Spare parts inventory planning in the Dutch railway infrastructure industry

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Award date:
2014

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Spare parts inventory planning in the Dutch railway infrastructure industry

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BSc Industrial Engineering — TU/e
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in partial fulfilment of the requirements for the degree of

Master of Science in Operations Management and Logistics

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Series Master Theses Operations Management and Logistics

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Abstract
This Master Thesis describes the development of an inventory control model to determine possible costs savings and the influence on availability of spare parts in the rail infrastructure industry. A model is developed with three alternative situations, different in available information and coordination. The three alternatives are compared with both a single-item and multi-item approach. Evaluation is on the aggregate target fill rate the system inventory costs. A case study to evaluate the alternatives is executed at voestalpine Railpro, with one central and eight local warehouses.
Acknowledgement
In this report the results of my master thesis project of the master program Operations Management and Logistics are presented. The research project has been carried out at voestalpine Railpro in Hilversum.

First I would like to thank my supervisor at Railpro. Wouter Lampe is the manager Marketing & Innovations at Railpro. I would like to thank you for the freedom you gave me to develop my own project, the time and interest spent in the project, and for involving me in all the relevant meeting and processes within the company. I also thank all the other people at Railpro, especially the M&I department, for their interest in the project, their willingness to help, and for the very nice work environment.

Furthermore, I would like to thank Marco Slikker for given me the opportunity to do this project under this supervision. Thank you for being always available, for reading and reflecting in great detail, and for keeping the focus on the research question when I was concerned with practicality issues. I would also like to thank Geert-Jan van Houtum for his help when choosing the mathematical models, and for his useful feedback and opinion.

Finally, I would like to thank friends, family and my girlfriend for their interest and support, for distracting me at the right moments and putting everything in the right perspective.

Jan van Oostrum
Eindhoven, April 2014
Management summary

Railpro is an independent service provider mainly serving the Dutch railway market. Carrying the right assortment and holding sufficient inventory to attain a high availability of products is an important business strategy for the company. In the last years the maintenance contracts between the infrastructure manager (ProRail) and the contractors change from Output Process Contracts (OPC) to Performance Based Contracts (PBC). Due to this change in contracting, the contractors are only sure to execute maintenance in a region for five years. When a region changes from one contractor to the other, the old constructor has an inventory that is (partly) worthless to him. Therefore customers want to get rid of their inventories, to prevent this for the future.

For Railpro these inventories are not such a problem because they can sell the products to another contractor or hopefully hold the inventory for the new contractor. Railpro has developed the concept off taking over the inventory of the contractor and hold it at the location of the customer (We will use the Dutch abbreviation VOL (Voorraad Op Locatie). With this concept there is new information and there are new opportunities available. This raises the question whether there are better approaches of managing inventories at Railpro (and the contractors together).

“What is the most suitable inventory model to supply spare parts in a (semi-)coordinated way, and what is the improvement potential in terms of cost savings and performance?”

An integrated model has been developed to investigate cost savings in different situations of available information and coordination. To determine possible saving potentials, three different situations are considered. One alternative model with one central location without any information of the other locations. Another model with optimization of one central location with the available information about the other locations. And the third alternative model where both central and local stock points are optimized. The objective for Railpro is to attain the agreed aggregate fill rates, while minimizing the inventory costs.

The developed models are based on the greedy approach with a two-moment approximation developed in Wong et al. (2007).

The model is applied in the current situation of Railpro which include one central warehouse and eight local warehouses.

The main conclusions are:
The developed model consisting of three alternatives is a useful tool in answering the main research question. Each alternative has a different scope of available information and control. In the first alternative, control is possible at the central location without any information of the rest of the supply chain. In the second alternative control of the central location is possible with additional information available from the stock points downstream in the supply chain. In the third alternative the central location and the downstream stock points can both controlled with

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1 A complete list of abbreviations can be found in Appendix A
the same information as in the second alternative (Section 4.2). All three alternatives are used with both a single-item and a multi-item approach which shows large differences in the results.

The three alternatives show clear differences in the results and show that with the ‘current practice’ of the uncoordinated situation (Alternative 1) and for the semi-coordinated situation of alternative 2 it is not possible to ensure the target fill rate agreements with the customers. In both situations it depends on the customer stocks whether the fill rates are attainable.

With the comparison of the six alternative models it is revealed that inventories within the supply chain can be reduced by 84% compared to ‘current practice’ while the target fill rates are met. It should be remarked that for the models with the lowest costs, the fill rates are also lower compared to the other models. The case study shows that the multi-item approach is superior to the single-item approach in all three alternatives. Available information about the customer inventories can decrease inventories with 10%-38%. When the central and local warehouses are optimized together system inventory costs can drop by 49%-84%. We will stress that these exact numbers are only valid for the given situation and based on the input parameters. However, from the sensitivity analyses of the input parameters we can conclude that most results are insensitive for different input values. The results of Alternative 2 for both Single-item and Multi-item are sensitive for the predetermined stock levels/demand rates. When the base stock levels are high compared to the demand rates this result in high local costs. When the base stock levels are low this results in high central costs or an infeasible solution, because the target fill rates cannot be reached.

The current structure and control of the rail infrastructure supply chain shows a starting point to search for improvements. However, the complexity with multiple players and different contracts can impede the practical implementation of a improved inventory control model (Chapter 2). Railpro does not take into account the different demands steams they face, there is no differentiated service for the different demand streams or any priority rules. Inventory control at Railpro (Section 3.1). When service levels are differentiated, pooling these demand streams together can save inventory costs of between 25% and 20% for the single-item case and multi-item case respectively (Section 7.5).

Overall we can conclude that we have developed a model that gives clear insights into the saving potentials for the rail infrastructure industry. And these potentials are worth to further investigate how these insights can be used in practice.

**The main recommendations are:**
The developed inventory control models are useful to evaluate given base stock levels for example to investigate the feasibility of predetermined stock levels when a new location is added to the VOL-concept.

The output of the models is based on the available information. The more reliable this information is the more reliable the output of the control models will be. The data about the demand rates can highly influence the results. An administration of failure demand or installed base management can increase this reliability, also returns are important when determining demand rates. Furthermore, it could be useful to think about the registration of different order
for inventory control purposes. Registration of the demand stream, contract region, stock point etc. can likely increase the performance.

For the multi-item models we made the assumption that all items have the same criticality. However, as discussed in Section 5.2.2 there are some items that are strategic to the contractors. We recommend analyzing the different criticalities of the products, this should be done in cooperation with the contractors (and ProRail). If there are some products with higher criticality we recommend first determining the base stock levels for these items, and letting the model start with these values. If there is a broader classification in two or three classes, then it might be useful to extend the model as we will describe later.

The models we developed for coordinating the supply chain show remarkable cost savings between the different alternative control mechanisms. And combined optimization of the different demand streams shows a large savings potential compared to the isolated optimization. It is therefore recommended to investigate if isolating the demand stream of replenishment to the VOL-locations will cause a higher increase in costs than the savings of the coordinated control for the replenishment demand. Or the model can be extended mended to use a combined (all demand streams) optimization approach. A threshold-based rationing rule should be implemented at the central location, this rule stops fulfilling demand for some stream(s) if the on hand stock drops below a certain level. This threshold-based rationing rule should also be implemented if it is decided to not use a coordinated control of supply chain.

In the system we analyzed there are multiple parties. The contractors determine (in cooperation with Railpro) the stock levels for the local warehouses and Railpro determines the central stock. If it is decided to use the kind of models we use in Alternative 3, all inventories need to be determined together. Therefore, to implement a coordinative model there should be some kind of agreement on who is determining the stock levels, and who has to pay for the inventory.

Further research:
More research is needed on efficient base stock levels as a starting point for the greedy approach. The influence of different starting points on the optimality of the results could be investigated. It is also relevant to do research on the comparison of Alternative 2 with the other two alternatives. A method to overcome the problem of insufficient local stock is proposed, but there might be other options to create a fair comparison. Furthermore the development of an efficient method to execute the greedy procedure can save lots of calculation time.
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VIII
1. Introduction
This report represents the result of my Master Thesis project on spare parts inventory control at voestalpine Railpro. Railpro is an independent service provider mainly serving the Dutch railway market. Carrying the right assortment and holding sufficient inventory to attain a high availability of products is an important business strategy for the company. In the last year they extended their service portfolio by taking over and managing the inventories of customers. This raises the question whether there are better approaches of managing inventories.

