12	11

This indicates that the optimal solution will never be found by the heuristic because it deviates from the theory this heuristic uses.

Comparison of the heuristic solution to the EOQ revealed that considering total costs the heuristic performs much better than the EOQ.

The above indicates that the heuristic for Q probably performs well and that the logic of only running it once (using Q=1) is correct since no better solution will be found by running it again (using the outcome for Q). The problem of a different order quantity approaching the hit rate better is a much smaller issue in the real problem since the central warehouse hit rate is approached precisely or very close due to the higher number of items.

Expensive items, low demand

Another test bed consisted of 29 items with fairly low economic order quantities and higher prices, divided over A, B and C items. Prices ranged from €60.64 to €157,276.95 and demand ranged from 0.007 to 0.105 on a daily basis.

The R,Q model performed really poor in this case. Both the deterministic EOQ formula and all order quantities equal to one outperformed the R, Q model. This is due to the fact that order costs are almost negligible compared to total costs. In the optimal solution the total order costs are only 1/45th of the total costs. Thus optimization of the order costs leads to very small cost improvements whereas change of inventory investment is significant. The reason is that the R,Q model uses hit rates on item level to calculate penalty costs and uses that as a direct input to the size of the order quantity. Though items with a high hit rate are relatively cheap in this example, keeping them on stock still is significantly more expensive than ordering the item more often. In the optimal solution 4 order quantities are lower than in the R, Q solution. Also the reorder points of 10 items are different. Nine of them are lower, only one is higher. This clearly shows that the problem is integral, by keeping one item more in stock (higher hit rate) of 11 items the stocks can be reduced by lowering the order point, order quantity or both. This explains why in this case calculating the optimal order quantity per item leads to bad results.

This test bed contained more expensive items and low order rates, which lead to focus on inventory cost. This shows partially why focus on stock keeping models for spare parts is on (S-1,S) models. For expensive items inventory cost are the most important, and focus on also optimizing order costs leads to more inventory. The model proposed probably works well if enough items that are cheaper to order than to keep on stock are modeled. In that case order costs can be optimized for these items and no artificially large order quantities are set for relatively expensive items.

When the same test is performed with just one item added with a lower price (€10,-) and demand of 0.02 per day, the model performs a lot better. Now the R, Q model outperforms the EOQ and Q=1. Order costs are still low compared to inventory cost (1/40th). Also for three items with a lower than heuristic optimal Q solution, the optimal Q has increased with one, so they are one step closer to the heuristic solution.

Conclusion

It seems that for large fill rates the heuristic model overestimates the optimal order quantity. Only overestimation of the optimal order quantity Q has been observed, so it might be beneficial to investigate how the heuristic can be improved to overcome this.

Because the enumeration shows that the optimal order quantity Q is not a stable solution it is difficult to categorize items to improve the performance further. It is not the case that for certain items the optimal order quantity is always equal to the EOQ or another value of Q. Adding just one part (as shown above) increases the optimal order quantity of three items, so a decision based on just individual item parameters is not possible.

Therefore the R,Q model should be used for all items. If enough relatively cheap items are included in the set of all items, the R, Q model will not stock too much inventory of expensive items and will outperform all other models.

6.1.2 SENSITIVITY ANALYSIS FOR INTEREST RATE AND ORDER COSTS

Since the heuristic (R, Q) model probably has a better performance when data from all items are used, it is also tested on the total dataset. All 4 models (mentioned in the beginning of this section) are tested for sensitivity to the parameters r (interest rate) and K (order costs) because these directly influence the order quantity Q.

Tested are several values of the interest percentage r (8%, 10% and 15%) and order cost K (€15, €25 and €50) to be able to tell something about the sensitivity of the models. These values have been chosen because they reflect reasonable values used within FEI. Standard 10% interest rate and €25 order costs are used. Results are shown in Table 28 in Appendix XIX. Figure 13 is a graphical presentation of sensitivity to total cost of these parameter values as a percentage deviation from the base case.

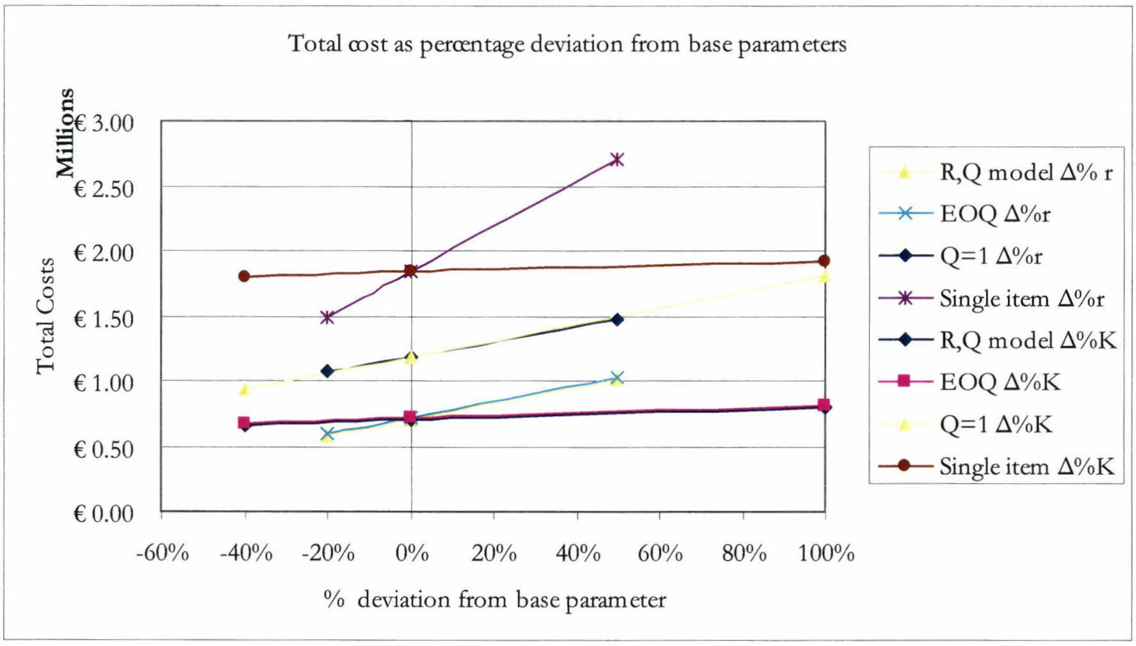


Figure 13: Total cost relative to parameter changes

The R,Q model outperforms the other models in every occasion. The difference is larger when order costs become more important than inventory costs as is shown by a larger deviation from the EOQ and Q=1 model when the interest percentage r decreases, or when the order costs increase. This is very clear because the Q=1 model does not take order costs into consideration, and the EOQ model underestimates the economic order quantity because it takes a deterministic approach and underestimates the number of orders that have to be placed.

Figure 13 shows the total costs and how these change when the parameters order cost (K) and interest percentage (r) change. It is interesting to notice that performance of both the EOQ and the R,Q model seem equally sensitive. All models are very stable towards deviations in order costs (except for the Q=1 solution, which neglects these costs). The models are more sensitive to deviations in the interest percentage, which is clear because inventory cost is about 6/7th of total cost in the base solution.

While the performance on total cost is relatively flat for changes of the order cost, this change does impact the inventory costs a lot. This leads to the following conclusion on the importance of parameters:

1. Interest percentage is very important for the total costs, and for determination of the order quantity. Therefore the interest percentage should be selected adequately so it reflects the real cost FEI makes on a yearly basis on their inventory.
2. The order cost K is important because it determines the weighing between ordering more often and keeping some more stock. Although this is important, the graph shows that total costs are not so dependent as on interest percentage. Therefore a raw estimate of order costs will still give a good approximation of the total cost incurred in the end, when the interest percentage reflects the inventory costs well.

6.1.3 MODEL SOLUTION COMPARED TO REAL DEMAND DATA

To obtain operational validity the proposed R,Q solution is compared to demand in 2006. This has been done by comparing order up to levels S of all local warehouses to demands. In this approach backorders are neglected and the local warehouse stock is assumed to always equal S.

Two datasets have been used to obtain the average demand parameters λ_{in}; demand in 2006, and demand from 2003 to 2006. The first is used to prove model performance if the demand parameters are exactly known. The latter is used to prove performance using the proposed parameters.

The stock levels S in the local warehouses are calculated using the R, Q model with these data. The outcomesare compared to item demand per month and per day. Monthly demand shows the minimum performance and corrects for not taking backorders into account. Daily demand reflects the real demand sizes per item per day.

For both these demand occurrences the hit rate has been calculated as the amount fulfilled from stock compared to the total amount demanded. For the daily demand also the order hit rate has been calculated as the number of orders delivered from stock divided by the total number of orders. An order is defined as the total amount of an item demanded on a day. All details are shown in Table 5.

Table 5: Achieved hit rates with new parameters

	demand over 2006				demand over 2003 - 2006			
	Londonderry	Dresden	Crolles	Italy	Londonderry	Dresden	Crolles	Italy
monthly demand	87%	71%	89%	77%	83%	69%	91%	67%
daily demand	93%	73%	89%	81%	90%	71%	91%	70%
order hit rate	94%	80%	88%	78%	92%	82%	91%	62%

This analysis shows the following:

In Dresden large single orders for items occur on a single day of up to 10 or 20 items. This is the main reason for the low hit rate there. This is shown by the fact that the order hit rate is larger than the hit rate for demand per day.

In Italy the order hit rate is smaller than the hit rate for demands per day (and ever for demands per month when 2003 – 2006 data is used). This indicates that often orders are placed for more than one item, but that often part of this order can be delivered from stock.

In Crolles the hit rate is very stable. It seems that here the assumption of a Poisson process for demand arrivals is largely valid.

In Londonderry also demands look pretty stable and Poisson distributed. Items are demanded more than once a month which is shown by the difference in performance for monthly and daily demand.

The above shows that it is important to further investigate the demands. Large orders may be due to preventive maintenance, and should be delivered from the central warehouse in that case. Orders for more than one part in Italy might occur because there is no warehouse nearby and engineers order more items to have some stock for the next time they might need it. If however demand for certain items always occurs with a quantity >1, this quantity should be used as if it is one item. In that case a compound Poisson process is approximated by a Poisson process.

Trends in demand are also important. This is probably caused by changes in the installed base, and is shown by the difference in performance when only demands from 2006 are used, or when demands from 2003 to 2006 are used.

Because demand at local warehouses in 2006 is not consistent with a steady Poisson process based on historical demand it is important to review the model outcomes with people who have local market knowledge. The installed base has changed and predictions must be made about changes in demand. Likewise if two items are always needed to repair one machine it does not make any sense to only stock one item.

Actual performance for the central warehouse cannot be compared this easily because the inventory position (this includes orders) is always between r+Q and r+1 and the lead time must be taken into account. The analysis shows that for monthly demand, if the inventory level is always at r+Q a 99% hit rate is reached. If the inventory level is at r+1 a 90% hit rate is reached for 2003 - 2006 demand, and a 92% hit rate for 2006 demand. A more sophisticated analysis is needed to obtain a real estimate for the actual performance of the central warehouse. Therefore a program could be build that simulates real demand occurrences and orders and takes the lead time into account. In this thesis such a program has not been build.

6.2 SINGLE-ITEM COMPARED TO MULTI-ITEM

The single item model has the worst performance in terms of total costs for all parameter settings. This is because the single item model stocks much more items because it needs to satisfy at least the hit rate constraint for all items, whereas the multi item models are able to level this so an average hit rate in the warehouse can be reached by stocking more cheap items with a high hit rate and less expensive items with a low hit rate. Because of this the single item model has much more inventory than the multi item model. This is especially apparent for the local warehouses where the decision often is stocking one or no items there. The single item model has to stock all items with a demand possibility (historical demand) because otherwise no hit rate is reached for this item. The single item model total cost function is very sensitive to changes in interest percentage because much stock is kept.

6.3 FURTHER SENSITIVITY ANALYSIS

The sensitivity analysis in section 6.1.2 was performed with the aim of validating the R, Q solution. Based on these results it can be concluded that it is best to use the R, Q model. This section further investigates the model sensitivity to other parameters. Lead time to local warehouses is investigated first, followed by lead time to the central warehouse. Finally the sensitivity to the hit rate constraint is investigated.

6.3.1 LEAD TIME TO LOCAL WAREHOUSES

Shipping once a week and shipping once a month has been compared to the current policy of shipping immediately. Weekly shipments have been modeled as 4 days lead time to all local warehouses except the local warehouse in Italy which has a 5 days lead time. These lead times are obtained as the average delay for shipping once a week plus the shipping time (so 3.5 + 1 or 2). Because the lead time in the model needs to be integer this is rounded down to 4 or 5 days. Monthly shipments are modeled similarly with 16 days lead time for the existing local warehouses and 17 days for Italy.

Figure 14 shows the total cost function of the four models for three tested lead times. Again the single item model has much higher costs than the multi item models, and is more sensitive to changes, which is explained by the fact that it must reach the target hit rate for all items, if by changing the lead time the target of one or more items becomes below target all of these items need more stock in the local warehouses.

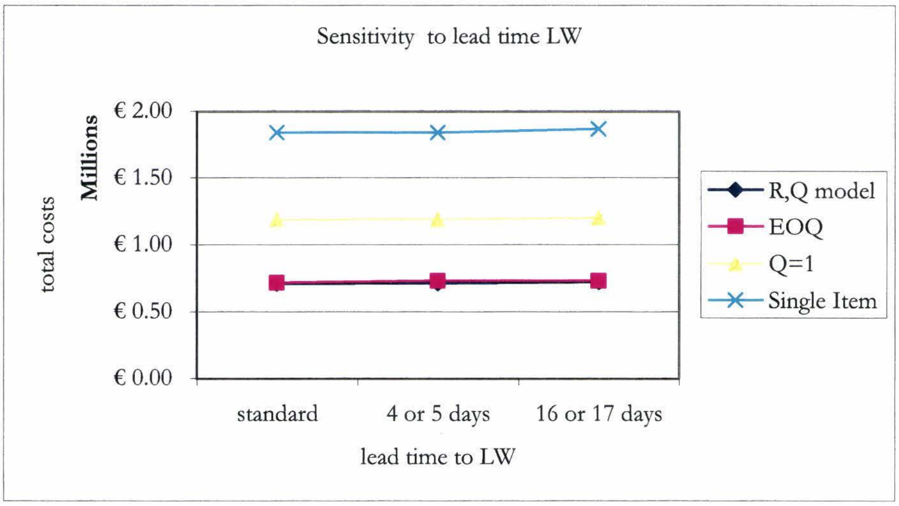


Figure 14: Sensitivity of total cost to local warehouse lead time

When the R, Q model is used shipping once a month only increases the total costs by €14,000 a year, and shipping weekly leads to €4,000.- extra costs. These costs are the extra inventory costs in the warehouses. Because the warehouses only pay when they receive items no extra inventory costs are accounted for the 4, 5, 16 or 17 days the items are in transport in this model.

These increases are only modest compared to total costs (2% for monthly shipments and 0.5% for weekly shipments) so it is worth investigating if more than this amount can be saved by consolidating shipments to local warehouses to weekly or monthly replenishments. The total transport costs to local warehouses in the location model are only €15,500.- per year. They depend on the size and weight of the shipments. Further analysis is needed to prove if consolidating shipments can lead to cost reductions, but with the already very low shipping cost of FEI and the dependency on total size and weight it does not seem a profitable option. For consolidating to weekly shipments a transport cost reduction of 25% is necessary to obtain a total cost reduction. For monthly shipments transport costs have to be lowered by 90% to obtain a total cost reduction.

6.3.2 LEAD TIME TO THE CENTRAL WAREHOUSE

The lead time to the central warehouse is an important parameter for the overall service to customers. The lead time influences the reorder point in the central warehouse directly. Because it has been noted that the repair time for items is uncertain, and because the lead times in the database might not be correct the sensitivity to this parameter has been investigated. Therefore total costs in the normal solution have been compared with a 50% reduction in average lead time for repairables, consumables and all items.

A decrease in average lead time for repairable items leads to an increase in total costs and inventory costs for the multi-item models. This is probably so because repairable items are expensive, often slow moving items and a reduction in lead time leads to higher hit rates with lower reorder points for repairable items. Because higher hit rates are achieved by these relatively expensive items, lower hit rates are achieved by relatively cheap items. This is shown in small decreases of the reorder levels of cheap items. Because hit rates are directly linked to inventory on hand, this means total inventory costs rise. Because repairable items are treated as consumables in this model no inventory cost is accounted during repair lead time. In fact FEI does have this inventory, so a reduction in repair lead time does lead to lower costs (lower reorder point means less parts in the pool), only this is not shown in the model because that only accounts costs for good (repaired or new) items in inventory.

For consumable items, and overall 50% reduction in average lead time leads to lower total costs, but changes in terms of percentages are small for the multi-item models. It is interesting to see the difference between the single- and multi-item models. For the single item model all reductions in average lead times lead to lower costs, and the reduction of consumables and repairables together leads to the reduction for all items. In the multi item model the overall cost reduction is averaged between the consumable and repairable lead time reduction. Details on this analysis are shown in Appendix XX.