An integrated model has been developed to investigate cost savings and service performance in different situations of available information and coordination. This report describes the environment, the different models and their results.

This report consists of eight chapters. Chapter 2 contains a description of the industry to have some background knowledge. In Chapter 3 the company and internal processes are described. Next, we describe the research design in Chapter 4. In Chapter 5 we will propose multiple inventory control models. The optimization procedures are explained in Chapter 6. In Chapter 7 the different alternatives are evaluated. In Chapter 8 the overall conclusions and recommendations are presented.
2. Dutch Railway Industry

The railway industry can roughly be described by the infrastructure of track and stations, and the utilization of the infrastructure by running trains.

The first Dutch railway was a 16 kilometer long track between Amsterdam and Haarlem, built and opened in 1839. In the years from then the network is expanded and mostly electrified to a total of 2,886 kilometers of which 1,982 kilometers are double track (or more) and 2,159 kilometer is electrified. Total track length is 7,033 kilometers. It is the third most extensive used network after Japan and Switzerland according to Prorail(2012).

In 1938 the Dutch Railways (Nederlandse Spoorwegen) was founded when the two largest Dutch railway companies at that moment formally merged. The Dutch Railways where responsible for the total exploitation of driving trains in The Netherlands, construction, maintenance, and operating the track and stations, and also driving trains. Part of their activities was also the supply and holding of railway products.

From 1995 to 2003 there were some major reforms resulting in different organizations each responsible for part of the activities which were formerly executed within the Dutch Railways. The Dutch Railways are now only responsible for running (most of) the trains, there are many other transportation companies for both passengers and freight. ProRail is owner of the infrastructure and responsible for the availability of the infrastructure. Both the Dutch Railways and ProRail are still completely state owned, but the Dutch Railways operate independent from the government. Different construction companies construct new track and maintain the existing network. Railpro is the continuation of the former Dutch Railways department of infrastructure product supply. Constructors and Railpro are private companies. Some key figures are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Key figures of the Dutch rail infrastructure</th>
</tr>
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<tbody>
<tr>
<td>±€2,000,000,000</td>
</tr>
<tr>
<td>7,195</td>
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<tr>
<td>2,731</td>
</tr>
<tr>
<td>404</td>
</tr>
<tr>
<td>27</td>
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<td>8</td>
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<tr>
<td>19</td>
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<tr>
<td>6</td>
</tr>
</tbody>
</table>

3
In the remainder of this Chapter we will describe the supply chain in Section 2.1. In Section 2.2 the control of the supply chain is described. Section 2.3 is about the main contracts and agreements. Section 2.4 is about the inventory control within the rail infrastructure industry.

2.1. Supply chain
This section is about the main processes and stakeholders concerned with product supply within the railway infrastructure. The main processes regarding product supply are represented in Figure 1. Reuse and recycling of products is actually executed, however this is not presented in this picture. One process can be executed by more than one party, and one party can be involved in more than one process. This will become clearer in the next Section.

![Figure 1: Main processes in product supply](image)

From the investigation of the supply chain it follows that there are three processes and corresponding flows of new products, *(re-)*Construction, Maintenance and Failure repair.

*(re-)*Construction is the building of railway track. This is planned a long time ahead, but this planning is not completely fixed.

Maintenance can be seen as preventive maintenance. Out of order of the railway track is planned one year ahead by the infrastructure manager. The contractor of that section is free to choose when to execute different maintenance activities.

Failure repair is corrective maintenance is case of an acute failure. These failures need to be (temporarily) repaired within a given time window. If the repair is temporarily at a later point in time maintenance is executed. Failures occur 'unexpected'; therefore demand is not planned at all.
2.2. Process control
This Section deals with the control of the processes that are present in the supply chain that we described in Section 2.1. A short description of all involved parties in the processes are given and per process the roles of the involved parties are described and the way they manage the process.

2.2.1. Parties operating in the Dutch railway industry
- **Engineering offices**: Organizations that are specialized in advising, managing, and execution of technical projects.
- **Suppliers**
  - *Original Equipment Manufacturers* (OEM's): Design and build single products
  - *System houses*: Deliver complete systems, consisting of several products. It could be that they only combine products. But it could also be that they design and build the products themselves.
- **Wholesalers**: Companies that buys the goods from the suppliers and sell them to the construction companies.
- **Construction companies/contractors**: These companies are responsible for (re)construction of the track, maintenance and failure repair.
- **Infrastructure manager (ProRail)**: The Dutch government has given ProRail the responsible for the complete heavy railway system in the Netherlands, except for two special sections (the Betuwe route *Freight* and High Speed Line (HSL)).

2.2.2. Processes
Below we give a description of the most important processes concerning product supply. Because this research is in cooperation with Railpro, their role is given extra attention.

*Product development*
Within the railway industry, product development is teamwork between different parties in the industry. The need of a new product can be observed by all parties. Most of the time in the process of developing and designing a new product several parties are involved. At Railpro it could be that a need is perceived for which no product exists in The Netherlands. Then a product manager can search for products used for other purposes that also fit to this problem or products that already are operational in foreign countries.

*Production*
This is mainly performed by OEM’s and system houses. Railpro also executes some small assembly operations.

*Supply*
It depends on the product and the product flow (Construction/Maintenance/Failure repair) if supply is direct from OEM/System house to constructors, or if there are wholesalers in between. Wholesalers normally can supply with higher service (shorter lead-times) but this most of the

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2 A complete list of abbreviations can be found in Appendix A
time comes with a higher price. Railpro is present in this process both as a wholesaler and, system house.

**Construction**
The design for new construction activities is made by the infrastructure manager, an engineering office or the construction company, or a combination of these parties. Construction of railway track is executed by construction companies which are managed directly by the infrastructure manager or an engineering office will manage the project on behalf of the infrastructure manager.

**Maintenance**
Constructors execute track maintenance. There are two types of contracts which will be discussed in Section 2.3.2. For these activities constructors hold inventory and order many products at suppliers/wholesalers who are holding inventory for these activities.

**Failure repair**
Within a given time window the constructor must solve the failure. Because of this time window, holding inventory is very important in managing this process. If a needed part is not available in case of a failure, trains cannot use that part of the track which has enormous impacts in terms of lost revenues as shown in Harris and Ramsey(1994).

**Reuse/recycling**
Within the railway industry several products are reused or recycled. Sometimes it is reused by the constructor, but it is also possible that some recycling or revision steps are needed. Therefore, it can be sent to the supplier/wholesaler.

**Infrastructure management**
The infrastructure manager (ProRail) has the following management objectives. Safety, Reliability, Punctuality, Sustainability, and low costs according to ProRail(2012). They divide, as an independent party, the transporter space on the track, and regulate the railway traffic, and they manage the construction, maintenance and safety of the rail network. In practice this means they decide when and how track construction and maintenance activities can/should be executed (the level of detail depends on the type of maintenance contract). Because ProRail need to secure the safety, reliability, punctuality, and sustainability as said earlier they try to secure the products used in the railway infrastructure. They approve new products and prescribe for some products how supply should be performed. For the supply, products are classified according to their financial risk and supply risk, an overview is given in Figure 2.
2.3. Contracts/agreements

Between the different parties described in Section 2.2.1 many different contracts are in place. Because these influence the interaction between different players involved in product supply, in this section the main characteristics of these contracts are described. The most common contracts and agreements are shown in Figure 3.

Exclusive supply rights (BEA) are covering the whole supply chain. Because of historical reasons (state owned Dutch Railways) and safety issues, ProRail give some companies the exclusive right to produce some products. All constructors are forced to purchase these products from the
assigned supplier(s). In Figure 2 (Section 2.2.2) an overview concerning different product regulations is presented.

2.3.1. Construction(ProRail-constructors)

Between ProRail and the constructors there are many different contract options, which will be discussed below. Due to these different contracts the roles (also for the engineering office) are different.

‘Bouwsteenbestek’

In this type of contracts the client (ProRail) specifies the requirements of the order(construction) in great detail. The client and supplier agree on a fixed price for the total project. If the client wants extra work that is not specified in the order, an additional price should be paid.

Design and Construct

In these types of contracts the order of the client is not in great detail but nearly all requirements are set. The supplier is responsible for designing a solution that met these requirements and after the approval of the client the supplier is also responsible for construction of his own design.

Design, Build, Finance, Maintain, and Operate

These contracts are an extension of the previous one where the constructor might also be responsible for the financing of the project, and also the maintenance and operation for a long period(20-30 years). The client can pay a price consisting of fixed and variable parts.

Best Value Procurement

This approach has the goal to have the most value for the lowest price. The contract can take different scopes as in the DBFMO contracts. The difference is however, that constructors get the chance to differentiate themselves on their core competences and innovativeness. The client only write down the most important requirements, the rest of the design is free for the supplier to make.

2.3.2. Maintenance(ProRail-constructors)

In the past Output Process Contracts (OPC) were the common contracts in railway maintenance and they are still in place. Since 2007, ProRail use Performance Based Contracts (PGO) that is now used for all tenders.

Output Process Contracts(OPC)

Different maintenance regions were "divided" between different contractors. Contractors can send an invoice for all cost they make. ProRail decides when certain maintenance activities should be executed. A picture of the OPC situation with only three contractors is in Figure 4.
Performance Based Contracts (PGO)
PGO contracts are introduced by the rail infrastructure manager to reduce maintenance costs. The main difference with the OPC's is the freedom of the contractor how to execute maintenance and to guarantee the agreed quality and safety levels. The tender is on total price for a period of 5 years. The contractor gets a penalty or premium for the state of track, performance etc. at the end of the contract period. The distribution of contract regions when for some regions the PGO contracts where applied is shown in Figure 5. PGO contracts are maintenance contracts which are relevant for this research. Because of these contracts Railpro has developed the concept of Inventory At Location (VOL) which is discussed in more detail in Section 3.2.

Product supply
The next four contracts are about the product supply and are made up between Railpro, ProRail and the contractors.

ProRail-stock (Railpro-ProRail)
There are some really essential parts, for instance unique parts installed at essential places. (*Disruptions due to unavailability will have enormous impacts in terms of lost revenues and poor service*). However, the demands of these parts are really low and unpredictable so that Railpro decided that they don't want to take the costs and risk for holding these products. Therefore ProRail themselves stock these products. The stock is located in Hilversum and controlled and handled by Railpro, who gets a fee for this. The fee is determined by open book calculation, and consist of many different parts. ProRail pays for, storage, insurance, examination, provision, extradition etc. Railpro also evaluates the inventory, so evaluate the current stock levels with historical demand, and give advice to ProRail to increase or reduce the stock levels.

Rail stock (Railpro-ProRail-Contractors)
ProRail pays a fee to Railpro, for Railpro holding specific products on stock that are actually unprofitable for Railpro. This is because of the low demand, but the high importance. ProRail wants this stock to be there, so failure mechanics can solve problems quickly. This is also the difference between ProRail stock and Rail stock. Rail stock is free available for constructors, they can order directly at Railpro. ProRail stock can only be employed by ProRail. For the Rail stock the fee is determined the same as with the ProRail stock, but there are additional fees because this stock is owned by Railpro.

VOL (Railpro-constructors)
Constructors pay Railpro for holding inventory at location of the constructor. More about this concept is described in Section 3.2.

Framework agreements
These are agreements in on price, quantity, quality, and delivery time.
2.4. Inventory control

Within the rail supply chain there are three levels where inventory is held, see Figure 6. First, the suppliers/producers hold inventory. Second, wholesalers (including Railpro) are holding inventory. And thirdly, contractors are holding inventory. Also ProRail has some inventory (ProRail stock) however, this is not indicated apart because this is a minor part, and it is stocked at a wholesaler and used by constructors. Until recently there was no integration or coordination between the three different levels.

![Figure 6: Levels of holding inventory](image)

Since February 2013 there is some integration within the supply chain by the introduction of the VOL-concept. The current situation is represented in Figure 7, Railpro has taken over some stock points of constructors, and control/stock some parts for ProRail.

![Figure 7: Representation of stock points within the supply chain](image)
3. **Voestalpine Railpro**

Within the Dutch railway industry Railpro is an independent service provider mainly serving the domestic market (less than 2% of turnover is achieved abroad).

**Mission:**
- *Striving for innovative power in the broadest sense.*
- *Railpro always provides superior solutions in the fields of rail-related products, logistical services, solutions and projects.*

Railpro has its origin in 1995 when the Dutch Railway sector became private. Departments that were engaged in purchasing, selling, and storage of infrastructure materials were put together as the company Railpro. Since 2002, 70% of Railpro is a subsidiary of the Austrian steel group voestalpine. The other 30% is owned by three Dutch railway constructors, namely Volker Rail, Strukton and BAM Rail. Railpro is active in the business-to-business market and delivers their services to constructors in the rail infrastructure market. In 2005 Railpro has changed their strategy due to market developments. They changed from the status of a material supplier to a focus on an integrated package of products, logistics, and services which they call the SLS concept.

<table>
<thead>
<tr>
<th>Supply</th>
<th>Logistics</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery and supply of thousands of rail-related products 24/7</td>
<td>Road, water and rail transport, wagon rental, and transportation planning</td>
<td>Innovative co-partner and product engineering</td>
</tr>
<tr>
<td></td>
<td>Forward stocking and warehouse management</td>
<td>Forward stocking</td>
</tr>
<tr>
<td></td>
<td>Logistics project advice</td>
<td>Tracking &amp; tracing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Pre-)assembly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse logistics</td>
</tr>
</tbody>
</table>

- **Supply:** Railpro delivers over 16,000 different products, of which half of them directly from stock. All products that Railpro has in stock are allowed to be used in the Dutch rail infrastructure. The product portfolio can be distinguished in two parts, BBM (BovenBouw Materialen) and ETM (Elektro Technische Materialen). BBM consist of all products for the rail track construction. ETM consist of signals, switch drives, and power supply.
- **Logistics:** Railpro also delivers logistic services. This could be by use of road transport, barge, and railway, to deliver materials to the customers construction site or warehouse. Railpro also owns 1,700 wagons which can be rented by customers.
- **Services:** These are additional services: return logistics, project management, and stock control for constructors and ProRail.

In 2009 Railpro took over René Prinsen Spoorwegmaterialen, a supplier of materials for rail track construction. Some financial figures for the last years are presented in Table 2. It can be observed that in the last two years the inventory is relatively high to the sales revenues for these years.
Table 2: Key financial figures (in millions)

<table>
<thead>
<tr>
<th>Year</th>
<th>Sales revenues</th>
<th>Net income</th>
<th>Inventory*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>€94.0</td>
<td>€2.4</td>
<td>€21.1</td>
</tr>
<tr>
<td>2011</td>
<td>€98.8</td>
<td>€4.0</td>
<td>€24.3</td>
</tr>
<tr>
<td>2010</td>
<td>€114.1</td>
<td>€5.8</td>
<td>€26.2</td>
</tr>
<tr>
<td>2009</td>
<td>€95.8</td>
<td>€6.2</td>
<td>€19.4</td>
</tr>
<tr>
<td>2008</td>
<td>€103.5</td>
<td>€4.4</td>
<td>€22.4</td>
</tr>
</tbody>
</table>

*Inventories comprises raw materials, finished goods, merchandise as well as services rendered, not yet chargeable. Inventories stated at the lower of cost or net realizable value. Cost are determined by the moving average price method. For the valuation of finished goods the moving average price has been used. Where appropriate a provision for obsolescence has been recorded* from Railpro annual report (2012)

Voestalpine

Railpro is part of the Austrian steel group Voestalpine AG. Voestalpine is active in steel, automotive, railway systems, profilform and tool steel industries. The Voestalpine group is structured in four divisions Steel, Special Steel, Metal Engineering and Metal Forming. Railpro is part of the Metal Engineering Division, which consist of six business units for Steel, Rail Technology, Wire, Seamless Tube, Turnout Technology and Welding Technology.

Organizational structure

Within Railpro there are two departments that are dealing with inventory holding, these are Marketing & Innovations (M&I) and the operations department (Operatie). M&I is responsible for the development of new concepts concerning inventory control and logistics. The operations department is responsible for the execution of these concepts in the operational phase. This project is executed at the Marketing & Innovations department (M&I), see Appendix B.

3.1. Inventory control at Railpro

In this Chapter we will investigate the current situation of inventory control at Railpro, with special interest in the VOL-concept. Therefore, we start with the description of the different demand streams at Railpro. Then, we will give a description of the distinguished product assortments within Railpro. Thereafter, we describe the inventory control of the VOL-concept in greater detail.