6.3.3 TARGET HIT RATE SENSITIVITY

The target hit rate is also an important input parameter for the model. While this parameter is usually assumed to be known and fixed, it is important that the model performs well for all reasonable target aggregate hit rates. The sensitivity analysis shows that again the R, Q model outperforms both the EOQ, Q=1 and single item solutions. The performance is summarized in Figure 15. For ease of interpretation only the EOQ and R,Q solution is shown in the figure. More details are shown in Table 29 in Appendix XIX. It shows that the R, Q model consistently outperforms the EOQ model. The difference in inventory costs increases when the hit rate increases; this is explained by the fact that inventory costs become more important when more inventory is needed. The difference in order costs also increases because the total order costs in the R, Q model decreases. This is explained by the fact that the order quantity increases when item hit rates (penalty costs) increase. Total costs difference stays approximately the same, though the largest difference is achieved when the hit rate is 95%.

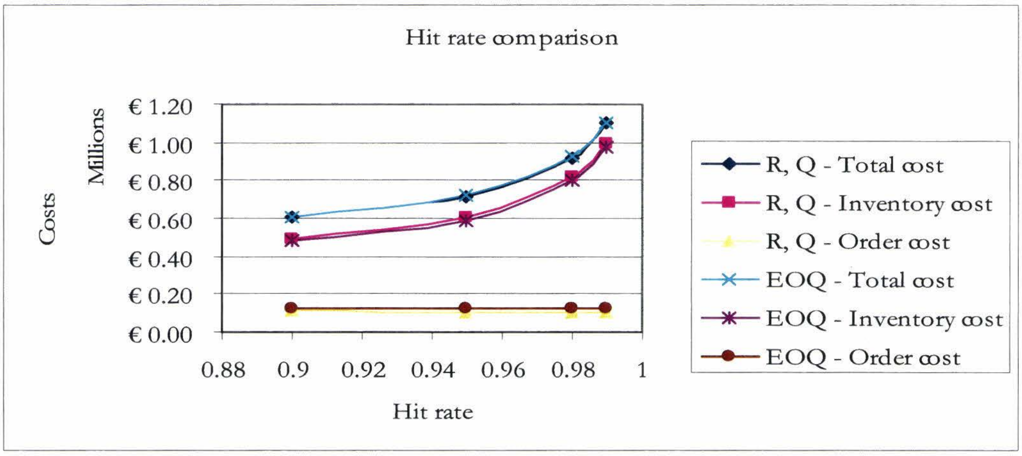


Figure 15: Hit rate sensitivity

6.4 CENTRAL WAREHOUSE WITHOUT A SERVICE CONSTRAINT

In literature it is shown that service levels should not be set for intermediate warehouses, only for service to end customers (Van Houtum et al 1996). In the presented model here though, a service level is set specifically for the central warehouse. This is necessary because FEI is accounted for service delivered from this warehouse, and because a lot of customers receive service directly from this warehouse. To test how this approach with a service level for the central warehouse influences total costs the following test has been done.

The target hit rate for the central warehouse is set to 0. The greedy heuristic will only decide to stock items there for service to the other local warehouses, since service levels in the central warehouse are not considered in the objective function anymore because the target is always reached.
Further because only a total of 5 warehouses can be modeled in the program the demand in the Italy warehouse is removed, and all demand not generated at the other local warehouses is inserted here. This is to make sure service is delivered to all customers of the central warehouse. The lead time to this virtual warehouse is set to 0.
For comparison the above model is compared to the original situation without the warehouse in Italy.

Table 6: Details comparison service level at CW vs no service level at CW

Multi Item (R,Q) Model	original (no lw 4)			LW 4 has all demand not at other LW		
Warehouse	HitRate	Inventory Turns	Inventory	HitRate	Inventory Turns	Inventory
Central	0.95	4.07	€ 5,267,402.00	0.84404	5.01	€ 4,274,765.00
Dresden	0.95	2.43	€ 211,351.00	0.95001	2.22	€ 231,282.00
Londonderry	0.95	2.65	€ 189,937.00	0.95	2.46	€ 205,128.00
Crolles	0.95	1.64	€ 250,939.00	0.95	1.55	€ 265,665.00
CW Demand not at LW				0.95	10.99	€ 1,818,912.00
Total		3.62	€ 5,919,629.00		3.15	€ 6,795,752.00
Inventory cost		€ 591,962.90			€ 679,575.20	
Order Cost		€ 105,412.45			€ 119,718.17	
Total Cost		€ 697,375.38			€ 799,293.34	

Table 6 shows that a service level at the central warehouse produces better results than when service levels are only set for local warehouses. Direct demand at the central warehouse is then modeled as an additional (virtual) local warehouse. While inventory turns at the central warehouse and the virtual warehouse with all other demands are higher in this solution, total inventory investment and thus inventory turns are lower. This is explained by the fact that in this situation inventory "reserved" for all customers that are not served by a local warehouse is not available for service to these local warehouse. This leads to somewhat higher inventory levels at the local warehouses, and to higher inventory at the central warehouse, because now two separate piles of stock must be built, to serve local warehouses, and to serve all other customers.

According to this analysis the modeling of the central warehouse with a service constraint as proposed is not only preferred by the company but also better in terms of total costs. Therefore it can be concluded that it is right to use the current modeling approach. If however the whole world could be modeled with this approach, and only service levels are set for end customers the above approach might lead to better results.

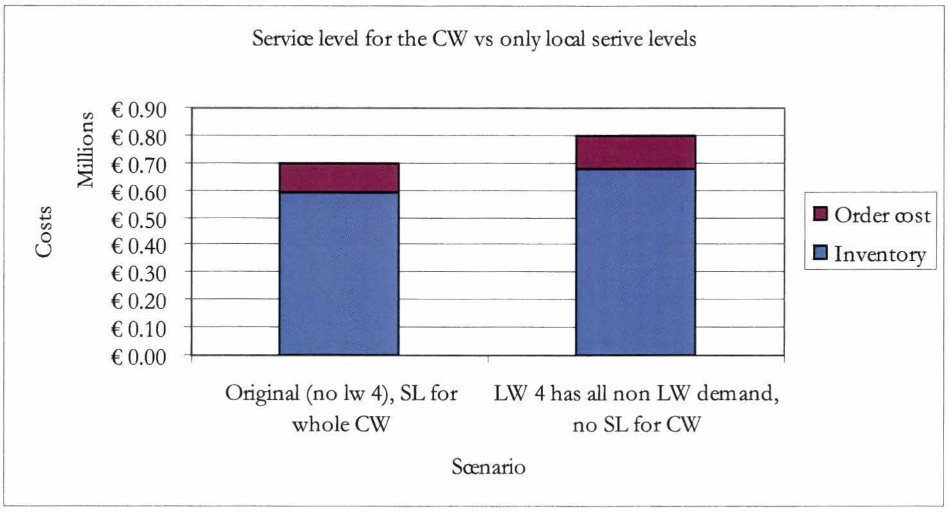


Figure 16: Performance with no service level for the central warehouse

6.5 PROPOSED INVENTORY COMPARED WITH CURRENT INVENTORY

The proposed (R,Q) model shows that with approximately € 5.3 million of inventory at the central warehouse it will be possible to provide a 95% service level to the customers. Because this differs a lot from the approximately € 12 million that currently is in stock at the central warehouse this has been compared on item level. Table 7 contains the model solution for every warehouse and the total costs. In this analysis, the focus will be on the central warehouse only because that gives the most interesting inventory difference. The much smaller local warehouse inventories can more easily be adjusted.

Table 7: Model solution

Multi Item (R,Q) Model

Warehouse	HitRate	Inventory Turns	Inventory	Total Cost	Order Cost
Central	0.95	4.07	€ 5,267,402.00		
Dresden	0.95	2.43	€ 211,351.00		
Londonderry	0.95	2.65	€ 189,937.00		
Crolles	0.95	1.64	€ 250,939.00		
Italy	0.95	1.2	€ 148,653.00		
Total		3.53	€ 6,068,282.00	€ 712,240.64	€ 105,412.45

Table 8 contains the actual difference between the current inventory at the central warehouse and the (R,Q) solution as proposed by the multi item model. The total inventory has been classified in non-moving parts; no demand was observed for these parts in the last four years, parts with excess stock; larger than the reorder quantity and reorder point, parts with too little stock; lower than or equal to the reorder point and not ordered above the reorder point, and well managed inventory, the rest.

Striking is that more than 46% of the items is non-moving stock. These stocks need further investigation. It could be new items, which clarifies why no demand has been observed yet, or it could be for production purposes. But probably a large part of these stocks needs to be devaluated because of risk of obsolescence.

Another large part of inventory is stocked too much. This is part of the inventory that can be managed more efficiently using the new model. For these parts the transition period has been investigated till the stock is within the new stock keeping parameters. This is important because it shows how fast FEI can move from the current spare parts management to the new management.

Too little stock might be because the reorder level has been raised by the new model, or because these parts have not received the proper attention. This is a great area for service improvement for FEI. €2.3 Million must be ordered on parts that are below the reorder point and have not been ordered enough to raise inventory above the new reorder point. This means service levels of these parts are too low. By ordering these parts FEI will directly increase its service to customers.

For all the above categories it must be stated that the actions proposed are actions on a general level. Evaluation per item is important for all classes because of item specific problems or characteristics.

Table 8: Difference current situation and model solution

	# items	Quantity	Value	Action
Total CW	5622	103657	€12,286,465.30	Adjust Q and R
Non moving stock	2552	56325	€2,802,157.82	Write off risk of obsolescence
Too much stock	1282	34857	€4,405,382.54	Transition period (14 days to 1150 years)
Too much stock within limits			*€ 2,261,177.51*	*(This is the amount within limits for this group)*
Too little stock	912	1884	€ 2,370,394.16	Order!
Inventory on hand too little stock	*133*	*366*	*€ 288,945.68*	*(This is the inventory on hand in this group)*
Inventory within new limits	1655	12109	€2,459,170.41	Adjust Q and R

Table 9 : Transition period details

Transition period (Years)		# items	Quantity	Value	cum value	cum inv decrease
0	< 0.5year	133	1216	€508,923.71	€ 508,924	€ 508,924
1	0.5 - 1.5 year	273	2079	€1,448,806.20	€ 1,957,730	€ 2,530,695
2	1.5 - 2.5 year	194	1625	€572,244.25	€ 2,529,974	€ 3,103,660
3	2.5 - 3.5 year	98	881	€252,263.71	€ 2,782,238	€ 3,390,503
4	3.5 - 4.5 year	159	766	€428,259.71	€ 3,210,498	€ 3,593,258
5	4.5 - 5.5 year	26	268	€94,357.22	€ 3,304,855	€ 3,688,948
6	5.5 - 6.5 year	42	955	€129,531.55	€ 3,434,386	€ 3,765,767
7	6.5 - 7.5 year	16	2427	€47,170.69	€ 3,481,557	€ 3,820,997
8	7.5 - 8.5 year	69	632	€97,125.85	€ 3,578,683	€ 3,869,488
9	8.5 - 9.5 year	6	204	€2,809.86	€ 3,581,493	€ 3,905,839
10	9.5 - 10.5 year	12	737	€360,384.87	€ 3,941,878	€ 3,941,878
>10	> 10.5 year	254	23067	€463,504.92	€ 4,405,383	

Table 9 shows how fast inventory can be lowered till the level specified by the model. This is calculated by dividing the total amount per part that is in stock too much by the average demand per year. This gives the transition period for every item in years. The cumulative inventory decrease is then obtained by summing all partial decreases so far, given the average demand per year. So within 1.5 years the total value of the parts under consideration can be lowered by € 2.5 million.

6.6 RESULTS SUMMARY

The R, Q model has always the best solution for all parameter changes. Therefore FEI should start using this model. The most important parameters for sensitivity to total costs are: (ordered from sensitive to not sensitive)

1. Hit rate constraint
2. Interest rate
3. Order costs
4. Local warehouse lead time
5. Central warehouse lead time

The proposed model with a service constraint for all warehouses performs better than a model without a service constraint for the central warehouse, the latter is proposed in most literature. This is because all orders at the central warehouse not generated from the local warehouses in Europe are then modeled as customer orders while part of it goes to regional warehouses.

About €6,000,000 of inventory in Europe is enough to reach a 95% hit rate at all warehouses. Currently the central warehouse in Eindhoven alone stocks about €12,000,000.

The inventory in the central warehouse currently does not reflect the proposed solution. It contains a lot of non- moving stocks, and about €2,300,000 must be ordered just to reach the proposed reorder level if this is not reached by outstanding orders. These items are definitely stocked at too low levels and are the easiest way to improve central warehouse performance.

Total costs are not very sensitive to central warehouse lead time, but reliable lead times are needed to deliver service to customers and make management easier (escalations cost a lot of effort and money). Therefore this must be investigated further. This also goes for repair times because they are modeled in the same way.

7 CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

- From the location model must be concluded that FEI should open a warehouse in the south of Italy.
- Delivery from the central warehouse is cheapest is also concluded from the location model.
- Using the R,Q model leads to the best performance in all cases investigated. Therefore FEI should use this model for future spare parts planning.
- All multi item models outperform the single item model. Therefore FEI should stop using a single item approach and switch to a multi item approach. For critical items it is possible to overrule the reorder point and order quantity afterwards to obtain a higher hit rate for this item. If this is a recurring situation, this reorder point can be fed to the start values of the multi item model. This should not be done for a large amount of items because it might tamper the performance of the multi item model, especially when other items become critical and it is forgotten that starting parameters were adjusted. Therefore it is better to adjust things afterwards.
- FEI currently stocks many items in the central warehouse in the wrong way according to this model. FEI should carefully review the proposed solution on item level and adjust R and Q for all items. Priority should go to ordering items that are stocked below reorder level. These items can greatly increase the performance of the central warehouse. These incorrectly stocked items include:
    - € 4,000,000 non moving items
    - € 4,400,000 items with too high inventory levels (overstock)
    - € 2,300,000 items stocked at too low inventory levels (understock)
- If the proposed model is used in Europe a total inventory of approximately € 6,000,000 would be enough for a 95% service level to all customers. Currently the central warehouse in Eindhoven alone has approximately € 12,000,000 inventory on stock.
- Consolidation of transport to local warehouses is not generally a good idea. Transport costs are relatively low and not much can be gained from consolidating shipments, while it leads to higher inventory levels.
- Demand at local warehouses does not seem to follow a stationary pure Poisson process for all items. Sometimes more than 1 item is ordered.

Recommendations for use of the model at FEI:

- For all warehouses but especially for the local warehouses FEI should check outcomes for sanity and advanced knowledge of the current situation. Stock levels must be adjusted to the changing installed base. For local warehouses it might be possible to calculate the average demand per item according to the changed installed base. FEI should investigate this further.
- Investigate the repair lead time in the ERP system.
- Investigate the lead time in the system for all parts; this has great influence on how many items to stock, and on performance levels reached with this inventory.
- Make sure the interest level at which inventory is accounted is the correct one. This greatly influences the order quantity and the ratio of inventory costs and order costs.
- Broaden the model to include warehouses and customers outside Europe as well. This is an opportunity to optimize stocks in other regions, which can also lead to lower stocks in the central warehouse. If focus is worldwide and on end users, no intermediate service levels should be set for the regional and central warehouses, only service to end customers should be penalized.
- Improve the historical demand rates by forecasting of demand and expert knowledge.

Demand is not stable but is assumed to be in the parameters, so these must be reviewed by experts.

Recommendations for further research:

- A more integral solution to jointly optimize R, Q in the central warehouse and S in the local warehouses might perform better than this heuristic solution. It would be interesting to investigate this in research.
- This thesis shows that in practice spare parts management performs better if the central warehouse does not use a (S-1,S) policy as literature suggests. It would be interesting to further research this and provide general recommendations on when this holds.
- Improve forecasting for spare parts. This model is solely built on historical demands. Research to support forecasting of these parts and possibly advanced knowledge (like after repair the probability on failure is smaller) can greatly enhance the performance of spare parts management.

8 IMPLEMENTATION PLAN

Essential for implementing the solutions presented in this thesis is the commitment and willingness for change. This commitment and willingness must be present with the management of FEI and is a prerequisite for success.
To reach this situation it is important to show them how the new method can improve the present situation and what the positive impact will be for FEI Company with respect to better service and lower inventory investment.

Equally helpful for employees is the fact that their working methods do not really change, though the model used, and the update procedure are different.
It is important that people believe in the outcome of the tool. This can be done by building trust and showing people how the tool works and how it can improve current spare parts management. For this an implementation plan has been made.

When *advanced knowledge* is mentioned in this part, this means knowledge of future demand, or no more demand, criticality, one time orders, preventive maintenance, or anything else that cannot be known from observing historical demand data.

Location model
The location model will probably not need to be used again because opening a warehouse is not a decision to make regularly. Though for the case FEI needs to investigate again where warehouse locations in Europe are needed a handout has been written to explain how the model works, how GAMS works, how the model must be solved, how the input should be interpreted, and how the model can be changed or adjusted to a new situation.
FEI is already working on obtaining a warehouse in Italy, so little is left for implementation of the results of the location model.

Stock keeping model
The remainder of the implementation plan will solely focus on the implementation of the proposed solution in the stock keeping model. A handout has been written on how this model works, which input is needed, how this input is obtained, and how the model should be interpreted.

Ease of use
Though this model is quite different from what was used before, not much will change for order planners. In the central warehouse already a reorder point and order quantity was in use. This does not change, so day to day operations stay the same.
Updating the order quantities and reorder points is different though. This is something that needs to be done only once every three months or so. Currently in Eindhoven an Access and Excel based tool is used that must be updated. Access and Excel still are the methods for information exchange and review in the new tool. Optimization though is done by a stand alone executable file that communicates with Excel. Use will not be more difficult than the current update procedure.
Updating the tool is something else. Whereas knowledge of Access and Excel is widely spread in this organization nobody knows a programming language like Delphi. To adjust (add more warehouses) the tool FEI must buy Delphi software and someone must learn to program in it.
Though this is a weakness, adjustment of the software is not necessary. All important parameters can be adjusted in the interface or the input file. No parameter value is fixed inside the program. This leaves many opportunities for FEI to test scenarios or use the tool for analysis without programming it.