3.1.1. Different demand streams (and returns)

The central warehouse of Railpro faces four different streams of demand in Hilversum and a stream of returns. These are created by the corresponding processes described in Section 2.2.2. The streams are displayed in Figure 8 and thereafter explained in more detail. It is plausible that these different demand streams interact with each other and that there are possibilities for savings when controlling all these demands together. However, due to the interaction and the special interest in the replenishment demand, we will 'isolate' the VOL-replenishments from the other demand streams. Later on we will try to extend the analysis by adding the two streams of Failure repair and Work package. In the remainder of this Section we will describe the different demand streams in more detail.
Work packages
A work package is composed of a number of parts and used in planned maintenance. Only a few parts of the package are used and the rest is returned from the construction site. A work package is a special case of a normal customer order, because the whole order needs to be delivered in full, a customer can order less than the base unit of measure, and they pay a fixed price for handling and shipment per package, these costs are not charged in the total price of the order but paid at the end of the month for all packages together.

Project demand
This demand stream consists of products that are requested for a specific project. Projects are most of the time large re-construction activities, which are usually completely planned. However, sometimes the planning horizon is short and therefore items are extracted from the safety stock. Items are reserved at most three months before the planned delivery date. The project demands are partly taken into account when determining safety stocks.

Failure repair
Contractors are responsible for the safety and availability of the railway track. When a failure occurs they need the right material (tools & spare parts) to repair the failed part. To have spare parts available they have some parts in their service vans, their stock points. However, it is not unusual that they don’t have the right parts and therefore request them at the central location of Railpro in Hilversum. These demands are hard to forecast because the demand is caused by a failure in the infrastructure.

VOL replenishments
At the VOL-locations, customer mechanics demand products from stock. These withdrawals are resupplied by replenishments from the central location in Hilversum. As with the normal failure repair demand, this demand stream is hard to forecast. The control of this demand stream is described in detail in Section 3.2.

Although it isn't a demand stream, we will deal with the Returns as well. At Railpro there is a considerable return flow. This flow consists of products that are leftover from large orders or work packages, or products that need to be revised. The revision flow consists of products that are taken out of the rail track. Sometimes because the whole route/system is substituted, and
sometimes the part is preventively replaced. These returns are important because they need to be considered when determining demand rates and controlling inventories.

3.1.2. Assortments
Products that Railpro sell (and stock) can be divided into different assortments. We will shortly describe the assortments, and their specific control. In total currently there are 8,000 SKU’s stocked.

Trading (±1900 SKU’s)
Products with a ‘regular’ demand (high availability) fit into this category. This assortment is kept on stock to deliver according to an aggregate fill rate (Percentage of order lines that is delivered within the requested time) of 96% over the total Trade assortment. To reach the target fill rate with ‘minimal’ costs, products with high demands and low cost prices get a high service level and vice versa. Products are categorized and service levels are assigned to the category, these levels range from 85% to 99%. The corresponding stock levels are determined with the software package SLIM4. The package uses desired service levels, planned supplier lead-times and historical demand data (24 months) to calculate the desired stock levels. For this the package uses eight different categories (Normal, lumpy, slow etc.). For each category it is determined how they forecast the demand and which demand distribution is used. The optimal reorder quantities are determined by the purchaser based on the Economic Order Quantity (EOQ) advice given by SLIM4. To determine these, ordering costs are estimated at €80 and holding costs of 25% are used.

Core (±1300 SKU’s)
These are products in the end of their lifecycle (low availability). There is no set safety stock for these items. However, some of these products were first in the Trade assortment or leftovers from a project and therefore still on stock. The goal is to deliver this assortment within the lead-time that Railpro suggests to the customer. For Core items the performance is measured in the order lines that are fulfilled within the delivery time specified by Railpro. This performance should be above 95%.

Others (±14000 SKU’s)
Information is not up-to-date (price, lead-time etc.), but products can be ordered at Railpro.

Strategic (±150 SKU’s)
These products are essential for the strategy of the company although given their demand and cost price they are not in the Trading assortment. These are stocked in Hilversum and are controlled with a high service level (safety stock).

Two other kinds of assortments are the ProRail-stock and Rail-stock, which are especially for the contracts as we described them in Section 2.3.2. These assortments consist of items from all four assortments we have described above.

3.2. VOL-Concept
As described in Section 2.3.2 ProRail makes use of performance based contracts of 5 years length. When a region changes from one constructor to the other, the old constructor has an
inventory that is (partly) worthless to him. Therefore, customers want to get rid of their inventories, to prevent this for the future. For Railpro these inventories are not such a problem because they can sell the products to another contractor or hopefully hold the inventory for the new contractor.

3.2.1. Supply chain
The VOL supply chain consists of two levels/echelons of inventory holding. The highest level is the central location in Hilversum, the second level are the VOL-locations (See also Figure 7).

Within the collection of VOL-locations there are two types, at some locations there is a Railpro employee present during working hours. Other locations are only visited weekly for inventory inspection and clean up. There are two types of products in the VOL-locations (Bulk and Failure), all items are part of the Trading assortment described in Section 3.1.2. The first type are most of the time cheap items, they are stored in a two-bin system. Failure parts are the more expensive ones that are stored in small quantities and replenished one-for-one. The goal of this research is the inventory control of spare parts, therefore we limit ourselves to the Failures items, which are about 60% of the SKU’s stored in the VOL-locations and they account for more than 80% to the inventory investment at the VOL-locations. The central inventory investment for the products that are part of the VOL-assortments is about 2/3 and 1/3 for respectively Failure and Bulk.

3.2.2. Inventory Control
The customer in cooperation with Railpro determines inventory levels at VOL-locations. At the moment mostly based on the wishes of the customer. For the future the customer expects a major role of advice from Railpro. The central inventory is determined as described in Section 3.1.2. The Bulk inventory is reviewed every week; if the first bin is empty it is send to the central warehouse to be re-filled. Each bin contains half of the agreed inventory level. When failure parts are taken from stock, the clerk or a mechanic scans them. At that moment automatically a replenishment order is created by the ERP system. Normal replenishments are delivered twice a week on Tuesday and Thursday. When determining the central stock, there is no special consideration of the demand at the VOL-locations and the target service levels. Demand at the VOL-locations is together with the other demand aggregated to determine central stocks in the way we described in Section 3.1

3.2.3. Contracts/Performance measures
Within the contracts that are made up between Railpro and the construction company the assortments, predetermined base stock levels and different performance measures are in place. The assortments and stock levels are determined in negotiation between Railpro and the customer. The customers pay a fixed holding percentage that is charged over the total selling price of the inventory. For the Bulk items the monthly performance measure is 1-(number of out of stocks/Total number of SKU's in the Bulk assortment). This means that if there are 100 Bulk SKU’s stocked and five times there is not sufficient inventory to fulfill the demand, the performance is 95%. For Failure items an aggregated fill rate measure is applied, which is direct service from the shelf. This means that if there are in a given time period (month) 100 order lines and five times there is not sufficient stock, the performance is 95%. Railpro has to replenish the VOL-locations in such a way that the aggregate fill rate measure is attained.
4. Research design

In this Chapter we first propose the research assignment in Section 4.1. This will be the basis for the conceptual model that is described in Section 4.2.

4.1. Research assignment

Since 2008 the Dutch rail infrastructure manager (ProRail) have introduced Performance Based Contracts (named PGO contracts). The main difference with the old contracts is the freedom of the contractor how to execute maintenance and to guarantee the agreed quality and safety levels. The contracts have a length of five years, when a region after the five years changes from one constructor to the other, the contractor has an inventory that is (partly) worthless to him. Therefore customers want to get rid of their inventories, to prevent them from having a worthless inventory. This phenomenon and the trend that contractors want to focus on their maintenance and prevention of failures results in a question for Vendor Managed Inventory (VMI) from the market. Railpro therefore, has developed the concept off taking over the inventory of the contractor and hold it at the location of the customer, this concept is called VOL which is the Dutch abbreviation for inventory at location. The current VOL-concept started in February 2013 with the first adoption of a customer location. Before that moment there was a comparable VOL-concept with some major differences. At the moment eight former customer inventories owned by Railpro, and it is expected more locations will be adopted in the future.

At the moment there is no coordination between VOL-locations and the central location in Hilversum. Constructors decide in negotiation with Railpro on the stock levels at VOL-locations. Railpro only manage the stock in Hilversum, without special consideration of the stock levels at VOL-locations (uncoordinated situation). Due to the adoption of the VOL-locations Railpro has new information available about the stock levels of the customers and its demand. To guarantee a certain service at the VOL-locations Railpro have to use this information (semi-coordination). When Railpro (in the future) has ‘full’ control over the VOL-inventories they can coordinate the whole system of central warehouse and VOL-locations (coordination). The question is whether (semi-)coordination can decrease the investments in inventories while maintaining the desired service or vice versa. This results in the following research question.

| What is the most suitable inventory model to supply spare parts in a (semi-)coordinated way, and what is the improvement potential in terms of cost savings and performance? |

To answer the above question the following sub-question has been formulated:

1. What is a useful classification of parts with respect to inventory control?
2. What is the current structure and control of stock points?
3. What are relevant Key Performance Indicators (KPI’s) of the VOL-locations?
4. Which inventory model is most suitable in an uncoordinated situation?
5. Which inventory model is most suitable in a semi-coordinated situation?
6. Which inventory model is most suitable in a coordinated situation?
7. What are the improvement potentials compared to the ‘current’ situation?

The first sub-question has been answered in Section 3.2, where we described the assortments within the VOL-concept. Sub-question 2 has been answered in Section 2.4 and 3.1. The KPI’s of sub-question 4 are treated in Section 5.2.1. Sub-questions 4-6 are dealt with in Chapter 5 and 6. In Chapters 7 we discuss sub-question 7.
4.2. Conceptual model
To answer the research question we have three different alternative situations, those results from sub-questions 4-6. We want to compare different situations to investigate what the impact of sharing information and coordinated inventory control is.

4.2.1. Alternative situations
First, we have a situation in which the information from the VOL-locations is not available/completely neglected. In the second situation we will use all information, however, only to control the central stock. The last situation is a situation in which all information is used to control both central and local stock points. This results in three different alternatives which are displayed in Figure 9 to Figure 11, which we now will explain in more detail. The pictures consist of two levels (echelons). The upper element is the central location of Railpro in Hilversum. The lower element(s) are the VOL-locations. Dotted lines are information about the demand, with \( D_j' \) the demand of location \( j \) that is faced by the central location. \( D_i \) is the demand faced by VOL-location \( i \). Solid lines are product streams with \( F_j \) the service constraint for that stream. The X's within the red ellipses indicate that the stock levels at that location are in the scope of control and we can optimize them. \( S_i \) means that they are predetermined and we cannot vary them.

![Figure 9: Alternative 1 (SI/MI)](image)

![Figure 10: Alternative 2 (SI/MI)](image)

![Figure 11: Alternative 3 (SI/MI)](image)
Spare parts inventories are characterized by items that are expensive and have low demand rates. In ‘normal’ inventories each item needs to be available with a given service level. In spare parts supply, most of the time the purpose is to have certain system availability. Within a machine, a cheap part could be even critical as an expensive part, therefore holding more of the cheap part and less of the expensive part will have the same performance with a lower investment. Criticality is related to the consequences caused by the failure of a part. When using multi-item spare parts inventory models compared with single-item models, in a single-location setting. Thonemann et al. (2002) show that costs savings of about 10% to 20% are possible. This is especially the case when there are large differences in costs between the different SKU’s. However, multi-item inventory models are more complicated than single-item models. Therefore, both types of models will get attention in the remainder of this report. Because we have both a single- and multi-item approach for each alternative, we end up with six different alternatives, See Table 3.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative1 (Single- Item)</td>
<td>1SI</td>
</tr>
<tr>
<td>Alternative1 (Multi- Item)</td>
<td>1MI</td>
</tr>
<tr>
<td>Alternative2 (Single- Item)</td>
<td>2SI</td>
</tr>
<tr>
<td>Alternative2 (Multi – Item)</td>
<td>2MI</td>
</tr>
<tr>
<td>Alternative3 (Single- Item)</td>
<td>3SI</td>
</tr>
<tr>
<td>Alternative3 (Multi – Item)</td>
<td>3MI</td>
</tr>
</tbody>
</table>

In Chapters 5 and 6 we will describe a mathematical model for each of the alternatives. Because, alternatives one and two are simplifications of alternative three, our description will focus on alternative 3, our main-model. When dealing with the other alternatives we will describe the adaptions to the main-model.
5. Inventory control system models
As we mentioned in Section 3.2 due to the adoption of the VOL-concept, Railpro has access to more information than before the introduction of the VOL-concept. Therefore we proposed our conceptual model in Section 4. In this Chapter we will propose a mathematical model for the situation and appropriate for the conceptual model. In Section 5.1 we will discuss some relevant literature. In Section 5.2 the selected model is described. The evaluation procedure is described in Section 5.3.

5.1. Literature
This Section briefly describes some literature related to the spare parts provisioning in the rail infrastructure industry. A preparative literature study for this research has been conducted by Van Oostrum (2013). The most relevant models are discussed below.

Wong et al. (2007) have proposed solution procedures for determining close-to-optimal stocking policies in a multi-item, two-echelon divergent system. The system consists of one central warehouse and several local warehouses. With each local warehouse having a target aggregate mean waiting time, while minimizing the overall inventory costs. Both the central and local warehouses are controlled by a (S-1, S) policy under continuous review. They propose several solution procedures of which they show the greedy procedure is relatively easy to use and give near-optimal results. The greedy procedure uses the decrease in the waiting time and the increase in costs. When the size of the problem increases (locations/products) the performance increases. In addition they propose a local search method that can be used to improve the solution that results from the greedy approach. They also show it is possible to use Graves (1985) approximate evaluation within the greedy procedure.

The approximation proposed by Graves (1985) is a method to determine the first two-moments on the steady-state distribution of ‘failed’ items. The term failed items is from a system with parts repair at the central location. However, it is also applicable in case of consumable parts as showed in Feeney and Sherbrooke (1966), in this case a new item is procured instead of repaired. Instead of calculating a convolution of the two different distributions of demand and ‘repair’ (supply), Graves proposes a method to fit a Negative Binomial Distribution (NBD) on the first two moments of the steady-state distribution of failed items per local warehouse. However, when mean and variance of the distribution are nearly equal the NBD does not perform well.

In Sluis (2006) the model of Wong et al. is applied to a practical situation that has many similarities with our situation. Sluis (2006) adapted the model of Wong et al. (2007) in several ways. An aggregate target fill rate measure is used instead of a waiting time constraint. System costs are based on a percentage on the cost price of a product instead of a fixed price per unit. Furthermore an approximation is used within the greedy procedure. Instead of calculating the decrease in distance to the target fill rate, the increase of the aggregate fill rate is used. This approximation results in bigger exceeding of the target fill rate, and higher inventory costs. For the determination of the expected level of outstanding orders at the local warehouses several combinations of distributions are used for a two-moment approximation.
5.2. Model description

In this Section we describe the model that we will use. The goal of the model is to minimize the system holding costs while the aggregate target fill rate is met for each local warehouse. A two-moment approximation is used to reduce the calculation time needed. To determine the base stock levels with the minimal holding costs we use a greedy procedure that is described in Section 6.1.2. This greedy procedure is except from the initial starting solution the same as proposed by Wong et al. (2007). The measurement of the system costs and aggregate fill rates is explained in Section 5.2.1, these are the same as in Sluis (2006). Sluis (2006) has also used a greedy procedure however he used an approximate method. To reduce the calculation time, the two-moment approximation by use of a Negative Binomial Distribution proposed by Graves (1985) is used to determine the expected level of outstanding orders at the local warehouses. This approximation is explained in Section 5.3.2. In Section 5.3 we will explain the evaluation procedure which is an exact procedure except for the two-moment approximation we mentioned earlier.

Our model, as we know, is never used before. Therefore, we have no references on the exact performance of the optimization model, however the evaluation procedure is reliable. The outcomes are almost exact, however we do not know how far they are from optimal. We expect useful results because there are only minor differences with the model developed by Sluis (2006).

Because of the different optimization alternatives in this research we also have different problem formulations. Each of the six different models has different constraints on the freedom of varying different parameters. Therefore the formal problem formulation for each alternative will be given in the next Chapter when dealing with the optimization procedure.