Potential improvements

This report highlights the possible improvements with this tool. Besides the final presentation also a presentation will be held at FEI to show all involved and interested the possible improvements with this tool.

Implementation planning

1. Verify and go through all input data, queries and the update procedure with FEI management; only if data used in this tool are trusted the outcome of the tool can be trusted.
2. Compare the results of the new tool to the current tool and understand the differences. FEI management has to become familiar with the output of this tool, how to interpret it, and how to adjust output or input to specific needs or advanced information.
3. TEST PHASE: If enough trust has been built in the preceding phases the tool can be used in the central warehouse. For a period of three months it is advised to check the outcome of the tool with the previous method, using the same parameters. The differences must be understood and adjustments should only be made for advanced knowledge and critical items. If the model provides unsatisfactory solutions the parameters should be checked and compared to the old model. Differences must be understood and possible errors corrected.
   The new model immediately provides data not available beforehand for the local warehouses. The local area managers should be contacted to explain the model and its implications to the service in their areas. If the inventory level at the central warehouse is satisfactory (for every part) the stock levels in local warehouses can be adjusted according to the model, in mutual agreement with the local managers who can provide advanced knowledge.
4. USAGE PHASE: After a successful test phase all system parameters (reorder point, order quantity, stock level) in the ERP system need to be updated according to the model (if this is not done already). The model only has to be run every three months, or when major changes in demand or other parameters have occurred. The model does not need to be run for new spare parts because they do not have demand history. New parts need to be managed by hand.
5. Monitor the performance of all warehouses in terms of inventory level, hit rate and turns; review changes that happen or deviations from what is expected.
6. When the new part of the ERP system becomes available which makes it possible to replenish local warehouses directly from Eindhoven, the stock levels from the model can be used after they have been reviewed and adjusted by (local) managers for advanced knowledge.

The above steps and only small changes to the current way of working must lead to the successful implementation of the tool. Important is that employees are able to interpret and understand the outcomes of this tool and that they have trust in that this tool provides a workable and good solution to their problems. Key for a successful use of this tool is the process of implementation and the confidence and commitment of FEI management. The part below lists the responsibilities and costs of this implementation.

People and responsibilities

The commitment of FEI management is crucial to obtain a good implementation of this tool. Therefore one manager should be formally responsible for successful implementation. This would preferably be the service logistics manager for Europe (currently Loek Halmans). This person is also responsible for, and mainly involved in phases 1 to 3 of the implementation planning.

About halfway phase 3 (when the manager at least has advanced understanding of the model) the employees can be involved intensively in learning to use the tool and understanding the tool. They will be the ones that will primarily use the outcomes of the tool (the reorder point, order quantity and order up to levels) but for them to trust these parameters it is important that they are involved in the implementation of the tool and at least understand partially what it does and how it works. They will be primarily responsible for using the outcomes and noticing unexpected behavior, exceptions, or unsatisfactory behavior. These same responsibilities can continue in phase 4.

Responsible for correctly updating the tool is the service logistics manager in the end. But if employees have developed enough understanding of the tool and the update procedure this could be done by an employee with enough Access and Excel knowledge. In this case it is very important that this person understands the parameters used in the tool, the spare parts used at FEI and the outcomes of the model. He must be capable to review if the outcomes are correct.
Especially in the beginning it would be better if the manager updates the tool himself, or in cooperation with the employee. Since it only has to be done every three months or so it does not take too much time.

For monitoring the performance (phase 5) and implementing new functionalities (phase 6) the service logistics manager is always responsible.

Time and Costs
Implementation of this tool will take the most time of the service logistics manager. Employees should also be involved, but it will take less of their time because they are not responsible.
Phase 1 and 2 of the implementation planning will take at least 10 to 20 hours from the manager to get acquainted with how the model works, verifying all parameters and getting a thorough understanding of the update procedures and data used. Equally important is that he understands the sensitivities of the model and is able to clarify why the outcome differs. It is important that he spends some time playing with the tool to develop this feeling.
During the test phase it will take a minimum of 3 hours per week from the manager to in detail compare the model solution with real demands and the previous method. This is just the time for comparing the theoretical performance, and the difference between this method and the previous method. If also employees are involved this will cost at least about 2 hours a week for discussions with everyone working with the tool. If at this moment already many orders are being placed because the new reorder points differ from the previous reorder points this might also take some extra time.
Communication with local managers for local warehouse inventory could be done in about 10 hours (2,5 hour per local warehouse) including a short presentation about the model, which could be sent by email.
When the tool is in use monitoring performance should be done weekly to check if adjustments must be made. This should be standardized by a query or download from MFGPRO and should not take more than half an hour per week.
Updating the tool with the same database as used in this thesis will take about one hour. Half an hour is needed to update all queries, run these and check the outcomes; updating the input file takes another 15 to 30 minutes. Running the model once takes about one hour, depending on the parameter settings. This should preferably be done in the evening because no interface is needed but it takes 100% of cpu (central processing unit) computing time. If a computer with two cpu's is used (like the desktops at FEI) this could be done during the day without having too much impact on regular work.

For further development of this tool FEI needs to buy Borland Delphi software, which costs approximately €1,100.-. No restriction on time can be given for further development of this tool. Reductions in computation time can be achieved and many more warehouses can be added. Before developing this tool further FEI should carefully think why it needs to develop this tool further and set clear goals for development.

Other costs for FEI include the extra inventory investment, for inventory that is not up to the new reorder levels (at least €2.3 million). This inventory is needed anyway to deliver service to customers and should not be seen as a direct cost of using this tool.

9 REFERENCES

Axsäter, S. (2006b), "A simple procedure for determining order quantities under a fill rate constraint and normally distributed lead-time demand", *European Journal of Operational Research,* 174, p 480 - 491

Axsäter, S. (2006), "Inventory Control", Springer Science+Business Media LLC, New-York

Axsäter, S. (1996), "Using the Deterministic EOQ Formula in Stochastic Inventory Control", *Management Science,* 42, p 830 - 834

Bours, S (2007), "Multi-item, two echelon stock control of spare parts at Stork Prints", *MSC Thesis,* Eindhoven University of Technology, Faculty of Technology Management, Eindhoven, #4505

Corbijn van Willenswaard, P.H. (2006), "Multi-item, multi-location stock control for the service parts provisioning of DAF Trucks N.V., *MSC Thesis,* Eindhoven University of Technology, Faculty of Technology Management, Eindhoven, #4479

Drezner, Z, Hamacher, H.W. (eds) (2001), "Facility Location: Applications and Theory", Springer-Verlag, Berlin

Eiselt, H.A., Sandblom, C.-L. (2004), "Decision Analysis, Location Models, and Scheduling Problems", Springer-Verlag, Berlin

Federgruen, A., and Zheng, Y. (1992), "An efficient algorithm for computing an optimal (r, Q) policy in continuous review stochastic inventory systems", *Operations Research,* 40, p 808 - 813

Gallego, G. (1998), "New Bounds and Heuristics for (Q, r) Policies", *Management Science,* 44, p 219 - 233

Graves, S.C. (1985), "A Multi-Echelon Inventory Model for a Repairable Item with One-for-One Replenishment", *Management Science,* 31, p. 1247 - 1256

Guide, V.D.R., Srivastava, R. (1997), "Repairable inventory theory: Models and applications", *European Journal of Operational Research,* 102, p. 1 - 20

Halmans, L. (2005), "Controlled Spare Parts Inventory Management", *MSC Thesis,* Eindhoven University of Technology, Faculty of Technology Management, Eindhoven, #4248

Kalchschmidt, M., Zotteri, G., Verganti, R. (2003), "Inventory management in a multi-echelon spare parts supply chain", *International Journal of Production Economics,* 81-82, p. 397 – 413

Sargent, R.G. (2005), "Verification and validation of simulation models", *Proc 2005 Winter Simulation Conf.,* ed. Kuhl, M.E., Steiger, N.M., Armstrong, F.B., Joines, J.A., p. 130 -143. Piscataway, New Jersey: IEEE.

Schlesinger, et al. (1979), "Terminology for model credibility", *Simulation,* 32, p. 103 - 104

Silver, E.A., Pyke, D.F., Peterson, R. (1998), "Inventory Management and Production planning and Scheduling", *John Wiley & sons,* New York, Third edition

Thijssen, I.C.M. (2006), "A literature review on spare parts", *bijzondere opdracht,* Eindhoven University of Technology, Faculty of Technology Management, Eindhoven

Van Aken, J.E., Van der Bij, J.D., Berends, J.J. (2003), "Bedrijfskundige Methodologie", *Collegedictaat,* Eindhoven University of Technology, Faculty of Technology Management (in Dutch)

Van Houtum, G.J., Inderfurth, K., Zijm, W.H.M. (1996), "Materials coordination in stochastic multi-echelon systems", *European Journal of Operational Research,* 95, p. 1 - 23

Van Houtum, G.J., Zijm, W.H.M. (2000), "On the relation between cost and service models for general inventory systems", *Statistica Neerlandica,* 54, p. 127 – 147

Van Kooten, J. (2006), "Calculation of Final Orders for Spare Part Inventories in the Prospect of Obsolescence", *MSC Thesis*, Eindhoven University of Technology, Faculty of Technology Management, Eindhoven, #4419

Wong, H., Kranenburg, B., Van Houtum, G.J., Cattrysse, D., (2005b), "Efficient Heuristics for Two-Echelon Spare Parts Inventory Systems with An Aggregate Mean Waiting Time Constraint Per Local Warehouse", *Working Paper*, Technische Universiteit Eindhoven, The Netherlands

Zheng, Y. (1992), "On Properties of Stochastic Inventory Systems", *Management Science*, 38, p 87 - 103

APPENDIX I GLOSSARY OF TERMS

β_n	Aggregated hit rate for warehouse n
β_{in}	Item hit rate for item i at warehouse n
$\overset{\frown}{\beta}_n$	Target hit rate for warehouse n
$\overset{\frown}{\beta}_{in}$	Target hit rate for item i at warehouse n
COGS	Cost Of Goods Sold
CW	Central Warehouse
EOPD	Electron Optics Product Division (parts produced in Eindhoven)
EOQ	Economic Order Quantity
FEI	FEI Company
FAB	Semiconductor Manufacturing
FIB	Focused Ion Beam
FPD	FAB Product Devision (parts produced in Hillsboro)
FRU	Field Replaceable Unit (Spare Part)
LW	Local Warehouse
MFGPRO	ManufacturingPro, the FEI ERP system.
Nano E	Nano Electronics market
Nano R&I	Nano Research and Industry market
Nano B	Nano Biology market
RMA	Return Material Authorization
SEM	Scanning Electron Microscope
ServLog	Service Logistics
SKU	Stock Keeping Unit
SLA	Service Level Agreement
SSD	Sales and Service Department
T&M	Time and Materials contract
TEM	Transition Electron Microscope
WW	World Wide

APPENDIX II ORGANIZATION CHART FEI COMPANY

The figure below shows the organization chart of FEI Company with respect to service logistics. Therefore only the highest levels are shown that are of importance for service logistics in Europe.

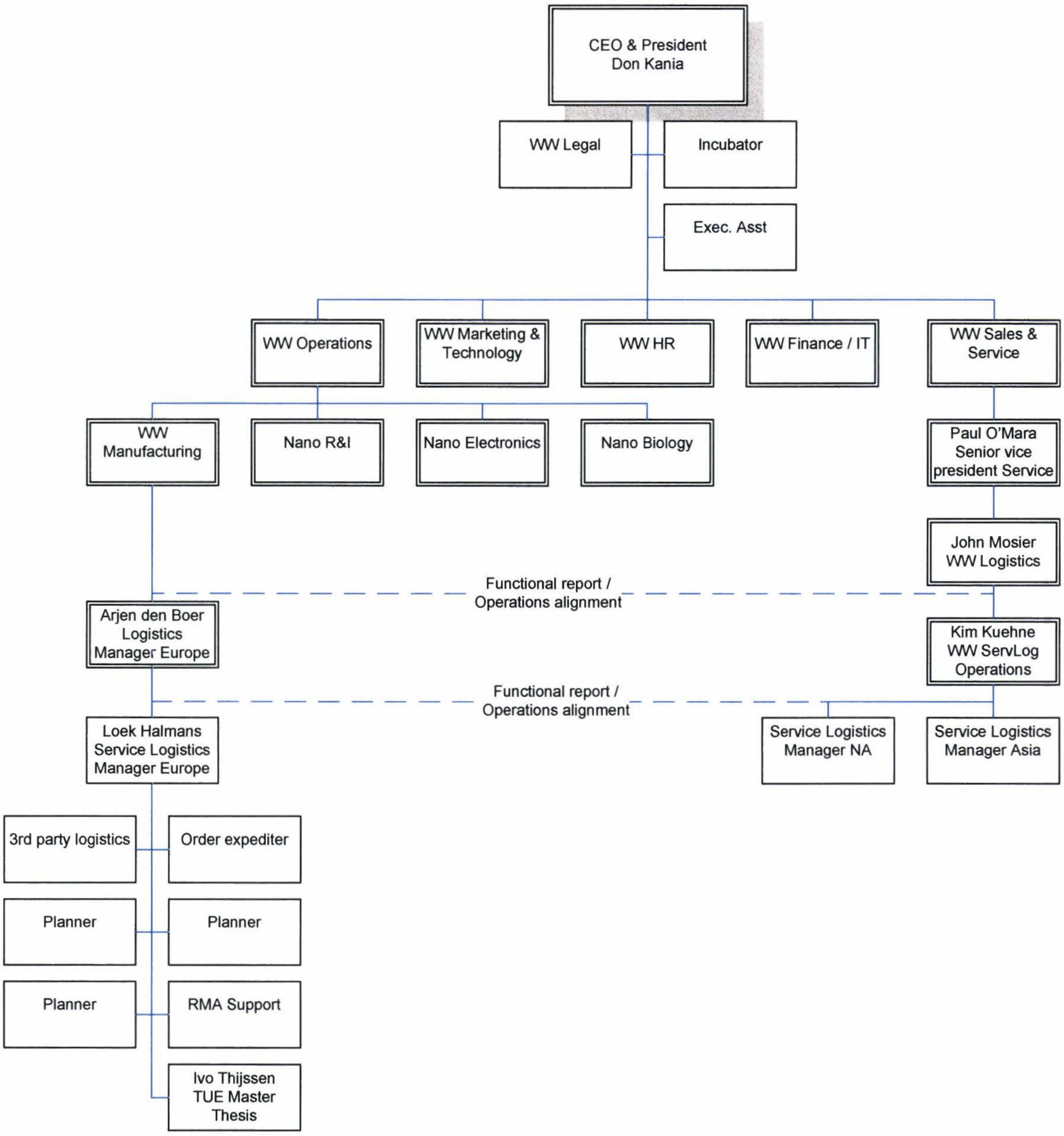


Figure 17: Organization chart FEI Company

APPENDIX III PROBLEM STRUCTURE

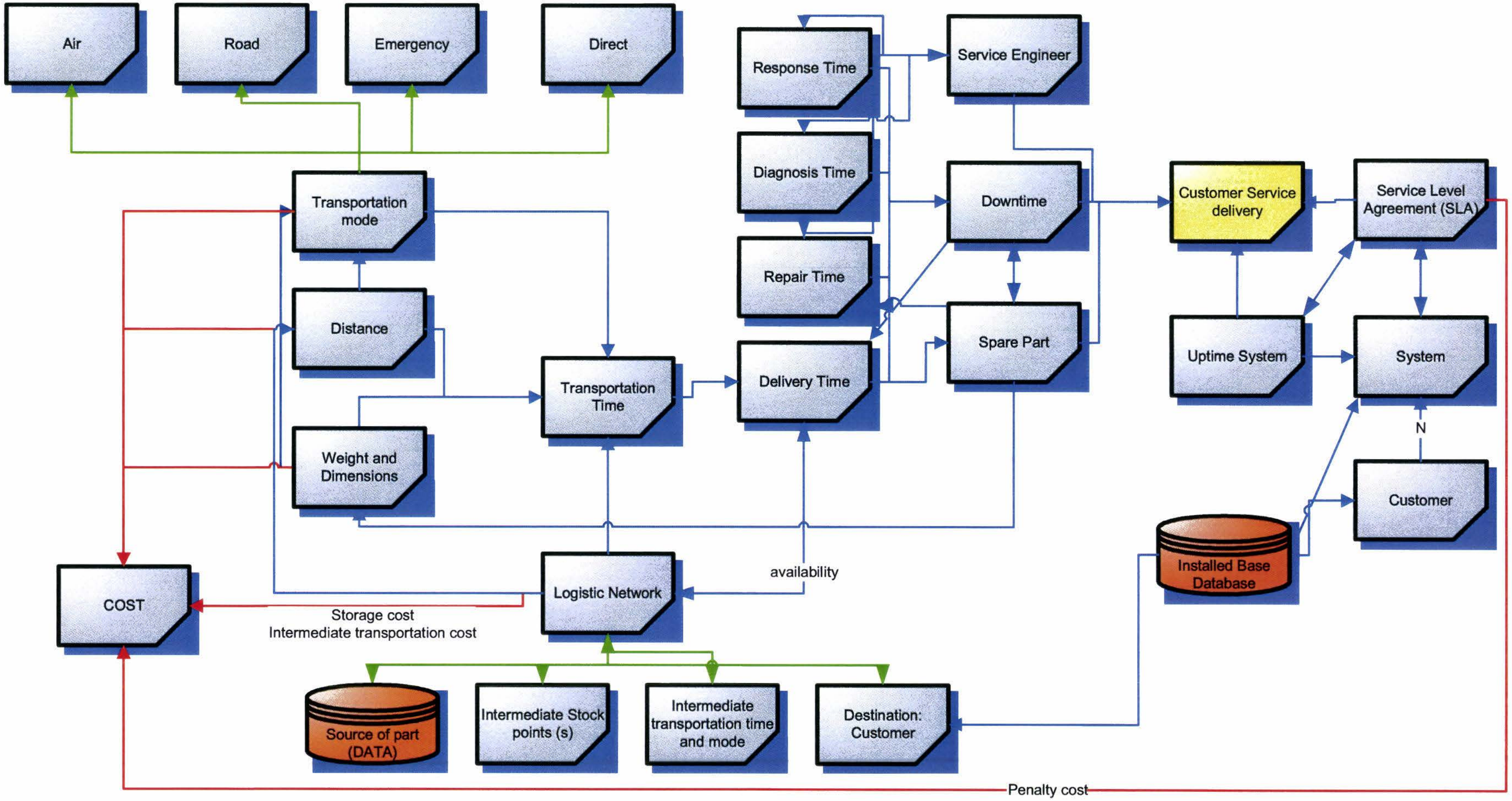
The problem structure and dependencies are shown in the figure below. The problem "customer service" is colored yellow. The part on the right and below the problem shows that customer service can be defined as the uptime of a system and the service level agreement with this customer. The SLA is specific for every system. The system and customer can be found in the installed base database. A customer can have N systems.