The set of local stock points is denoted as $J$ and the central stock point had index 0. The complete set of locations is denoted as $J^0$. $I$ denotes the set of SKU’s. We assume that the demand for each SKU $i \in I$ at location $j \in J$ follows a Poisson process with a constant rate $\lambda_{ij}$. A base stock policy is used to control the inventories at all warehouses, and $S_{ij}$ denotes the base stock level for SKU $i \in I$ at location $j \in J^0$. $S$ is a vector with all base stock levels for item $i$. $S$ is a matrix with all base stock levels for all SKU $i \in I$ and all locations $j \in J^0$. Once demand occurs at a local stock point it is satisfied immediately if there is stock on hand. A one-for-one replenishment policy is applied: if demand is satisfied, immediately a new spare part is requested from the central warehouse. And the warehouse immediately requests an item from the outside supplier. The order and ship time for component $i$ from the central location is denoted $L_{ij}$ and for the time between the outside supplier and the central location is denoted $L_{i0}$. These lead-times are assumed to be deterministic. Further, we assume that backordered demands for each SKU $i \in I$ at each location $j \in J$ are treated First Come First Served. A holding costs percentage $h_{ij}$ of the cost price is counted per time unit for each unit of spare part $i \in I$ that on average will to be at location $j \in J$.

For each local stock point a certain service level for the availability of spare parts can be requested. This service level is discussed in Section 5.2.1. We denote $F_j$ as the target aggregate fraction of demand of SKU $i \in I$ at local stock point $j \in J$ that is delivered immediately upon
request. The notation of all other parameters is given in the remainder of this report, when we describe the equations they are used in. An overview is given in Appendix C.

5.2.1. Performance measures
This Section describes the two performance measures that we use to evaluate the system performance. These are the total system cost and an aggregate fill rate measure.

System costs
The objective is the sum of holding costs for each product and each location which is represented by Equation (1). In this equation, $h_{ij}$ represents the yearly holding cost percentage, and $P_i$ the cost price of unit $i$. The cost price is determined by the moving average price method (Voortschrijdend Gemiddelde Prijs/VGP). $I_i(S)$ is the distribution of stock on hand for item $i$ at location $j$, based on total base stock policy for the whole system $S$. $h_{ij}$ can both differ per location and per SKU. This value can both differ for SKU $i$ as location $j$, for the locations this is explained in Section 7.1.4. For the SKU's the percentage we will not use different values, however is enables the possibility to incorporate the risk obsolescence. The central inventory is only dependent on the central demand and central base stock levels ($S_0$)

$$C(S) = \sum_{i=1}^{l} h_{i0} * P_i * E[I_{i0}(S_0)] + \sum_{i=1}^{l} \sum_{j=1}^{j} h_{ij} * P_i * E[I_{ij}(S)]$$  \hspace{1cm} (1)$$

In this equation the first part are the holding cost at the central warehouse where the last part are the holding costs for the local warehouses. We do not include the in-transit holding costs because these will not differ between the alternatives we compare (because of the assumption of one-for-one replenishment). When determining the total expected holding costs the following term for the in transit holding cost can be added to equation(1). We will not include these costs in this report.

$$C^t(S) = \sum_{i=1}^{l} \sum_{j=1}^{j} h_{ij} * P_i * \lambda_{ij} * L_{ij}$$  \hspace{1cm} (2)$$

Aggregate fill rate
Contractors in the rail infrastructure industry are responsible for the availability of the infrastructure in their contract region. To prevent down time they store spare parts in their warehouses. When there is an urgent failure and they do not have the right spare parts available in time they are penalized. However, this is only the case when they use more time than they get free of charge in their contract. In discussions with one of the contractors, they propose a time based backorder cost per minute late. However, it is hard to determine when a backorder is resulting from an urgent item request, therefore we will not use this performance measure. We will use the definition from Kranenburg and Van Houtum (2013) which is also applied in the two-echelon, multi-item situation of Sluis (2006). The aggregate fill rate is defined as the fraction of the total demand that is fulfilled from stock, which is a weighted average of the individual item fill rates. This is a quantity/event oriented performance measure; the time before a backorder is fulfilled has no influence on the performance. As described in Section 3.2, at the moment the contracts between Railpro and the contractors are based on an aggregated fill rate for the Failure assortment. This fill rate is specified as the number of order lines that are available directly from the shelf. Though the Railpro fill rate is different from the one we will use, it is expected this has no big influence because of the small (we expect most of the time one) items per order line.
The item fill rate is calculated with equation (3). When there is a positive stock the demand can be fulfilled immediately and otherwise not. \( Z_{ij}(S_{io}) \) is the level of outstanding orders for item \( i \) at location \( j \), which is based on the central stock \( S_i \) for item \( i \).

\[
\beta_{ij}(S_i) = \sum_{x=0}^{s_{ij}-1} P(Z_{ij}(S_{io}) = x), \quad \text{for all } i \in I, \text{ and } j \in J
\]  

With \( \beta_{ij}(S_i) \) being the item fill rate, then the aggregate fill rate is given by equation (4), \( \lambda_{ij} \) being the demand rate for item \( i \) at location \( j \) and \( \lambda_i \) being the total demand for location \( j \).

\[
\beta_j(S) = \sum_{i=1}^{I} \frac{\lambda_{ij}}{\lambda_j} \beta_{ij}(S_i), \quad \text{for all } j \in J
\]  

Despite having different amounts of information as well as different options to control the supply chain, we will evaluate all alternatives with the same performance measures. To have a fair comparison between the different alternatives, we will evaluate them all in the same manner. For each alternative we measure the performance as the total system inventory costs and the aggregate performance \( F_j \) (even for alternative 1).

5.2.2. Assumptions

For the model that we propose, several assumptions are made. We now will discuss which assumptions are reasonable and which are questionable and could have a major impact on the results. For the latter one we will later execute sensitivity analyses on the results.

- **All items are equally important (multi-item models)**

Each backorder/fulfilled demand for an item is equally important. This is the case for the major part of the assortment. However, there are some products that have a high level of criticality (impact of consequences). Therefore, they should ‘always’ (with a higher availability percentage) be available to prevent the contractor getting a financial penalty from the infrastructure manager (ProRail). These products are like the products within the strategic assortment of Railpro (Section 3.1.2) and can be treated with special consideration. We will evaluate the possible impact of this assumption and propose some options how to deal with these items in the conclusions and recommendations in Chapter 8.

- **Demand at location \( i \) is described by a stationary Poisson distribution.**

A Poisson process is widely accepted in literature to describe the demand process for spare parts, because their demand rates are low and irregular. However, to test whether this is indeed the case, we conducted a Chi-Square goodness-of-fit test (see Appendix E). Due to the low demand rates we do not have enough data to test the demand process for each product at each location. Also for the largest locations still the observations per category were too small. We therefore tested the demand per item at the aggregated level. We can conclude that the Poisson distribution could not be rejected, and therefore is a reasonable representation of the number of demands per time period at the aggregate level.

- **The outside supplier has endless stock and a deterministic lead-time.**

If we look at the historical supplier lead-times we observe that lead-times for the same item and from the same supplier can vary significantly. This is partly because the underlying assumption of infinite supply at the outside supplier. For lead-times from central to local stock points the
lead-time is also variable because the supply is only two-times a week. The sensitivity of the lead-time will be tested in Section 7.4.3.

- A one-for-one replenishment policy is applied for all SKU-s at all warehouses
We assume that there is no batching of orders at the local as well as the central location. Items that are requested for failure repair are immediately requested from the central location which in turn requests an item from the outside supplier. For the local warehouses this is a common assumption according to Van Oostrum (2013), and in our situation this is the practical situation (Section 3.2.2). However, for the central location some form of batching may be desired. Reasons for this may be setup costs for production, minimum order quantities, or fixed ordering and delivery costs. We recommend a model extension for central batching in the recommendations in Section 8.2.2.

- Facilities operate 24 hours a day, 7 days a week with continuous review
For failure repair this is indeed the case. However, replenishments are only send two times a week on Tuesday and Thursday. Therefore, we will check in Section 7.4.3 whether the length of the replenishment lead-time will influence the results.

- Demands that cannot be fulfilled immediately are backordered and fulfilled first come first served (FCFS).
As we mentioned in Section 3.1.1 there are no clear priority rules for different demand streams or customers. Therefore, this assumption looks reasonable.

- There are no capacity constraints on storage or transport.
This is a reasonable assumption because there is space available if expansion of the inventory is required.

- There is no lateral supply in the distribution network
Local stock points are only supplied by the central location. In the normal operations transshipments are not allowed, however there are transshipments occasionally. This assumption is therefore conservative and can be the reason for a model extension that incorporates the possibility of transshipments.

- No fixed costs at any location
Fixed costs are not relevant for the decision on the base stock levels.