The part on the left shows what customer service for FEI Company consits of. A service engineer, service time and a spare part are essential to deliver customer service.
Service time consists of, and is influenced by, response time, diagnosis time, repair time and delivery time of a spare part. The service engineer influences response time, diagnosis time and repair time.
The delivery time of a spare part is influenced by the required service time. The spare part itself influences the estimated repair time.

Delivery time consists largely of transportation time. Another fraction is handling time which is not shown in the figure.
The transportation time is influenced by the weight and dimensions of the product, the distance to travel, the transportation mode used and the logistic network. The required delivery time influences the choice of the logistics network which consists of the source and destination of the spare part and possibly intermediate stock points and intermediate transport.
The logistics network influences the distance to be traveled. The distance and weights and dimensions influence the transportation mode, which has effects on transportation time.
Transportation mode consists of air, road, emergency and direct transport.
Costs in this model are influenced by the choice of SLAs, the logistics network, transportation mode, distance and weights and dimensions.

Problem Structure FEI

This diagram shows what the problem consists of
The key problem is colored yellow
Round orange shapes show data
Blue lines show dependencies and influences
Green lines are decompositions
Red lines show cost drivers



APPENDIX IV CUSTOMER LOCATIONS

Data are obtained from the installed base database of September 29, 2006.

Table 10: Installed base per country

country	**systems**	**%**	**Cum %**	**contract**	**%**	**Cum %**
Germany	785	27%	27%	271	24%	24%
France	448	15%	43%	214	19%	43%
UK	448	15%	58%	214	19%	62%
Italy	355	12%	70%	64	6%	67%
The Netherlands	207	7%	77%	106	9%	77%
Spain	120	4%	82%	57	5%	82%
Swizerland	111	4%	85%	46	4%	86%
Belgium	109	4%	89%	41	4%	89%
Sweden	80	3%	92%	40	4%	93%
Austria	66	2%	94%	18	2%	94%
Denmark	52	2%	96%	28	2%	97%
Norway	36	1%	97%	5	0%	97%
Finland	30	1%	98%	13	1%	99%
Ireland	19	1%	99%	14	1%	100%
Tunisia	8	0%	99%	2	0%	100%
Croatia	5	0%	99%		0%	100%
Luxembourg	4	0%	99%		0%	100%
Romania	4	0%	100%		0%	100%
Portugal	3	0%	100%		0%	100%
Slovenia	3	0%	100%		0%	100%
Estonia	2	0%	100%	1	0%	100%
Serbia Montenegro	2	0%	100%		0%	100%
Hungary	1	0%	100%		0%	100%
Slovakia	1	0%	100%		0%	100%
total	2899			1134		

Table 11: Important locations in Europe

Location	**# systems**	**customer**	**contracts**	**fastest contract**
Dresden, Fermany	31	Infineon, AMD	T&M	T&M
Munich, Germany	13	Infineon	T&M	T&M
Crolles - Grenoble, France	13	ST /Stima	24, 48, 72, T&M	24
Londonderry, North Ireland	12	Seagate	4	4
Leixlip, Ireland	8	Intel	24	24
Rousset, France	5	ST	72	72
Agrate, Italy	5	ST	standard	48
Avezziano, Italy	4	Micron	48, standard, T&M	48
Catania, Italy	4	ST	standard	48
Caen, France	3	Philips	48	48
Tours, France	2	ST	24, 48	24

Regensburg, Germany	2	Infineon	T&M	T&M
Villach, Austria	2	Infineon	48, 72	48
Stockholm, Sweden	1	Infineon	T&M	T&M
Casablanca, Morocco	1	ST	T&M	T&M
Manchester, England	1	Photronics	24	24

Figure 18 shows the locations of customers in Europe. More than one system can be concentrated on a spot, then only the above one is shown (red on top of black, and black on top of blue). Because the software used was the North American version locations are not precise, but always inside the right country. However, the exact location turned out not to be of importance for the model used.

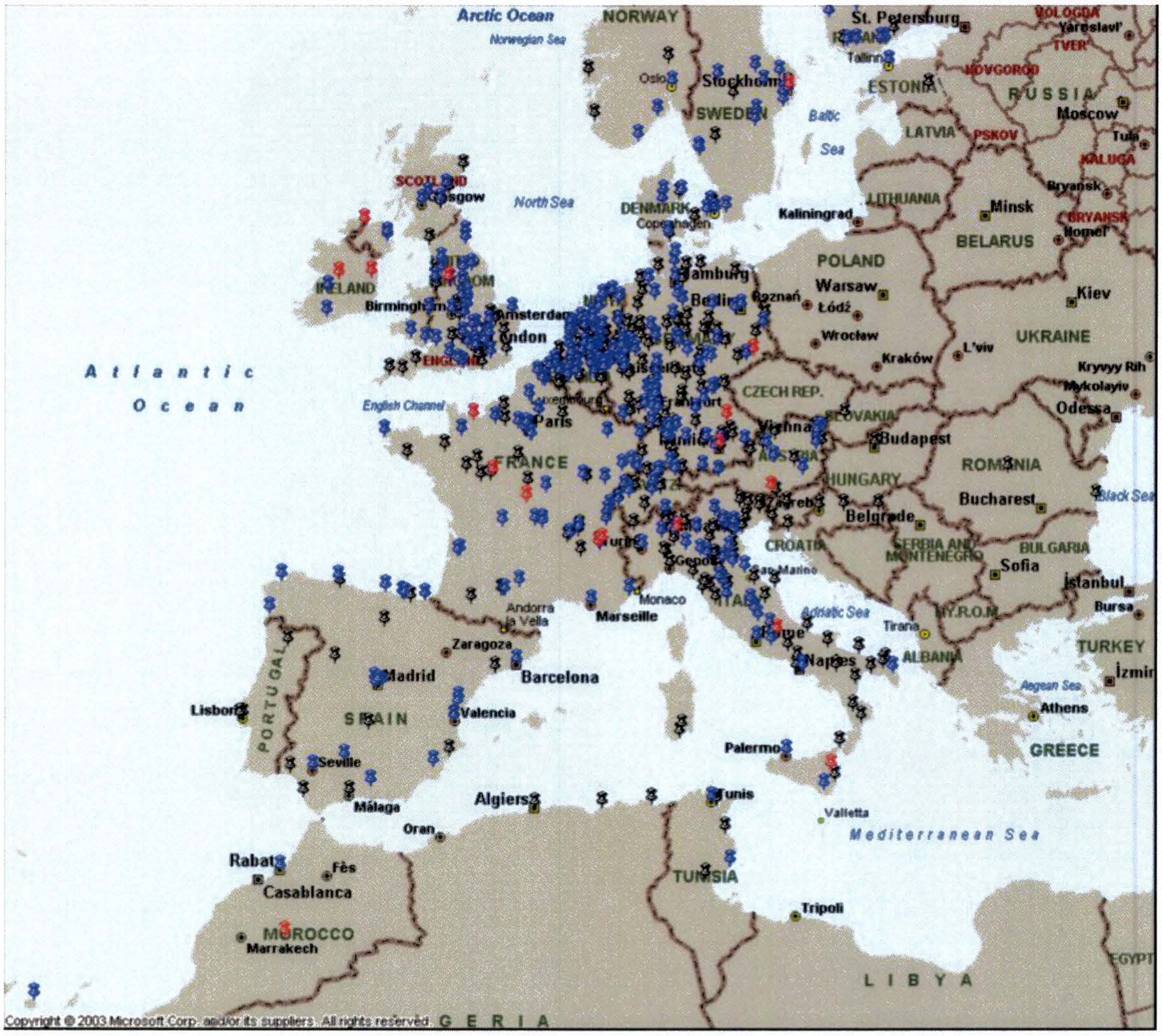


Figure 18: Customer locations in Europe

Legend:
Red mark: Customer with less than 4 hours response time
Blue mark: Customer with a contract
Black mark: Customer without a contract (T&M, warranty, nothing)

APPENDIX V CUSTOMER SERVICE

V.1 CONTRACTS

For service logistics the installed base of FEI is of importance, and the service to be delivered to this installed base. Therefore contracts are examined in more depth. Contracts can be divided into two groups, standard contracts and special contracts. There are two important dimensions on which a contract is focused; labor and response time, and parts. The different contract types are shown in the table below.

Table 12: Contract types

	Labor	**Parts**
Basic	Included, no response time	Customer pays
Standard	5D 8H 48R	Included
Premium	5D 8H 24R	Included

Special Nano RIB	Not included	Limited amount
Special Nano E	7D 24H 4R or on-site	Included

The data in the labor column indicates service response times. 5D 8H 48R (standard contract) for example means that service to this customer is available 5 days a week, 8 hours per day, with a response time of 48 hours. This response time indicates within which time an engineer must have been on site with the customer. It does not indicate that he must have analyzed the problem or must have fixed it. The special contracts can, in general, be divided into two market-based groups. Nano RIB (Research, Industry and Biology) contracts are usually cheaper forms of contracts in which customers only pay for a limited service because they do not have the funds to pay for full service. Nano E (Nano electronics) special contracts usually also specify uptimes or Mean Time To Repair (MTTR) for their systems. Penalties can also be included here if FEI does not deliver the agreed service level, which is usually measured over a 13 month moving average. These are only a few customers but they have a large installed base of systems. It is very important for FEI to serve these large customers well.

FEI year reports give the impression that 70% – 80% of the installed base is serviced by FEI on contractual basis. Managers also assume this, but the actual data on the installed base give a different overview. Currently (installed base data 29 September 2006) only 36% of all installed systems are serviced under contract by FEI; the majority of systems is only serviced as T&M (Time & Material). This means that there is no service level agreement with the customer but that they pay for the time and material needed for service if they request this.

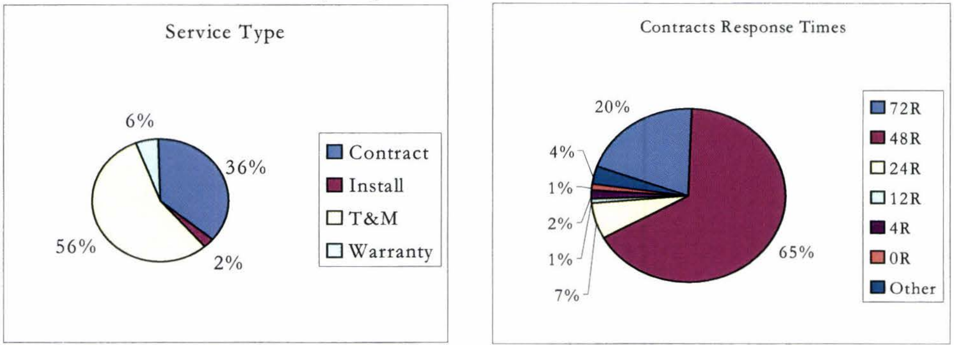


Figure 19: Service type & Contract type of the installed base

Important conclusions from Figure 19 above are that only a very small amount of the installed base requires a response time below 24 hours. This suggests that though not stated formally also repair parts have to be there quickly. World wide operations materials & logistics director John Mosier stated that that these important customers must have parts available to them within one hour. This is especially true for 64 systems that have response times smaller than 4 hours.

At least 86% of the contracts specify response times of 48 hours and more. For these customers in general spare part delivery within 24 hours would be fine. If these contracts are taken together with the customers without a contract, more than 95% of the installed base does not need to have service parts available within 24 hours.

V.2 SERVICE

FEI faces problems to deliver customer service in an optimal way. During the importance of service to their customers was frequently highlighted. Service is also part of their mission. Therefore customer service for FEI has been investigated in more depth, especially how service to the end customer is related to spare part availability. Appendix III shows what the problem consists of.

Below the dependency between a service level agreement with the customer and delivery time of a spare part is explained.

1. A Service level Agreement (SLA) defines uptime, this gives a time window in which the machine must be checked, repaired and up and running again.
2. How many repairs are expected in a timeframe gives a target for the repair time; if two failures in a month are expected, the target repair time will change and only be only half a day.
3. This target repair time consists of checking the machine, ordering a part, part delivery, repairing the machine, testing and then the machine is running. The expected times in this process lead to a target for the availability of the spare part.
4. This target availability might be used or a constraint based on this.

This is shown schematically below:

	Example
Service agreements: uptime or MTTR for system	*95% uptime*
↓	↓
Time limit for repair	*1.5 day down per month (24h usage)*
↓	↓
Target repair time	*1 day (if 1 failure per month)*
↓	↓
Target part availability (can depend on expected repair time of failure)	*example 95% in one hour*
↓	↓
Constraint on delivery time at customer site	*delivery lead time < 1hr*

The constraint on delivery time of a spare part at a customer as defined above can be specific per system, location, customer, part needed and time already spent on servicing the system as is shown by the dependencies above. This is a very complicated constraint and it will lead to different constraints in almost identical situations. Therefore it is better to simplify this constraint to a standard delivery time, or some different standard delivery times so that a consistent and constant service can be delivered by the organization.

The Figure 20 shows historical hit rates in important warehouses.

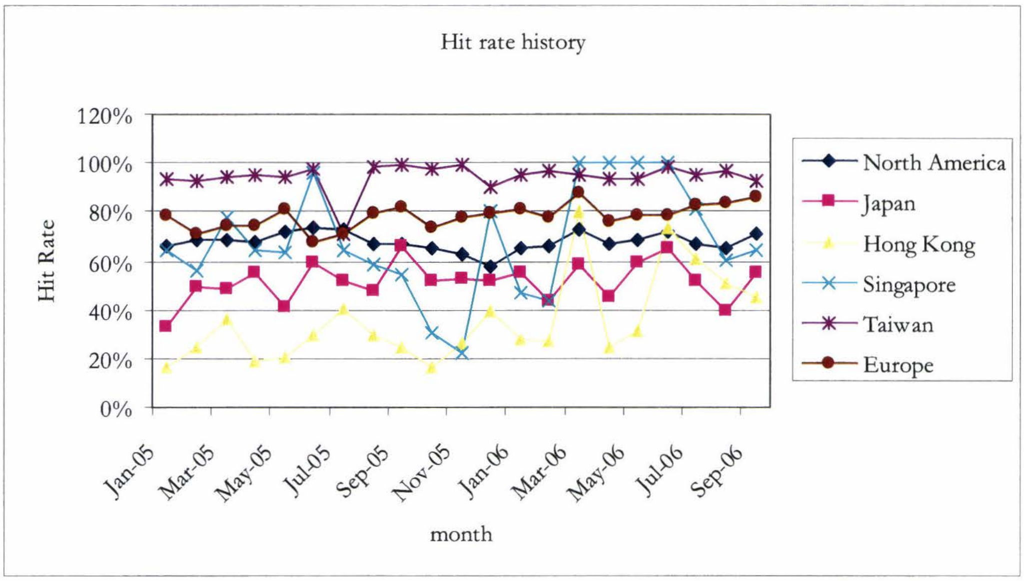


Figure 20: Hit rate history

The hit rate fluctuates a lot over the months. Therefore a more appropriate view can be obtained by looking at a moving average of the hit rate. Using a moving average flattens the fluctuations and makes it possible to observe trends. The ten point moving average of the hit rate is shown in the figure below.