- Holding costs at all locations are linear.
The method of charging inventory holding costs is using a fixed percentage per SKU, per location on the inventory cost price. For the local stock points there is not agreed upon a percentage to charge on the inventory, as we will discuss in Section 7.1.4. We therefore test the sensitivity for this in Section 7.4.4.

- Ordering and handling costs are neglected.
For all products that are incorporated in this project the replenishment quantity is one. As described in Section 3.2. After each withdrawal of a Failure item immediately a replenishment order is created.
Some of the discussed assumptions are disputable. For these assumptions we will execute sensitivity analyses in Section 7.4.

5.3. Evaluation procedure
For our evaluation we need the total costs and the aggregate fill rate per location, as we determined in Section 5.2.1. For this evaluation we follow the method of Wong et al. (2007) including the two-moment approximation of Graves (1985) and the adapted service measures which are also used in Sluis (2006).

We first calculate the costs at the central location in Section 5.3.1. To determine the local performance measures we first need to determine the distribution for the number of outstanding orders. This is described in Section 5.3.2. by explaining the two-moment approximation. By use of this approximation we can determine the local inventory costs in Section 5.3.3 and the aggregate fill rates in Section 5.3.4.

5.3.1. Central costs
To determine the total system cost we first calculate the central holding costs with the following equation:

\[ C_0(S) = \sum_{i=1}^{l} h_{i0} \cdot P_i \cdot E[I_{i0}(S_i)] \]  (5)

The first two terms are the holding cost percentage and the cost price for an item. The third term is the expected average inventory level, which is determined with equations (6) and (7). With these equations we determine which part of the inventory used to fulfill demand and therefore which part is left over and kept on stock.

\[ E[I_{i0}(S_i)] = E(S_{i0} - D_{i0})^+, \quad \text{for all } i \in I \]  (6)

In this equation \( S_{i0} \) is the base stock level we evaluate and \( D_{i0} \) in the average lead-time demand that is Poisson distributed. \( Z^+ \) is the maximum of \( \{Z, 0\} \).

\[ E[I_{i0}(S_i)] = \sum_{x=0}^{S_{ij}} (S_{i0} - x) \cdot P(D_{i0} = x), \quad \text{for all } i \in I \]  (7)

For the central location we assume that the supplier has excess capacity. We therefore can use Palm’s theorem according to Palm (1938), to determine the expected pipeline stock. Define \( \lambda_{i0} = \sum_{j=1}^{l} \lambda_{ij} \), as the total demand for SKU \( i \) at the central location. Let \( D_{ib} \), \( i \in I, j \in J^0 \), denote the total demand during time interval \( L_{ib} \). Then \( D_{i0} \) is Poisson distributed with parameter \( \lambda_{i0}L_{i0} \).

\[ P(D_{i0} = x) = \frac{(\lambda_{i0}L_{i0})^x}{x!} e^{-\lambda_{i0}L_{i0}}, \quad \text{for all } i \in I, \text{ and all } x \in \mathbb{N}_0 \]  (8)

5.3.2. Two-moment approximation
For the local stock points it cannot be assumed that the supplier(central location) has endless stock. We need to incorporate the influence of backorders at the central location. This results in the following term for the expected local inventory.
\[ E\left( l_{ij}(\mathcal{S}) \right) = E\left( S_{ij} - D_{ij} - B_{ij}^{(j)}(S_{i0}) \right)^+, \quad \text{for all } i \in I, \text{ and } j \in J \]

We have the extra term \( B_{ij}^{(j)}(S_{i0}) \), which represents the backorders at the central location due to the demand at location \( j \). Together with the local demand \( (D_i) \) this results in the convolution \( Z_{ij} = D_{ij} + B_{ij}^{(j)}(S_{i0}) \), being the level of outstanding orders at location \( j \in J \) for item \( i \in I \). With \( D_{ij} \sim \text{Poisson} \left( L_{ij} \lambda_i \right) \). To determine the probability distribution of \( B_{ij}^{(j)}(S_{i0}) \) and to calculate the convolution much calculation time is required. This calculation time can be reduced by fitting a standard discrete probability function on the first two moments of the level of outstanding orders \( Z_{ij} \). We can calculate the expectation and the variance of \( Z_{ij} \) with equations (9) and (10).

\[
E[Z_{ij}] = \lambda_{ij}L_{ij} + \frac{\lambda_{ij}}{\lambda_{i0}}E\{B_{i0}(S_{i0})\}, \quad \text{for all } i \in I, \text{ and } j \in J \tag{9}
\]

\[
\text{Var}[Z_{ij}] = D_{ij} + \left( \frac{\lambda_{ij}}{\lambda_{i0}} \right)^2 \text{Var}\{B_{i0}(S_{i0})\} + \left( \frac{\lambda_{ij}}{\lambda_{i0}} \right) \left( 1 - \frac{\lambda_{ij}}{\lambda_{i0}} \right) E\{B_{i0}(S_{i0})\}, \quad \text{for all } i \in I, \text{ and } j \in J \tag{10}
\]

For these equations we need the expectation and the variance for the number of central backorders \( B_{i0} \) and the first two moments for the local demand \( D_i \). The expectation and variance of \( D_i \) are the same and equal to \( L_i \lambda_i \) because of the Poisson distribution. The first two moments of \( B_{i0} \) are calculated with the following equations.

\[
E\{B_{i0}(S_{i0})\} = E(D_{i0} - S_{i0})^+ = E(D_{i0} - S_{i0}) + E[I_{i0}(S_{i0})], \quad \text{for all } i \in I \tag{11}
\]

\[
E\{B_{i0}(S_{i0})\} = \lambda_{i0}L_{i0} - S_{i0} + \sum_{x=0}^{S_{i0}} (S_{i0} - x) P(D_{i0} = x), \quad \text{for all } i \in I \tag{12}
\]

\[
E\{B_{i0}(S_{i0})^2\} = D_{ij} + (D_{ij})^2 - 2 \cdot S_{i0} \cdot D_{ij} + S_{i0}^2 - \sum_{x=0}^{S_{i0}} (S_{i0} - x)^2 P(D_{i0} = x), \quad \text{for all } i \in I \tag{13}
\]

When \( S_{i0} \approx 0 \) when nearly all demand at the central location is backordered the distribution of \( Z_{ij} \) is approximately a Poisson distribution, this is also the case when there is excessive stock. To determine when to use the Poisson distribution or a fitted function we use a decision method of Adan et al.(1995). Let

\[
C_x = \frac{\text{Var}[Z_{ij}]}{E[Z_{ij}]} \quad a = C_x^2 - \frac{1}{E[Z_{ij}]}
\]

When \( a \) is zero \( (\text{Var}[Z_{ij}] = E[Z_{ij}]) \) we will use a Poisson distribution, otherwise we will use the Negative Binomial Distribution (NBD). In practice we will use a Poisson distribution when \( a \) smaller than 0.002. This will not harm the results, and eliminates calculation problems due to very large numbers when using the NBD.

25
**Poisson distribution**

When the Poisson distribution is appropriate, the distribution of $Z_{ij}$ is approximately a Poisson distribution with rate $E[Z_{ij}]$, as determined with Equation (9).

$$P(Z_{ij} = x) = \frac{E[Z_{ij}]^x}{x!}e^{-E[Z_{ij}]}, \quad \text{for all } i \in I \text{ and } x \in \mathbb{N}_0$$

**Negative binomial distribution**

To fit the negative binomial distribution we use the method of Graves (1985). The distribution for $Z_{ij}$ is approximated by a negative binomial distribution, this is the variant where the distribution is defined in terms of the random variable $x$, being the number of failures before the $r$th success. This might be confusing because in our case a failure means that we have enough stock to fulfill the demand, $x = S_{ij}$.

$$P(Z_{ij} = x) = \binom{x + r - 1}{x} p^r (1 - p)^x, \quad \text{for all } x \in \mathbb{N}_0 \quad (14)$$

Because we not only want to use integers, but also real numbers for $r$, we calculate the individual binomial coefficients with the multiplicative formula according to Kranenburg and Van Houtum (2013).

$$\binom{x + r - 1}{x} = \prod_{i=1}^{x} \frac{(x + r - 1)}{i} \quad (15)$$

$r$ and $p$ are positive parameters ($0 < p < 1$) such that

$$E[Z_{ij}] = \frac{r(1 - p)}{p} \quad (16)$$

$$Var[Z_{ij}] = \frac{r(1 - p)}{p^2} \quad (17)$$

So, $p = \frac{E[Z_{ij}]}{Var[Z_{ij}]}$, and then $r = E[Z_{ij}] \times \left( \frac{p}{1 - p} \right)$.