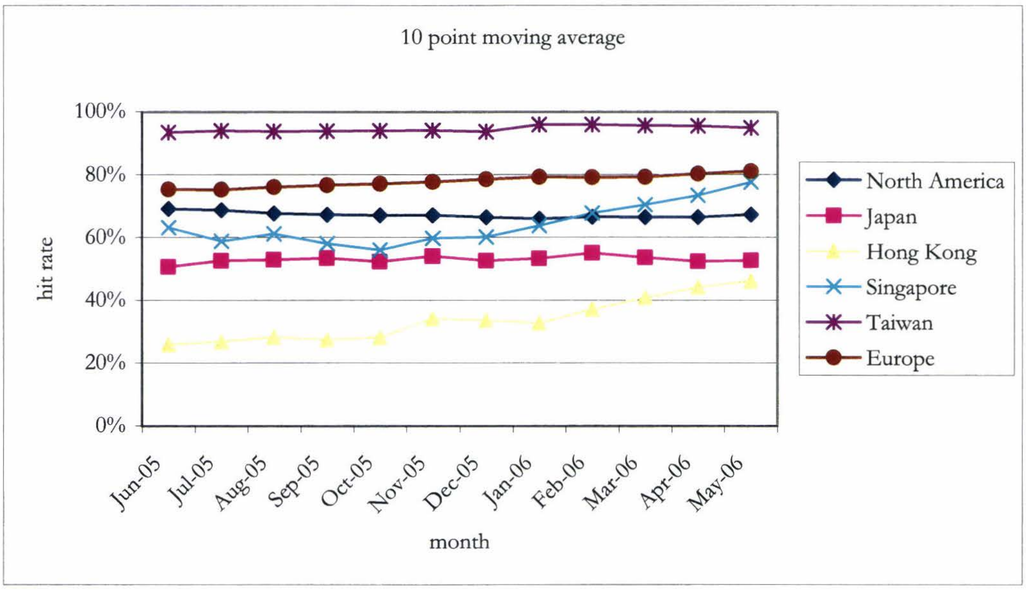


Figure 21: Hit rate moving average

Important observations in the figure above are that the hit rate in Taiwan is very good on average, about 95%. Hit rates in Hong Kong and Singapore have been increasing since the beginning of 2006 and the hit rate in Europe has been improving a little continuously. In general hit rates in the warehouses are low. Less than 50% hit rate is a very bad performance and shows that in 50% of the cases the warehouse is virtually nonexistent.

Hit rate gives a good approximation what the customer service level is in the regions. Therefore the other performance measure of warehouses is also investigated; the inventory turns (the number of times the total inventory is sold per year). The target for inventory turns is 2 per year. The following figure shows the inventory turns per month at the central European warehouse, so the monthly target is 2/12≈0.1666.

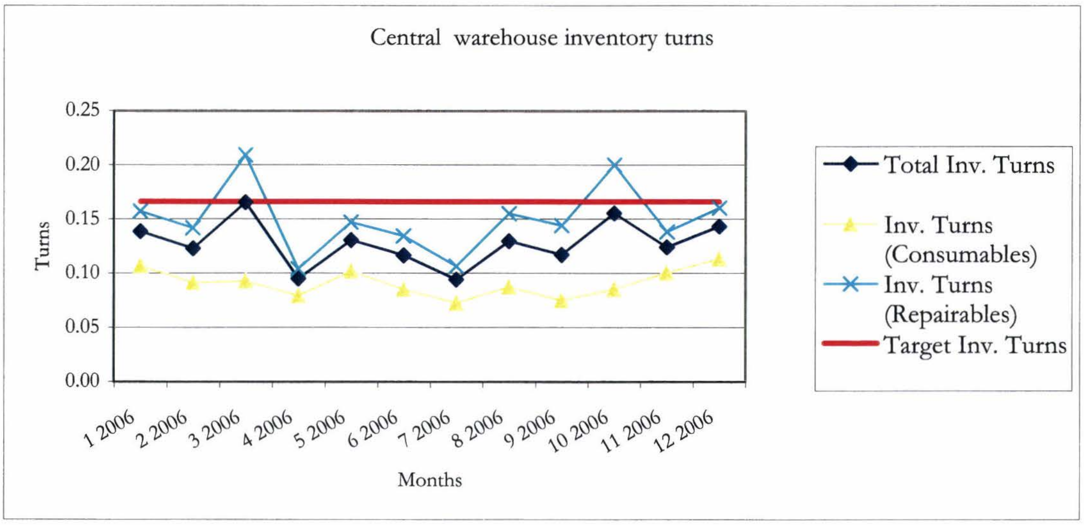


Figure 22: Central warehouse inventory turns

The comparison of hit rate with inventory turns leads to the idea that the wrong inventory is stocked at FEI. The hit rate is low, and the inventory turns are below target. Alternatively the targets could be unrealistic, but that does not seem to be the case.

VI.1 ECONOMIC PERFORMANCE OF SERVICE LOGISTICS

The profit and loss account of FEI Europe BV for 11 months (January to November 2006) gives a good overview of important revenues and expenses for FEI Europe BV. The financial data does show revenues; fines have never been observed by the accounting department. Fines do exist but are not represented in the financial overview because they consist of free warranties and free service periods.

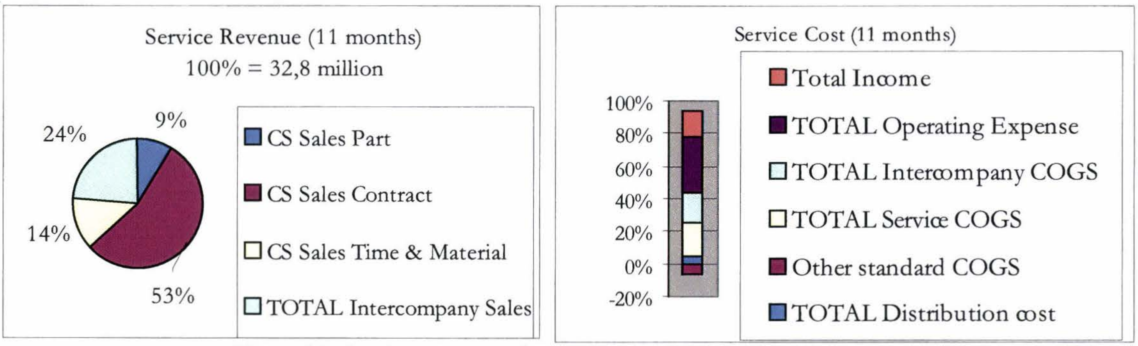


Figure 23: Service revenue and cost

Figure 23 shows that the contract sales are the majority of income for FEI Europe BV. The figure on the right shows the division of costs for FEI Europe. It is important to notice that distribution cost are only 5,5% of revenues. The distribution cost can be seen as a combined cost for stock keeping, handling and transportation. Missing is the financial cost of stock keeping, the inventory cost. The major cost factors are operating expenses and Cost Of Goods Sold (GOGS). These costs are also shown in more detail in the table below.

Table 13: Service Cost

Service Cost (11 months)	€	%
TOTAL Distribution cost	1.778.426,97	5,42%
Other standard COGS	(2.255.485,90)	-6,87%
TOTAL Service COGS	7.853.368,91	23,92%
TOTAL Intercompany COGS	6.637.555,14	20,22%
TOTAL Operating Expense	12.927.345,93	39,38%
Total Income	5.884.809,56	17,93%

These data suggest that distribution cost is a relatively small part of total expenses, though it is still 1,8 million euros.

To check if these data are consistent and to get a more in depth view on distribution cost, the year orders have been analyzed. The year orders have a total value of 2,2 million euros. This is somewhat higher than the 11 month overview, but still it would be around 6% of total revenues. Figure 24 shows how year orders are divided. The major expenses here are outbound service and warehousing. Import duties are tax payments that do not belong to the scope of this project.

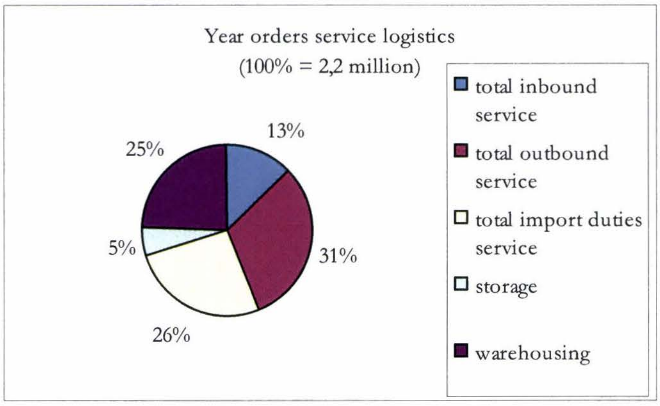


Figure 24: Year orders service logistics Acht

These financial data suggest that service is an important revenue for FEI. It also shows that the costs for distribution and warehousing of spare parts are a relatively small portion of these revenues, Operating expenses are the major cost drivers. This suggests that the focus for FEI should be on delivering profitable service to customers. As always focus should be on minimizing costs but no significant improvement in cost reduction is to be expected from optimizing the logistics network for FEI Europe.

It should be noted that inventory costs are not considered here. If it is possible to lower inventory positions this might lead to another cost reduction as well.

This paragraph goes into detail into the important parameters and cost drivers in the model. The first part deals shortly with customer locations in Europe and important customers. That is the reality that is approximated. Then customer demand, transport cost and warehouse cost are analyzed. Finally a part is written about the Lagrange multiplier.

Customer locations

To take service level agreements as the goal for a model makes individual customers very important. However to keep the model usable customer demand must be coupled in groups. To get an overview of the geographical dispersion of customers in Europe the installed base per country has been analyzed and all customers have been plotted on the map of Europe. Table 14 shows that 5 countries have 77% of the installed systems in Europe and also 77% of contracts are in these countries. Therefore these countries are the most important countries to be modeled. Appendix IV shows the full tables and figures.

Table 14: Installed base top 5 countries

country	systems	%	Cum %	contract	%	Cum %
Germany	785	27%	27%	271	24%	24%
France	448	15%	43%	214	19%	43%
UK	448	15%	58%	214	19%	62%
Italy	355	12%	70%	64	6%	67%
The Netherlands	207	7%	77%	106	9%	77%
Total	2899			1134		

Also the important customers (requiring 4 hours of response time according to management) have been analyzed in more detail; again the abovementioned appendix shows the full details. It is important that the two largest sites are located in Germany, in Dresden 31 systems have been installed and in Munich 13. There are a total of 107 important systems in Europe.

Customer demand

The actual demand of all customers can be extracted from Microsoft Access databases. In this way, from one database the demand in Europe from 2003 till 2006 could be obtained. Because there are more than 10.000 items and for determining warehouse locations we are interested in total demand per location, the sum over all demand for all items has been taken as an aggregated measure of demand.

Then this aggregated demand can be analyzed per customer, per country or in total. These raw data do not show any trends or regularities if plotted. Therefore Statgraphics has been used to analyze the data. It turns out that the completely raw data cannot be fit to any distribution. Monthly demand per country can in some cases be modeled by a normal distribution though the fit is not great. This is due to the fact that more outliers exist than would be expected in a normal distribution. The fit in the middle area is pretty good. Yearly demand has too few demand instances to obtain a good fit. Because of this situation it is very difficult to forecast these data reliably. Therefore the model will use historical data instead of using a forecast.

The assumption of total demand can be justified since orders are processed as they are received and shipments are not consolidated at the moment.

The actual demand used in the model is the expected total demand over 2006. This is obtained by taking the actual demand in the database (updated till November 13th 2006) and multiplying that demand by 1 + 48/365, the number of days left in that year. Appendix XI shows the data used as customer demand and country demand in the model.

Transport cost

Transportation of service items, but also of microscopes is done by logistics service providers. FEI does not own any transportation equipment. For service items transport is usually done per individual item (unless an order contains more than one item).

FEI has contracts with UPS, FedEx and DHL. These contracts are revised on a yearly basis. At the moment FEI still profits from Philips contracts. Because of that they have very good prices for express transportation, especially from Eindhoven to the rest of Europe.

UPS is the preferred supplier for transportation, and is by contract the preferred supplier of FEI warehouse partner Panalpina.

Loek Halmans (European service logistics manager) : "We mainly use UPS and FedEx because they have better service times than DHL. Though DHL is better quality and more reliable, we prefer to have the quicker response times and deal with the problems in case a packet gets lost. "

UPS and FedEx have largely the same cost structure. The area codes are identical except for a division in zone 5 (e and m for FedEx).

DHL has a different cost structure, so also service might differ here from service of FedEx and UPS. For example parts of Germany, France and United Kingdom as well as Netherlands, Belgium and Luxembourg are area code 1 for DHL whereas UPS and FedEx only consider Netherlands, Belgium and Luxembourg to be area code one.

Dimensions and weight are important for the pricing of a shipment using the above service providers. However no data on dimensions or weight are stored in the databases of FEI so these data cannot be analyzed. According to Loek Halmans an average package has the size of a shoe box and weighs about 5 kg. With the current contracts and an average package of 5 kg UPS is always cheaper than FedEx.

For this model the UPS express freight tariffs have been taken as the transportation cost because these are the cheapest, most items are shipped using UPS at the moment and they are the preferred supplier.

Because of the structure of express service providers like UPS some locations near customers provide worse service although they are located closely to each other. This is because for UPS the main hub for express service is located in Cologne and for FedEx in Zaventem (near Antwerp). This means that all packages are shipped there first and then distributed throughout Europe. So Eindhoven is actually a pretty good location for reaching customers quickly through these service providers.

Because these service providers only provide overnight service, with 8:30 as the earliest guaranteed delivery time, dependent on the location, also other ways of transport can be considered to reach more customers with one warehouse. Otherwise a warehouse in for example Dresden would not add service to a customer in Munich (delivery is overnight as it is from Eindhoven) whereas a courier service or taxi could reach the customer within 4 hours. So for customer sites located near to other warehouses (within 4 hours) also express transportation is considered against a cost of €0,68 per kilometer on top of the other transportation costs. This is a guess based on the current contract prices arranged with Van den Boogaard, an express courier service used by FEI in Eindhoven.

Appendix XII shows the transport cost calculations, handling cost at the central warehouse are also included in this cost. If a local warehouse is used in a city also an additional cost of €10,- is included for local transport from the warehouse to the customer location. This is based on the cost in the Crolles and Grenoble area.

There is a difference in the reliability of delivery times of UPS express (guaranteed before a certain time) and a fast courier service (no guarantee). This has not been modeled. For courier service immediate access to the part was considered and transport times based on a route planner (www.routenet.nl) were used.

Warehouses

At the moment FEI has three important local warehouses in Europe and one central warehouse in Eindhoven. As with transport, warehousing is not owned by FEI and specific service providers provide warehousing for FEI. Costs for rented warehouse space include:

- A price per square meter, pallet space or shelf space per week
- A cost per handling or handling hour of inbound and outbound shipments
- A cost for standby service, access to the warehouse when it is closed
- Local transport can be arranged by most warehouses.

The first two parameters are important for local warehousing cost. Standby cost and the arranging of local transport are not used in the model. The first cost driver, rented space, depends on the assortment and size of the local warehouse. This might depend on the demand of customers that is served through this warehouse, but also depends on the function of the warehouse. It might be decided for example that all local warehouses should have a standard assortment of critical items that will be replenished once they are consumed. In that case a warehouse will have a standard cost independent of how much demand is covered by this warehouse.

On the other hand, also some critical consumable items might be stocked in a warehouse; in that case the size of the warehouse will depend on the total demand that is served by this warehouse.

Since decisions on what to stock have not yet been made an assumption must be made here on the cost of local warehouses. In the second part of this thesis the focus might be on the problem of what to stock in local warehouses.

Handling cost is typically a variable cost that only depends on the number of shipments made through the warehouse.

On top of the cost of these rented warehouses also the cost of inventory investment has to be considered. The inventory investment cost is obtained by taking 8% of the inventory price, this is the cost of capital for FEI. Inventory is accounted against the internal cost price, not against customer price. So this inventory investment cost is actually a lower bound on this cost. Also obsolescence cost (Van Kooten 2006) is not taken into account.

For warehouse cost both a fixed and a variable amount will be modeled, in order to be able to adjust the model to reality as much as possible. For the three warehouses that are currently operated the real expenses over 2006 and the inventory investment will be taken as the fixed warehousing cost.

The central warehouse is modeled with a fixed cost of €100.000,- though the real cost is approximately €1,3 million. This is done so that the model will not try to eliminate the central warehouse since this stock cannot be eliminated. €100.000,- has been chosen because it is much higher than the cheapest and most expensive warehouse, so other warehouse options are still viable.

Handling cost of local warehouses is added to the variable component of warehousing cost. For nonexistent warehouses a slightly higher variable warehousing cost is used than for existing warehouses because the estimated fixed cost is lower there.

An analysis of current warehouse cost and inventory investment can be found in Appendix VIII. Appendix X shows the warehouse cost that has been used in the model.

Since these data do not show a consistent investment in inventory two different scenarios on warehouse cost will be selected for the model; one based on the cheapest warehouse and one based on the more expensive warehouses.

Lagrange multiplier

In the current model the Lagrange multiplier is an input variable, but if the cost of not meeting a customers' service level agreement is unknown, a good way to obtain 'good' values for λ_j is to calculate certain break even points. These break even points can be calculated for every decision. One useful break even point to calculate is when shipping from the central warehouse is just as expensive as shipping from a local warehouse located at the customer site. In that case the slack time multiplied by the Lagrange multiplier must equal the extra transport and warehousing costs for using that local warehouse. This is shown in the equation below. Because all parameters except λ_j are known it is possible to calculate λ_j from this equation.

$$
\begin{aligned}
& C_i^{inv} Y_{ij} w_j + C_i^{loc} X_i + w_j C_{ij} Y_{ij} = C_k^{inv} Y_{kj} w_j + w_j C_{kj} Y_{kj} + \lambda_j S_j \\
& i, k \in I \ , \ i \neq k \\
& j \in J \\
& \textit{Where k is the central warehouse and i is the local warehouse at the customer site}
\end{aligned}
$$

The equation above shows how to calculate a λ_j that will decide between distribution from the central warehouse, or distribution from the local warehouse. If λ_j is larger than the value calculated here it will be cheaper to deliver from the local warehouses, if it is smaller, delivery from the central warehouse is cheaper than delivery from the local warehouse. These calculations can be used to make the model more robust and force a decision, but using an estimate for the real penalty cost increases the strength of the model in facilitating decision making. Therefore in model the estimates for the real penalty cost are used. The break even values for lambda are shown in Appendix XI.

Warehouse location data and cost:

France: ECTRA:

€4,- per inbound or outbound shipment
€10,- per square meter storage space per month

Crolles:

- 30 m2
- 40 inbound lines per month
- 40 outbound lines per month

Minimum cost €500,- per month

Rousset:

- 12m2
- 20 inbound lines per month
- 20 outbound lines per month

Minimum cost €100,- per month

UK, Londonderry: Wincanton:

- VMI cost €600,- to €690,- per month with an average of €660,- over 2006.

Germany, Dresden: EMOS Spedition (through Panalpina):

€30.00 per warehouse handling hour
€35.00 per administration hour

€ 2.50per pallet per week
€1.50 per shelf per week

- 90 shipments per year (in- and outbound). Inbounds usually contain 1 item, but in 30% 2-3 items
- 18 m^2 pallet products
- 16 m^2 small parts (106 shelves of 50x30 cm)

328 items of 168 products are stored

Table 15: Warehouse space cost

space cost	**amount**	**Dresden**	**Londonderry**	**ECTRA**
square meter price per month	42			€ 10.00
pallet price per week	18	€ 2.50		
shelf price per week	106	€ 1.50		
yearly cost		€ 10,608.00	€ 7,920.00	€ 5,040.00

Inventory cost

Besides the space cost also inventory cost is of importance. From the ERP system of FEI the data on total number of items inside the three warehouses and the value of these items is put in Table 16. The table shows the data as obtained from the ERP system, number of different items stored, total quantity stored, total value of the inventory and the average value.

Table 16: Inventory cost

	Location			
Inventory	**Dresden**	**Londonderry**	**ECTRA**	**Grand Total**
Count of Item Number	149	176	51	376
Sum of QOH	327	352	60	739
Sum of Ext Cost	€ 305,656.84	€ 295,727.45	€ 56,716.80	€ 658,101.09
average item price	€ 934.73	€ 840.13	€ 945.28	€ 890.53

Total warehousing cost

8% of the inventory investment is taken as capital costs; on top of that the warehousing cost must be added to get the total fixed warehousing cost.

Table 17 below shows that not one average warehouse exists. Though the warehouses in Londonderry and Dresden have kind of similar inventory investment and space cost also here there are differences. Londonderry has stored more items, a larger amount on hand and a lower average item cost and storage is cheaper.

In the ECTRA warehouses a completely different stock policy is in place. While storage space rented is about the same as in Dresden, they pay far less for this space (this can be compared to the price Dresden would pay if everything were stored on pallets). They stock far fewer items in the warehouse, only 60 opposed to more than five times that number in Dresden and Londonderry. In a follow up analysis it turned out that data on the ECTRA warehouse stock in MFG PRO were not realistic. Therefore for ECTRA also an estimate will be used in the model.

Table 17: Total fixed warehouse cost

warehouse cost	**Dresden**	**Londonderry**	**ECTRA**	**Grand Total**
8% investment	€ 24,452.55	€ 23,658.20	€ 4,537.34	€ 52,648.09
space	€ 10,608.00	€ 7,920.00	€ 5,040.00	€ 23,568.00
total	€ 35,060.55	€ 31,578.20	€ 9,577.34	€ 76,216.09

analysis	**Dresden**	**Londonderry**	**ECTRA**
# items ordered	330	278	330
variable investment	74.10	85.10	13.75
variable on space	€ 32.15	€ 28.49	€ 15.27
variable on total	€ 106.24	€ 113.59	€ 29.02

Overhead cost

This is the cost of management of local warehouses like visits, stock counts etc. At the moment no management policy is in place so nothing can be said about these costs in the current situation.

APPENDIX IX GAMS MODEL

This appendix contains a simple version of the model in GAMS because of readability. The actual model contains 15+1 warehouse locations and 30 customer locations.

```
set i local warehouses / lw0*lw5/
set j customers        / Eindhoven, Brussels, Dresden, Londonderry, Crolles, Paris, Avezzano /

Parameters
w(j) demand at customer j
      /  Eindhoven   200
         Brussels     50
         Dresden     100
         Londonderry  80
         Crolles      50
         Paris        50
         Avezzano    50 /

SLA(j) service level agreement with customer j in hours
      /  Eindhoven    24
         Brussels     24
         Dresden      24
         Londonderry   1
         Crolles       4
         Paris        24
         Avezzano    24 /

lrm(j) Lagrangian relaxation multiplier
      /  Eindhoven   1000
         Brussels    1000
         Dresden     1000
         Londonderry 1000
         Crolles     1000
         Paris       1000
         Avezzano    1000 /

cloc(i) cost of opening a local warehouse
        / lw0      45000
          lw1      45000
          lw2      45000
          lw3      45000
          lw4      45000
          lw5      45000 /

cinv(i) cost of handling and holding inventory at local warehouse i
        / lw0      10
          lw1      10
          lw2      10
          lw3      10
```

```
          lw4         10
          lw5         10 / ;

Table c(i,j) costs for delivery to customer i through warehouse j
     Eindhoven  Brussels   Dresden    Londonderry      Crolles     Paris          Avezzano
lw0      1      141        716        1302             943         446            1614
lw1     141     141        1500       2513             1800        755            3174
lw2     716     925        716        3095             2060        1469           3068
lw3    1302     1352       2509       1302             2826        1750           4368
lw4    943      998        1833       3185             943         1034           2571
lw5    1614     1701       2170       4056             1900        1934           1614 ;

Table t(i,j) delivery times from local warehouse to customer
     Eindhoven  Brussels Dresden  Londonderry Crolles  Paris  Avezzano
lw0      1      3        24           24       24      24     48
lw1      3      1        24           24       24      24     24
lw2     24      24       1            48       24      24     24
lw3     24      24       48           1        24      24     48
lw4    24       24       24           24       1       24     24
lw5    48       48       24           48       24      24     1    ;

Variables
      y(i,j)  decision to ship demand of customer j through warehouse i
      x(i)    decision to  open local warehouse i
      z       total cost
      S(j)    slack on SLA

binary variable y ;
positive variable s;

equations
  cost        define objective funtion
  open(i,j)   observe that a warehouse is opened if a shipment must be made from this warehouse
  supply(j)     observe that a customer is served from one lw
  SL(j)       observe that the service level agreement is fulfilled ;

cost..   z =e= sum(i, (cinv(i)*sum(j, y(i,j)*w(j)))) + sum(i, cloc(i)*x(i))+ sum((i,j), c(i,j)*y(i,j)*w(j)) +
sum(j,(lrm(j)*S(j)));

supply(j).. sum(i, y(i,j)) =e= 1;
SL(j).. sum(i, t(i,j)*y(i,j)) =l= SLA(j)+ S(j);
open(i,j).. x(i) =g= y(i,j);

model test /all/ ;

solve test using mip minimizing z ;
```

Table 18: Variable and fixed inventory cost in model

		Variable	Fixed
	lw i	**cinv**	**cloc**
Eindhoven	lw0	0.00	100000.00
Londonderry	lw1	8.00	31578.20
Leixlip	lw2	9.00	25000.00
Dresden	lw3	8.00	35060.55
Munich	lw4	9.00	25000.00
Regensburg	lw5	9.00	25000.00
Crolles	lw6	9.00	25000.00
Rousset	lw7	9.00	25000.00
Caen	lw8	9.00	25000.00
Tours	lw9	9.00	25000.00
Agrate	lw10	9.00	25000.00
Avezziano	lw11	9.00	25000.00
Catania	lw12	9.00	25000.00
Villach	lw13	9.00	25000.00
Stockholm	lw14	9.00	25000.00
Manchester	lw15	9.00	25000.00

APPENDIX XI DEMAND IN LOCATION MODEL

Table 19: Demand in location model and Lagrange break even point

i	demand	SLA	Lagrange break even point	
Londonderry	250	1	1475.06	
Leixlip	54	24	1627.00	
Dresden	230	4	2427.88	
Munich	94	24	2232.03	
Regensburg	9	24	2097.67	
Crolles	88	4	1661.79	
Rousset	80	4	1652.88	954.00
Caen	35	24	1604.15	
Tours	6	24	1569.22	
Agrate	64	24	1639.09	
Avezzano	14	24	574.05	
Catania	33	24	582.35	
Villach	35	24	1283.32	
Stockholm	0	24	2083.33	
Manchester	29	24	2129.91	
Germany	2007	24		
France	1974	24		
UK	815	24		
Italy	706	24		
Netherlands	450	24		
Spain	415	24		
Switzerland	267	24		
Belgium	377	24		
Sweden	64	24		
Austria	155	24		
Denmark	136	24		
Norway	19	24		
Finland	75	24		
Ireland	61	24		
Croatia	0	24		
Luxembourg	3	24		
Romania	0	24		
Portugal	0	24		
Slovenia	21	24		
Estonia	7	24		
Serbia	0	24		
Hungary	0	24		
Slovakia	0	24		

🟨	Rousset lagrange multiplier decision for delivery from Crolles or central warehouse

APPENDIX XII COST MATRIX LOCATION MODEL

c(i,j) j (customers) all other countries -->

	i	Londonderry	Leixlip	Dresden	Munich	Regensburg	Crolles	Rousset	Caen	Tours	Agrate	Avezzano	Catania	Villach	Stockholm	Manchester	Germany	France
Ehv	lw0	20,78	20,78	22,11	22,11	22,11	20,78	20,78	20,78	20,78	23,39	23,39	23,39	20,78	25,21	20,78	22,11	20,78
lon	lw1	30,78	184,66	41,58	41,58	41,58	41,58	41,58	41,58	41,58	50,89	50,89	50,89	41,58	51,83	40,78	41,58	41,58
leix	lw2	184,66	30,78	41,58	41,58	41,58	41,58	41,58	41,58	41,58	50,89	50,89	50,89	41,58	51,83	41,58	41,58	41,58
dres	lw3	38,92	38,92	32,11	341,03	256,71	38,92	38,92	38,92	38,92	42,36	42,36	42,36	38,92	51,77	38,92	42,11	38,92
mun	lw4	38,92	38,92	341,03	32,11	108,47	38,92	38,92	38,92	38,92	42,36	42,36	42,36	231,55	51,77	38,92	42,11	38,92
reg	lw5	38,92	38,92	256,71	108,47	32,11	38,92	38,92	38,92	38,92	42,36	42,36	42,36	316,55	51,77	38,92	42,11	38,92
crol	lw6	50,43	50,43	50,43	50,43	50,43	30,78	202,34	40,78	40,78	48,92	48,92	48,92	50,43	52,29	50,43	50,43	40,78
rous	lw7	50,43	50,43	50,43	50,43	50,43	202,34	30,78	40,78	40,78	48,92	48,92	48,92	50,43	52,29	50,43	50,43	40,78
caen	lw8	50,43	50,43	50,43	50,43	50,43	40,78	40,78	30,78	40,78	48,92	48,92	48,92	50,43	52,29	50,43	50,43	40,78
tour	lw9	50,43	50,43	50,43	50,43	50,43	40,78	40,78	40,78	30,78	48,92	48,92	48,92	50,43	52,29	50,43	50,43	40,78
agr	lw10	49,12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	33,39	43,39	43,39	49,12	60,67	49,12	49,12	49,12
avez	lw11	49,12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	43,39	33,39	43,39	49,12	60,67	49,12	49,12	49,12
cat	lw12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	49,12	43,39	43,39	33,39	49,12	60,67	49,12	49,12	49,12
vil	lw13	51,84	51,84	51,84	230,22	315,22	51,84	51,84	51,84	51,84	51,65	51,65	51,65	30,78	57,82	51,84	51,84	51,84
stock	lw14	50,27	50,27	50,27	50,27	50,27	50,27	50,27	50,27	50,27	62,79	62,79	62,79	50,27	35,21	50,27	50,27	50,27
man	lw15	40,78	41,58	41,58	41,58	41,58	41,58	41,58	41,58	41,58	50,89	50,89	50,89	41,58	51,83	30,78	41,58	41,58

handling cost panalpina	7,5			
handling cost		in variable warehousing cost		
local transport	10	(guess)	based on crolles	
semi local transport	20	(guess)		
semi local express	🟥			

distance (km) source: www.routenet.nl

(i,j) j (customers)

	i	Londonderry	Leixlip	Dresden	Munich	Regensburg	Crolles	Rousset	Caen	Tours	Agrate	Avezzano	Catania	Villach	Stockholm	Manchester
Ehv	lw0															
lon	lw1		241													559
leix	lw2	241														335
dres	lw3				469	345										
mun	lw4			469		127								308		
reg	lw5			345	127									433		
crol	lw6							267	805	623	367					
rous	lw7						267		1004	797						
caen	lw8						805	1004		263						
tour	lw9						623	797	263							
agr	lw10						367					667	1377			
avez	lw11										667		778			
cat	lw12										1377	778				
vil	lw13				308	433										
stock	lw14															
man	lw15	559	335													

van den boogaard	0,34	per km
2way tarif	0,68	per km

Express cost

	i	Londonderry	Leixlip	Dresden	Munich	Regensburg	Crolles	Rousset	Caen	Tours	Agrate	Avezzano	Catania	Villach	Stockholm	Manchester
Ehv	lw0															
lon	lw1		164													380
leix	lw2	164														228
dres	lw3				319	235										
mun	lw4			319		86								209		
reg	lw5			235	86									294		
crol	lw6							182	547	424	250					
rous	lw7						182		683	542						
caen	lw8						547	683		179						
tour	lw9						424	542	179							
agr	lw10						250					454	936			
avez	lw11										454		529			
cat	lw12										936	529				
vil	lw13				209	294										
stock	lw14															
man	lw15	380	228													

Table 20: Service level scenarios

Customer location	SLA Scenario 1	Scenario 2	Scenario 3
Londonderry	1	4	24
Leixlip	24	4	24
Dresden	4	4	24
Munich	24	4	24
Regensburg	24	4	24
Crolles	4	4	24
Rousset	4	4	24
Caen	24	4	24
Tours	24	4	24
Agrate	24	4	24
Avezzano	24	4	24
Catania	24	4	24
Villach	24	4	24
Stockholm	24	4	24
Manchester	24	4	24

APPENDIX XIV GRAPHICAL OVERVIEW OF WAREHOUSES TO OPEN

The figure below contains all warehouses that are to be opened in the base case of any scenario.

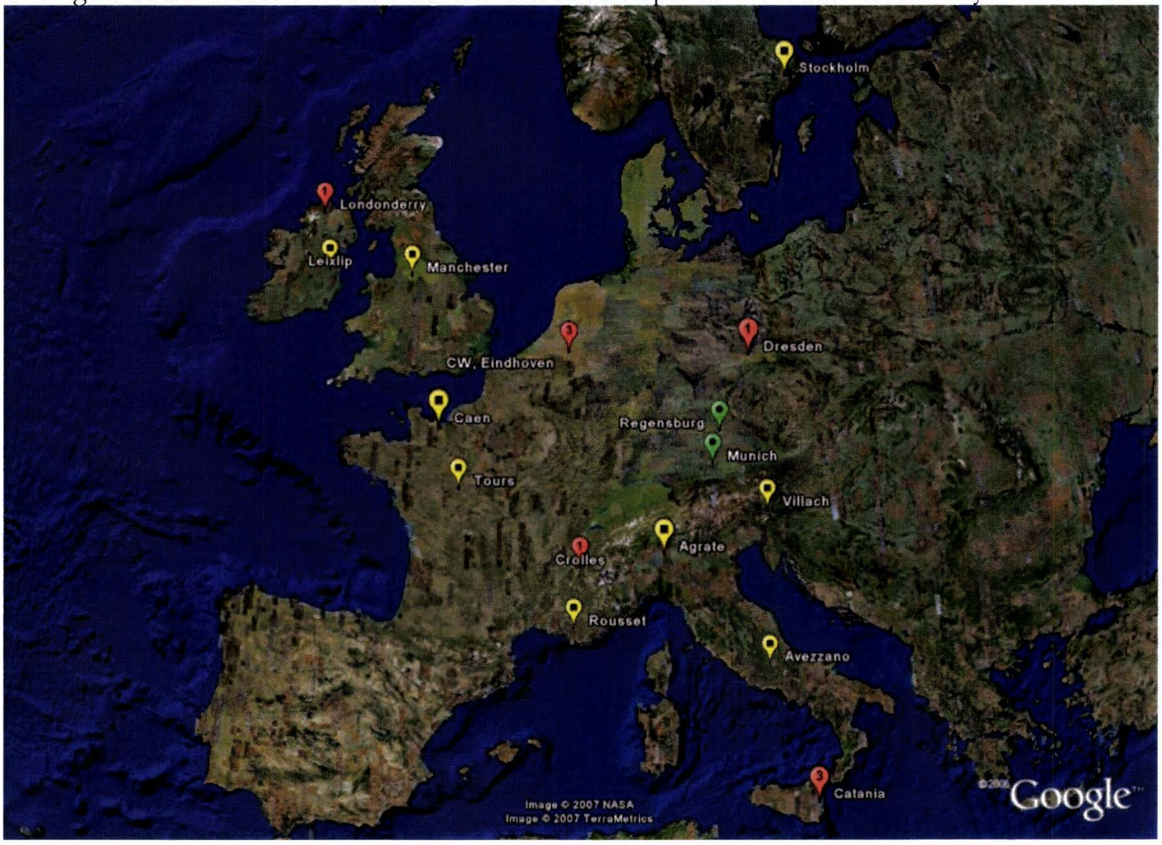


Figure 25: Warehouses opened in base cases and candidates

Legend:

Red mark 3:	Eindhoven and Catania are opened in any scenario (scenario 3)
Red Mark 1:	Londonderry, Dresden and Crolles are opened in Scenario 1 and 2
Green Mark:	Regensburg and Munich are opened in sensitivity analysis of scenario 2
Red Mark A:	Rousset is opened in scenario A and C (when warehouse cost is low)
Red Mark D:	Stockholm, Caen, Munich and Tours are opened in scenario D and C
Yellow mark:	Leixlip, Manchester, Caen, Tours, Rousset, Stockholm, Villach, Agrate and Avezzano are never opened. These customers might not receive their wished service level because it is cheaper to deliver to them from the central warehouse or to use taxis instead of a warehouse.

Table 21 shows when which warehouse is opened in base cases.

Table 21: Details of warehouses to be opened in base cases

Warehouses opened

Warehouses		**scenario**		
Place	**#**	**1**	**2**	**3**
Eindhoven	lw0	1	1	1
Londonderry	lw1	1	1	
Leixlip	lw2			
Dresden	lw3	1	1	
Munich	lw4			
Regensburg	lw5			
Crolles	lw6	1	1	
Rousset	lw7			
Caen	lw8			
Tours	lw9			
Agrate	lw10			
Avezzano	lw11			
Catania	lw12	1	1	1
Villach	lw13			
Stockholm	lw14			
Manchester	lw15			
Total		5	5	2

Demand at opened warehouses

Warehouses		scenario		
Place	#	1	2	3
Eindhoven	lw0	7881	7818	8529
Londonderry	lw1	250	304	
Leixlip	lw2			
Dresden	lw3	230	239	
Munich	lw4			
Regensburg	lw5			
Crolles	lw6	169	169	
Rousset	lw7			
Caen	lw8			
Tours	lw9			
Agrate	lw10			
Avezzano	lw11			
Catania	lw12	46	46	46
Villach	lw13			
Stockholm	lw14			
Manchester	lw15			

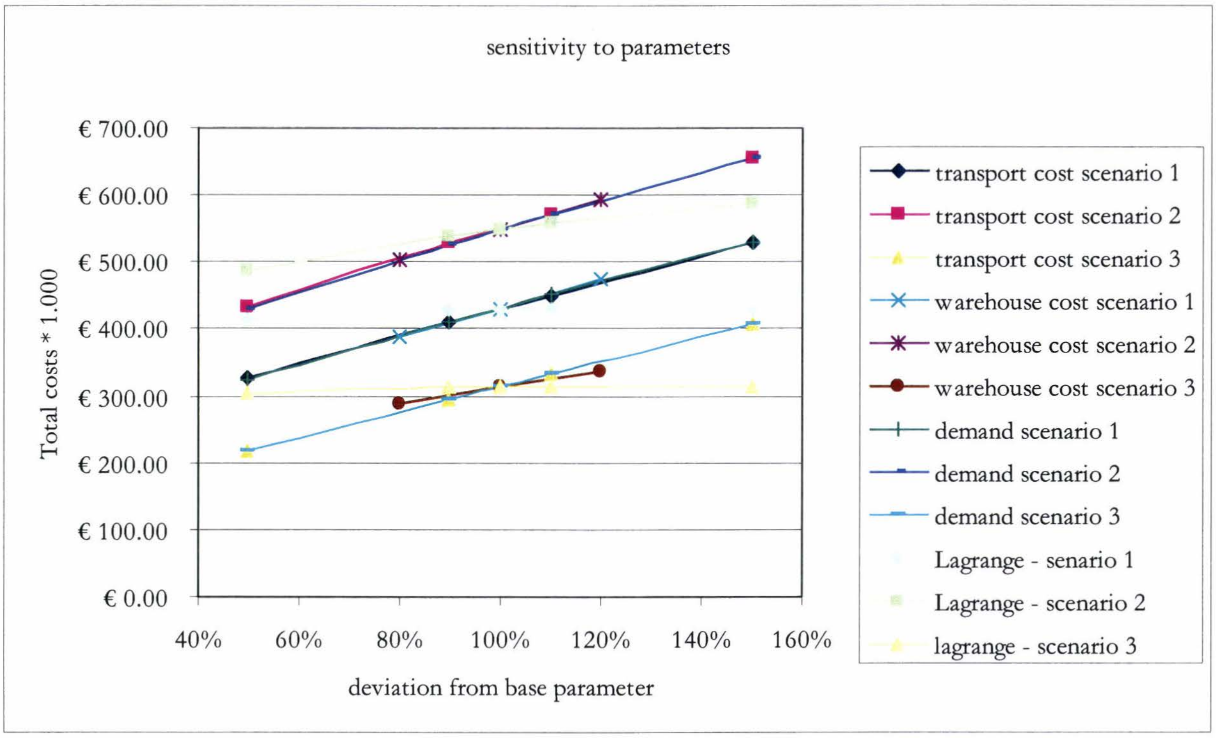


Figure 26: Sensitivity analysis graph warehouse locations

Table 22: Sensitivity analysis table warehouse locations

values * 1000	scenario 1	scenario 2	scenario 3
Transport cost			
50%	€ 326.63	€ 434.01	€ 219.54
90%	€ 410.00	€ 528.37	€ 294.83
100%	€ 430.85	€ 550.31	€ 313.65
110%	€ 450.99	€ 571.55	€ 332.47
150%	€ 528.55	€ 653.50	€ 407.76
Warehouse cost			
80%	€ 387.52	€ 503.14	€ 288.65
100%	€ 430.85	€ 550.31	€ 313.65
120%	€ 474.17	€ 593.64	€ 338.65
Demand			
50%	€ 323.74	€ 430.17	€ 219.32
90%	€ 409.42	€ 527.74	€ 294.78
100%	€ 430.85	€ 550.31	€ 313.65
110%	€ 451.50	€ 572.11	€ 332.51
150%	€ 531.08	€ 656.28	€ 407.97

Scenario 1:

Scenario 1 is the most realistic scenario. It is the service that FEI currently wants to provide to its customers. It turned out that for the majority of important customers delivery faster than within 24 hours is not yet necessary. The analysis of this scenario leads to a very stable outcome with respect to warehouses to be opened. In all cases of the sensitivity analysis 4 local warehouses are opened; Londonderry, Crolles, Dresden and Catania. Only when demand increases or when transportation cost increases one difference occurs; Rousset then has to be supplied by the central warehouse instead of by the warehouse in Crolles. This is because the lambda tradeoff between delivery from Crolles and delivery from the central warehouse is close to 1000 (±954). A slight variation in demand then leads to delivery from the central warehouse instead of from the Crolles warehouse. This reflects exactly the problems faced by FEI for this location. The current solution is to stock some fast moving consumables at the customer and deliver the rest of the demand from Crolles. That leads to lower taxi costs. This is a bit too detailed for this general model because demand is not analyzed per part here, but it does show how close to reality this model is.

Scenario 2

This scenario is very good for testing the performance of the model. For every customer location a decision has to be made between delivering within the SLA and having warehouse or taxi cost, or having penalty cost. It also provides useful insights in which locations are interesting to open a warehouse if customer service is to be increased, and which locations are not interesting at all.

Interesting is that the warehouses to be opened are the same as in scenario 1, the current situation.

Only when demand or transportation cost decreases by 50%, another decision is made. In that case the warehouse in Regensburg must be opened instead of the warehouse in Dresden. This is because the Regensburg warehouse is cheaper than the Dresden warehouse (for the warehouse in Dresden real costs have been taken into account whereas the warehouse in Regensburg has an estimate of €25,000 costs). Note that it is very unlikely that demand or transport costs will fall by 50%.

If warehouse cost becomes cheaper by 20% also another decision is made. In that case besides the warehouses already to be opened in the base case also the warehouse in Munich must be opened. This clearly is weighted by using taxis or opening a warehouse. This shows that if the customers in the surroundings of Dresden, Regensburg and Munich would start to demand a higher service it could be beneficial to make a decision between having another local warehouse or cheap transport. This model does not take into consideration if the stock in a warehouse changes when more customers are served from that warehouse. In case this happens, of course analysis with the stock keeping model would give insight in these costs and this can further facilitate the decision.

With respect to which customer is served by which warehouse some more changes now.

In the base solution the local warehouse in Londonderry is used for Londonderry and Leixlip, the warehouse in Dresden is used for Dresden and Regensburg, the warehouse in Crolles is used for Crolles and Rousset, and the warehouse in Catania is used for Avezzano and Catania. All other customers are served from the central warehouse.

The same changes occur as in scenario 1 with respect to the customer in Rousset. If demand, or transport costs rise just a bit, it will be cheaper to deliver from Eindhoven instead of from Crolles.

In case the warehouse in Regensburg is opened, when demand or transport cost drops 50%, this warehouse will be used to deliver customers in Dresden, Regensburg, Munich and Villach.

When warehousing becomes cheaper and also the warehouse in Munich is opened, this warehouse will be used for Regensburg, Munich and Villach, and the Dresden warehouse then only serves the customers in Dresden.

Though quite some changes occur in this model with respect to which customer is served by which warehouse the overall performance of the model is quite stable. The number of warehouses to be opened does not change much. Total costs do change a bit when decisions change, but not so significantly. Over the total 100% change in demand (the largest change in cost) a deviation from the base solution cost is only 3%. This gives the idea that for substantial differences it might be beneficial to reevaluate the base decision, but that in general this decision is robust and it is not necessary to respond quickly to changes in the market since only marginal cost savings are possible.

Scenario 3:

Scenario 3 is the simplest scenario to be analyzed. It can be used as a minimum cost solution to show FEI what increased service will cost compared to base service. It also identifies that a warehouse in Italy is needed (which is not yet present) because even the most basic service, within 24 hours delivery is not possible there. In this case a warehouse in Catania is needed, which will also deliver service to customers in Avezzano. Agrate Brianza, another city with important customers in Italy can be reached from the central warehouse within 24 hours and does not need service from this new, local warehouse.

This scenario is completely insensitive to changes in any of the parameters and behaves completely linearly.

Sensitivity to the Lagrange multiplier

A difference between sensitivity to the other parameters and the Lagrange parameter is that the total cost function is less sensitive to changes in the Lagrange parameter. While the total costs increase almost in a linear manner for changes in the other parameters, this is not the case for changes in the Lagrange muliplier. This is because it directly influences the decisions. Table 23 shows the total costs for changes in the Lagrange multiplier.

Table 23: Sensitivity total costs for Lagrange multiplier

	values * 1000		
Lagrange multiplier	scenario 1	scenario 2	scenario 3
50%	€ 414.45	€ 487.78	€ 304.50
90%	€ 430.00	€ 538.67	€ 313.65
100%	€ 430.85	€ 550.31	€ 313.65
110%	€ 430.85	€ 559.06	€ 313.65
150%	€ 430.85	€ 589.13	€ 313.65

Striking changes when the Lagrange parameter changes:

In scenario 1 and 3 the warehouse in Catania is closed when the parameter is 50%.

In scenario 1 and 2 also delivery to Rousset will be done from the central warehouse when the Lagrange parameter becomes less than 90% or 50% of the base value. This is the same as for other parameter changes.

In scenario 2 an additional warehouse in Munich is opened when the parameter is 110% or 150%. When the parameter is 150% also an extra warehouse in Agrate Brianza is opened.

When the parameter is only 50% Leixlip will receive shipments from the central warehouse.

APPENDIX XVI POISSON DISTRIBUTION FITTING

The demand on item level at the warehouses has been analyzed with a χ^2-goodness of fit test to check if the Poisson distribution can be proved. This has been done because the stock keeping model has to use the Poisson process for demand. The data analyzed contains demands from January 2003 till November 2006.
The aggregated demand data that will be used for the location model (not on item level) could not be fit to the Poisson or normal distribution.

The Poisson process is the most common distribution used in spare parts literature. This is because if the time between two failures can be described by an exponential distribution, then the number of failures in a certain period is described by a Poisson distribution. Because demand rates for spare parts are often related to part failures and they are low and erratic, the Poisson process can often be used to describe this demand.

The analysis has been done for quarterly demand. This aggregation has been taken because of the very low demand rates at FEI. Because of aggregation per quarter the demand seems smoother, which facilitates the statistical analysis. Also because demand is very low, a threshold value for the analysis has been taken. To be part of the analysis at least 12 items must have been used at the warehouses in the period under consideration. This has been done because with a too small dataset the chance on fit is too small; a minimum dataset is needed to obtain a statistical significant outcome. Taking 12 as the minimum cumulative order size over almost 4 years means that only items are analyzed that were ordered on average 3 times in a year at that specific warehouse, similarly once every 4 months.
Because negative demand can occur when an ordered item is not needed in the end, the data have been checked on negative values. For the local warehouses no negative demands occur, they are all smoothed by the aggregation per quarter. For the central warehouse still some negative demands existed. These have been subtracted from demand in the month(s) before the negative demand occurred. The dataset of quarterly demand now reflects the 'real' demand that has been consumed by customers.

Table 24: Percentages of fitted Poisson distribution

Quarterly				
	# items	Fit probability		
Warehouse	demand ≥ 12	fit 0.10	fit 0.05	fit 0.01
Central	971	64.3%	69.5%	80.2%
Dresden	19	47.4%	52.6%	63.2%
Londonderry	16	56.3%	68.8%	68.8%
Crolles	5	60.0%	60.0%	60.0%

From the table above it can be concluded that in 80.2% of the cases it cannot be rejected that the demand at the central warehouse can be classified as a Poisson distribution if 99% certainty is needed before this hypothesis is rejected. This percentage will even be higher if a larger number of minimum demand is taken for the central warehouse. Three orders per year on a worldwide level can be classified as a very slow moving item. For the local warehouses the same percentage is lower, between 60% and 68.8%, which can be explained by the much lower demand rates at the local warehouses. The larger the demand (and thus the dataset), the better statistical analysis will perform.

Other explanations for demand not fitting to a Poisson distribution in this case include that

preventive maintenance orders are included in the spare parts orders. These preventive maintenance orders are typically larger and more frequent, and therefore disturb the demand distribution generated by failing parts.
Trends are also known to disturb the fitting of a stable distribution. This is especially true because demand depends on the installed base, which grows constantly. When newer systems are installed they will create demands for new spare parts, that have not been demanded before. The analysis above does not take a change in the installed base of customers into account. When the monthly data for local warehouses was analyzed, indeed significant trends are observed: 20% of the items in Crolles, 25% of the items in Londonderry and 5% of the items in Dresden have significant trends. For quarterly demand in the central warehouse 27% of the items were observed to have significant trend. Significant in these trend analyses is 95%.
Seasonality, another reason that could disturb stationary demand distributions is not known to exist at FEI. Preventive maintenance might be shown as some seasonality if this takes place on a regular schedule.

Whenever new systems are installed spare parts stocks have to be stocked on forecast anyway because no historical demand information is available. More analysis and results can be found below.

Details

This part contains more detailed and other analysis for the Poisson distribution. Analysis has been done for monthly aggregated demand as well as for quarterly aggregated demand. Yearly demand has not been considered as aggregation because this leads to only 4 data points per item which is too low for statistical significant analysis.

Because monthly demand is more erratic than demand per quarter the fit is usually less than for demand per quarter. Also for monthly demand there are many more instances where demand is negative. For the central warehouse these have all been set to 0 in the monthly analysis because of the large number of occurrences. (The total matrix for central warehouse demand is 984 x 48 > 47 thousand values). The monthly analysis thus does not reflect 'real' demand so well as the quarterly demand. Details are shown in the table below.

Table 25: Details Poisson distribution fitting

Monthly

				Fit probability	
Warehouse	demand	# items	fit 0.10	fit 0.05	fit 0.01
Central	≥12	984	49.3%	54.5%	63.5%
	≥30	442	46.8%	50.5%	60.6%
	≥50	269	42.8%	46.8%	57.6%
Dresden	≥5	38	23.7%	28.9%	34.2%
	≥10	23	39.1%	47.8%	56.9%
	≥12	19	47.4%	57.9%	63.2%
Londonderry	≥5	42	28.6%	28.6%	28.6%
	≥10	17	70.6%	70.6%	70.6%
	≥12	16	68.6%	68.8%	68.8%
Crolles	≥5	38	5.3%	5.3%	7.9%
	≥10	11	18.2%	18.2%	27.3%
	≥12	7	28.6%	28.6%	42.9%

Quarterly

			Fit probability		
Warehouse	demand	# items	fit 0.10	fit 0.05	fit 0.01
Central	≥12	971	64.3%	69.5%	80.2%
	≥30	438	67.6%	74.0%	82.2%
	≥50	263	69.6%	77.2%	86.7%
Dresden	≥5	38	34.2%	39.5%	47.4%
	≥10	23	39.1%	47.8%	60.9%
	≥12	19	47.4%	52.6%	63.2%
Londonderry	≥5	42	45.2%	52.4%	57.1%
	≥10	20	60.0%	75.0%	75.0%
	≥12	16	56.3%	68.8%	68.8%
Crolles	≥5	33	24.2%	24.2%	27.3%
	≥10	10	50.0%	50.0%	50.0%
	≥12	5	60.0%	60.0%	60.0%

Most insight in the EOQ and how it relates to stochastic inventory theory is provided by Zheng (1992). This article contains an analysis of the (R, Q) system and proves these following statements with regard to the EOQ in an (R, Q) model:

1. The deterministic EOQ underestimates the total cost (inventory, backorders and order cost) because it does not take the chances on demand that arrives into account. Therefore the real inventory and backorder costs will be higher.
2. The deterministic EOQ underestimates Q, so EOQ is a lower bound for the Q in the stochastic model
3. The EOQ with penalty cost gives a better result than the EOQ without penalty cost since the EOQ with penalty cost is larger.

Tight bounds on deviation from the optimal cost for using the deterministic EOQ instead of the optimal (r,Q) are established by Zheng (1992) (0.125), Axsäter (1996) (0.1180) and Gallego (1998) (0.0607).

There are some different approaches in literature. Most of them are based on cost models, which means that penalty cost must be known.

Only the article of Axsäter (2006b) uses a fillrate approach, which is more applicable to my model, though the article of Axsäter uses a normal distribution instead of Poisson distribution. In this article both r and Q are optimized. This article uses tabulated values and interpolation to solve this problem for given values of the fillrate.

Other literature uses a cost model with penalty costs. Here a difference is made between jointly optimizing (R, Q) and just adjusting Q. If just Q is to be adjusted the fillrate can be used to calculate a backorder cost and approximate Q. In the book of Axsäter (2006) is stated that this approximation is valid if only Q is optimized, but not for jointly optimizing r and Q. More details about when cost models and service models are equivalent is provided in the article of Van Houtum and Zijm (2000). They prove that a cost model can always be used and is equivalent to a service model if the modified fill rate (γ) is used as service measure; for α and β service levels this cannot be proved for the general situation.

The article of Gallego (1998) only focuses on the optimization of Q. So in this case it is valid to calculate a penalty cost using the hit rate obtained from the multi item model.

Joint optimization of r and Q is done in the article of Federgruen and Zheng (1992), who provide a simple heuristic to calculate the optimal (R, Q) combination. This would be useful though an estimate for the penalty cost is needed, which cannot directly be obtained from the hit rate (Axsäter 2006, formulas 5.61, 5.67, 5.68)

Solution procedure

From the literature above different potential solutions have been generated. Joint optimization of R and Q seems a logical step, but because no reliable calculation procedure for penalty costs is available it is difficult to estimate the performance of such an approach. Therefore this approach has not been selected.

The only article that uses a fillrate approach does so by using tabulated values for different fillrates. This does not seem a useful approximation for a multi item model because a lot of different fill rates are possible in this model.

The most promising is the article of Gallego (1998), which uses a heuristic to calculate the optimal order quantity.

Gallego notes that the time average probability of being out of stock is equal to $\frac{h}{h+p}$, which is also known as the newsvendor ratio. According to Axsäter (2006) this can be used to calculate the penalty costs for an optimization of Q. Secondly Gallego develops bounds and heuristics for an optimal determination of Q. Of special interest here is the special part written on the Poisson case.
Notation:

H_i : *Distribution of holding costs for item i*
K : *Order costs per item*
Q_i^* : *Optimal order quantity*
Q_i^d : *deterministic EOQ for item i*
λ_i : *Poisson demand parameter for item i*
L_i : *Leadtime for item i*
h_i : *holding cost for item i*
p_i : *penalty cost for item i*

In this case the bounds on the order quantity are:

$$\sqrt{\frac{2K\lambda_i}{H_i}} \le Q_i^* \le \sqrt{\frac{2K\lambda_i + (h_i + p_i)L_i\lambda_i}{H_i}} \qquad \text{(eq. 5.19)}$$

And the heuristic for the optimal order quantity is:

$$Q_i^g = \min\left(\sqrt{2}, \sqrt[4]{1+\left(\frac{(C_i * r + p_i)T_{in}}{2K}\right)^2}\right)Q_i^d \qquad \text{(eq. 5.20)}$$

Where Q_i^d is the deterministic EOQ:

$$Q_i^d = \sqrt{\frac{2K\lambda_{i0}}{C_i * r}} \qquad \text{(eq. 5.21)}$$

The $\sqrt{2}Q_i^d$ part of the formula comes from a heuristic that is tested in the paper. It turns out that using $\sqrt{2}Q_i^d$ has an upper bound on total cost of 6.07% if K is relatively small. For large order cost K the optimal order quantity goes to Q_i^d. Therefore the heuristic in (eq. 5.20) has been suggested and is tested to have a relative cost increase of maximum 6.07%. In the case of Poisson demand this heuristic has been tested for several different parameter settings, and the average cost increase was 0.32% with a maximum of 2.64% cost increase.

The penalty costs needed in the heuristic of Gallego (1998) are calculated according to the newsvendor ratio for time average probability of being out of stock as stated in the beginning of the paper of Gallego; or similarly from Axsäter (2006):

$$Fillrate(\beta_i) = readyrate = \frac{p_i}{h_i + p_i} \qquad \text{(eq. 5.22)}$$

$$p_i = \frac{C_i * r * \beta_{i0}}{(1-\beta_{i0})} \qquad \text{(eq. 5.23)}$$

The order quantity is determined in 4 steps:

1. Calculate the deterministic EOQ (from (eq. 5.21))
2. Calculate the penalty costs (from (eq. 5.23))
3. Calculate the heuristic Q^g (from(eq. 5.20))
4. Round Q^g to the nearest integer ≥ 1

APPENDIX XVIII STANDARD PARAMETERS AND SOLUTIONS STOCK KEEPING MODEL

Table 26: Standard parameters stock keeping model

Standard parameters:		
Order cost K:	25	euro
Interest parameter r:	0.1	
Target hit rate minβ	0.95	for all warehouses
Lead time Londonderry	1	day
Lead time Dresden	1	day
Lead time Crolles	1	day
Lead time Italy	2	days
For the single item model:		
Class A minβ:	0.95	for all warehouses
Class B minβ:	0.95	for all warehouses
Class C minβ:	0.9	for all warehouses

Table 27: Detailed standard solution all models

Multi Item (R,Q) Model

Warehouse	HitRate	Inventory Turns	Inventory	Total Cost	Order Cost
Central	0.95	4.07	€ 5,267,402.00		
Dresden	0.95	2.43	€ 211,351.00		
Londonderry	0.95	2.65	€ 189,937.00		
Crolles et al	0.95	1.64	€ 250,939.00		
Italy	0.95	1.2	€ 148,653.00		
		3.53	€ 6,068,282.00	€ 712,240.64	€ 105,412.45

Multi Item Model eoq

Warehouse	HitRate	Inventory Turns	Inventory	Total Cost	Order Cost
Central	0.95	4.18	€ 5,123,624.00		
Dresden	0.95	2.44	€ 211,121.00		
Londonderry	0.95	2.64	€ 190,636.00		
Crolles et al	0.95	1.64	€ 250,641.00		
Italy	0.95	1.21	€ 148,085.00		
		3.62	€ 5,924,107.00	€ 721,734.57	€ 129,323.87

Multi Item Model Q=1

Warehouse	HitRate	Inventory Turns	Inventory	Total Cost	Order Cost
Central	0.95	4.39	€ 4,875,037.00		
Dresden	0.95001	2.44	€ 211,295.00		
Londonderry	0.95	2.67	€ 188,849.00		
Crolles et al	0.95	1.64	€ 250,705.00		
Italy	0.95	1.2	€ 148,332.00		
		3.78	€ 5,674,218.00	€ 1,189,221.46	€ 621,799.68

Single Item Model

Warehouse	HitRate	Inventory Turns	Inventory	Total Cost	Order Cost	# sku
Central	0.96572	1.45	€ 14,812,625.00			4947
Dresden	0.98698	0.6	€ 851,457.00			338
Londonderry	0.98927	0.85	€ 591,332.00			276
Crolles et al	0.98979	0.52	€ 785,999.00			416
Italy	0.99326	0.6	€ 297,808.00			183
		1.24	€ 17,339,221.00	€ 1,842,617.59	€ 108,695.46	

Table 28: Model performance 4947 parts

r = 0.10 K = 25 overview 4947 parts

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 606,828.20	€ 105,412.45	€ 712,240.64	0.00%	0.00%
EOQ	0.95	€ 592,410.70	€ 129,323.87	€ 721,734.57	1.33%	-2.38%
Q=1	0.95	€ 567,421.80	€ 621,799.68	€ 1,189,221.46	66.97%	-6.49%
Single Item	0.96572	€ 1,733,922.10	€ 108,695.46	€ 1,842,617.59	158.71%	185.74%

r = 0.08 K = 25

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 491,094.64	€ 98,515.05	€ 589,609.71	0.00%	0.00%
EOQ	0.95	€ 478,153.92	€ 119,894.40	€ 598,048.34	1.43%	-2.64%
Q=1	0.95	€ 453,937.44	€ 621,799.68	€ 1,075,737.10	82.45%	-7.57%
Single Item	0.96585	€ 1,392,491.36	€ 100,477.49	€ 1,492,968.88	153.21%	183.55%

r = 0.15 K = 25

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 893,869.05	€ 120,917.28	€ 1,014,786.26	0.00%	0.00%
EOQ	0.95	€ 877,699.95	€ 147,977.60	€ 1,025,677.55	1.07%	-1.81%
Q=1	0.95	€ 851,132.70	€ 621,799.68	€ 1,472,932.34	45.15%	-4.78%
Single Item	0.96566	€ 2,583,015.90	€ 124,736.36	€ 2,707,752.31	166.83%	188.97%

r = 0.10 K = 15

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 592,727.70	€ 76,235.00	€ 668,962.67	0.00%	0.00%
EOQ	0.95	€ 582,887.70	€ 92,800.03	€ 675,687.75	1.01%	-1.66%
Q=1	0.95	€ 567,421.80	€ 373,079.81	€ 940,501.58	40.59%	-4.27%
Single Item	0.96528	€ 1,718,450.40	€ 78,645.57	€ 1,797,095.94	168.64%	189.92%

r = 0.10 K = 50

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 636,225.90	€ 164,691.81	€ 800,917.72	0.00%	0.00%
EOQ	0.95	€ 614,043.90	€ 198,881.86	€ 812,925.75	1.50%	-3.49%
Q=1	0.95	€ 567,421.80	€ 1,243,599.37	€ 1,811,021.14	126.12%	-10.81%
Single Item	0.96651	€ 1,761,440.00	€ 167,484.48	€ 1,928,924.50	140.84%	176.86%

Leadtime LW = 30

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		

R,Q model	0.95	€ 628,707.90	€ 105,412.45	€ 734,120.37	0.00%	0.00%
EOQ	0.95	€ 614,178.80	€ 129,323.87	€ 743,502.64	1.28%	-2.31%
Q=1	0.95	€ 589,264.00	€ 621,799.68	€ 1,211,063.66	64.97%	-6.27%
Single Item	0.96572	€ 1,790,593.20	€ 108,695.46	€ 1,899,288.67	158.72%	184.81%

Leadtime LW = 7

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 613,833.10	€ 105,412.45	€ 719,245.52	0.00%	0.00%
EOQ	0.95	€ 599,260.30	€ 129,323.87	€ 743,502.64	3.37%	-2.37%
Q=1	0.95	€ 574,443.40	€ 621,799.68	€ 1,196,243.07	66.32%	-6.42%
Single Item	0.96572	€ 1,736,746.30	€ 108,695.46	€ 1,845,441.72	156.58%	182.93%

Table 29: Hit rate sensitivity table

hitrate = 0.90 overview 4947 parts

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.9	€ 493,802.00	€ 111,891.52	€ 605,693.50	0.00%	0.00%
EOQ	0.9	€ 482,709.20	€ 129,323.87	€ 612,033.03	1.05%	-2.25%
Q=1	0.9	€ 458,915.20	€ 621,799.68	€ 1,080,714.84	78.43%	-7.06%
Single item	0.93847	€ 1,464,184.50	€ 110,795.82	€ 1,574,980.31	160.03%	196.51%

hitrate = 0.95

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.95	€ 606,828.20	€ 105,412.45	€ 712,240.64	0.00%	0.00%
EOQ	0.95	€ 592,410.70	€ 129,323.87	€ 721,734.57	1.33%	-2.38%
Q=1	0.95	€ 567,421.80	€ 621,799.68	€ 1,189,221.46	66.97%	-6.49%
Single item	0.96572	€ 1,733,922.10	€ 108,695.46	€ 1,842,617.59	158.71%	185.74%

hitrate = 0.98

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.98	€ 819,974.20	€ 103,303.82	€ 923,278.05	0.00%	0.00%
EOQ	0.98004	€ 801,694.20	€ 129,323.87	€ 931,018.11	0.84%	-2.23%
Q=1	0.98	€ 774,222.80	€ 621,799.68	€ 1,396,022.47	51.20%	-5.58%
Single item	0.97498	€ 1,962,026.10	€ 108,331.87	€ 2,070,357.94	124.24%	139.28%

hitrate = 0.99

	Aggregate Fillrate CW	Costs			Δ% Best Cost	Δ% Inventory Cost
		Inventory	Order	Total		
R,Q model	0.99	€ 997,497.80	€ 102,960.25	€ 1,100,458.08	0.00%	0.00%
EOQ	0.99	€ 977,204.20	€ 129,323.87	€ 1,106,528.10	0.55%	-2.03%
Q=1	0.99	€ 949,286.70	€ 621,799.68	€ 1,571,086.43	42.77%	-4.83%
Single item	0.97786	€ 2,121,199.70	€ 108,174.83	€ 2,229,374.58	102.59%	112.65%

for the single item model only hit rate of A items is adjusted, B=0.95, C=0.90

Table 30: Total costs for changes in central warehouse lead time

Total costs		Half leadtime to CW for:		
	No changes	Repairables	Consumables	All
R, Q model	€ 712,240.64	€ 723,342.71	€ 695,098.12	€ 708,670.07
EOQ	€ 721,734.57	€ 731,971.06	€ 701,480.88	€ 714,752.54
Q=1	€ 1,189,221.46	€ 1,199,598.27	€ 1,167,081.33	€ 1,179,582.18
Single item	€ 1,842,617.59	€ 1,644,924.44	€ 1,799,731.14	€ 1,602,037.99

% total costs compared to standard		Half leadtime to CW for:		
	No changes	Repairables	Consumables	All
R, Q model	100%	102%	98%	99%
EOQ	100%	101%	97%	99%
Q=1	100%	101%	98%	99%
Single item	100%	89%	98%	87%

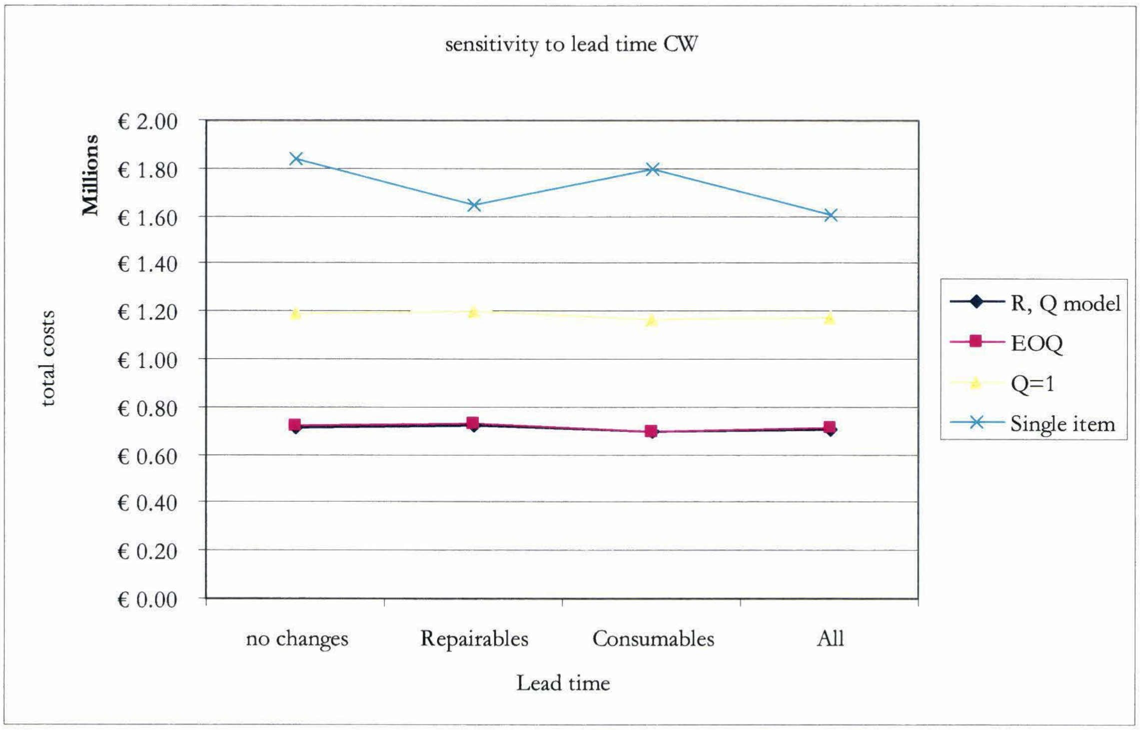


Figure 27: Total costs sensitivity to central warehouse lead time changes