Parameter $r$ is the number of successes until the experiment is stopped, $p$ is the chance of success in each experiment, and $k$ is the number of failures before the $r$th success.

The distributions for $Z_{ij}$ to calculate the expected holding costs and fill rate for the local stock points are determined and summarized in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Distribution fitting decision making</th>
</tr>
</thead>
<tbody>
<tr>
<td>If $a &lt; 0.002$</td>
</tr>
<tr>
<td>$Z_{ij}$ is Poisson distributed with parameter: $\lambda = E[Z_{ij}]$</td>
</tr>
<tr>
<td>If $a \geq 0.002$</td>
</tr>
<tr>
<td>$Z_{ij}$ is a Negative Binomial Distribution with parameters: $x = S_{ij}$ $p = \frac{E[Z_{ij}]}{Var[Z_{ij}]}$ $r = E[Z_{ij}] \times \left( \frac{p}{1 - p} \right)$</td>
</tr>
</tbody>
</table>

5.3.3. **Local costs**

Now we have determined the distribution for level of outstanding orders at the local stock points, we can calculate the holding costs at these locations. The equation for this is the following equations from Section 5.2.1.
We need to sum both over all items and all de-central locations. The first two terms are the holding costs and cost price of an item. The third term is the expected average inventory with the same type of equation as when we determined the central holding costs. However, this time we use the stochastic function $Z_{ij}$ which we have described in the previous Section.

\begin{equation}
E[I_{ij}(S_i)] = E(S_{ij} - Z_{ij})^+
\end{equation}

\begin{equation}
E[I_{ij}(S_i)] = \sum_{x=0}^{S_{ij}} (S_{ij} - x) \cdot P(Z_{ij} = x), \quad \text{for all } i \in I, \text{ and } j \in J
\end{equation}

### 5.3.4. Local aggregated fill rate

As explained in Section 5.2.1, the individual item fill rates are dependent on the base stock level $S_{ij}$ and the distribution of $Z_{ij}$ which is either a Poisson distribution or a Negative Binomial Distribution.

\begin{equation}
\beta_{ij}(S_i) = \sum_{x=0}^{S_{ij}} P(Z_{ij}(S_{ij}) = x) , \quad \text{for all } i \in I, \text{ and } j \in J
\end{equation}

The aggregate fill rate for a location is the weighted average of the item fill rates.

\begin{equation}
\beta_j(S) = \sum_{i=1}^{l} \frac{\lambda_{ij}}{\lambda_{i0}} \beta_{ij}(S_i), \quad \text{for all } j \in J
\end{equation}
6. Optimization procedure

This Chapter contains the problem descriptions for the different alternatives of our model that we proposed in Section 4.2.1. In Section 6.1.1 the goal function for the main-model (Alternative3MI) is determined with its constraints, and the optimization approach is explained. In Section 6.2 we describe the problem and the optimization algorithm for the five other alternatives. Section 6.3 describes how we implemented the model into Excel. In Section 6.4 we verify and test the model.

6.1. Alternative 3MI

This Section discusses the optimization procedure for alternative 3MI, which is our main-model with ‘full’ coordination with a system approach. To let the model perform according to the performance measures we proposed in Section 5.2.1, we first, will put forward the model description for the situation in which we have the most freedom to vary the base stock levels (Alternative3, Multi-item). Thereafter we will propose the optimization approach. This procedure is a greedy approach from Wong et al. (2007). However, as discussed in Section 5.2 we will use a different service measure than in original article. The basic idea of this procedure is to add different units to different locations in an iterative way. Each iteration, a unit of stock for item $i \in I$ is added at location $j \in J$ such that we gain the largest ‘decrease in distance to the target fill rate’ per extra unit of additional cost, or to say “the biggest bang for the bug”.

6.1.1. Problem definition

The objective for Railpro is to minimize the expected total system costs, while the expected aggregate location fill rates, $\beta_j(S)$ exceed the target fill rates, $F_j$ for each location $j$. This problem can be formulated as follows:

$$
\min C(S) = \sum_{i=1}^{l} h_{i0} * P_i * E[I_{i0}(S)] + \sum_{i=1}^{l} \sum_{j=1}^{J} h_{ij} * P_i * E[I_{ij}(S)]
$$

s.t.

$$
\beta_j(S) \geq F_j, \quad \text{for all } j \in J
$$

$$
S_{ij} \in \mathbb{N}_0, \quad \text{for all } i \in I, \text{and all } j \in J^0
$$

6.1.2. Algorithm

The basic idea behind the greedy algorithm is to determine the inventory for all items and locations by adding units in an iterative way. We start with a first efficient solution and then each iteration one unit of stock is added for item $i \in I$ at location $j \in J^0$ such that we gain the largest decrease in distance to the set of feasible solutions per extra unit of additional costs. This is repeated until a feasible solution is obtained.

Normally the greedy approach is started by setting all base stock levels $S_{ij} = 0$. Due to possible calculation problems in Excel we start the greedy approach with initial base stock levels. This calculation problem might occur when demands become so high the difference between the cumulative probabilities of a base stock level of one or zero is not observable. We therefore will start the algorithm by setting all base stock levels at an initial starting point this will be $S_{ij} \geq \max\{[\lambda_{ij} L_{ij}], 0\}$. This is the same starting solution that is used in single-location problems.
to ensure convexity defined by Kranenburg and Van Houtum (2013). However, in our situation this is not guaranteed.

Secondly, we calculate for each combination of item \( i \) and location \( j \) what happens with the system costs \( \Delta C_{ij}(S) \) and the fill rate \( \Delta D_{ij}(S) \) when we add one extra unit, \( R_{ij} = \frac{\Delta D_{ij}(S)}{\Delta C_{ij}(S)}, i \in I, j \in J^0 \). The difference in expected costs is calculated with equation (23).

\[
\Delta C_{ij}(S) = C(S_i + e_j) - C(S_i), \quad \text{for all } i \in I, \text{ and all } j \in J^0
\]  

In this equation, \( e_j \) is a vector with size \(|J^0|\) with the \( j \)-th element equal to 1 and all other elements equal to 0. The distance \( D_{ij}(S) \) is the distance between the current aggregate fill rates \( \beta_j(S) \) and the target fill rate \( F_j \). The decrease in distance to the desired fill rate should be calculated for each product at each location

\[
\Delta D_{ij}(S) = \sum_{j=1}^{J} [F_j - \beta_j(S)]^+ - \sum_{j=1}^{J} [F_j - \beta_j(S_i + e_j)]^+, \quad \text{for all } i \in I, \text{ and all } j \in J^0
\]  

Next in step three we search for the highest value of \( R_{ij} \) with the combination of \( i' \in I, j' \in J^0 \) that gives the largest decrease in distance per unit cost. We increase the base stock level of item \( i' \) at location \( j' \) with one unit.

In step four we recalculate the values of \( R_{ij} \) for all combinations of products and locations. There are also procedures that only update the \( R_{ij}'s \) for the item that is added somewhere. We choose to recalculate all values for \( R_{ij} \) after each iteration to get a solution as close as possible to the target fill rate. Because after each iteration it might be possible that one of the \( R_{ij} \) values is not valid anymore. This is possible if an item is added at some location and for that location the target fill rate is then reached. Then all \( R_{ij} \) values for that location should be zero. The same holds for the central location when all target fill rates at locations with demand for item \( I \) are met, then the \( R_{io} \) for that item should be zero. And the same holds when the ratio not need to be zero, but the distance is smaller than the previous calculation \( \Delta D_{ij}(\text{change in distance}) \).

In step 5 we check whether we met the target. If not we repeat step two and three till we have met the target fill rate for each location.

\[
\beta_j(S) \geq F_j, \quad \text{for all } j \in J
\]  

Now we will describe the optimization algorithm formally.

**Step 1** Set \( S_{ij} \geq \max\{[\lambda_{ij}L_{lj}], 0]\), for all \( i \in I, \text{ and all } j \in J^0 \)

**Step 2** Calculate \( R_{ij} (\Delta C_{ij} \text{ and } \Delta D_{ij}) \), for all \( i \in I, \text{ and all } j \in J^0 \)

**Step 3**

a. Let \( i' \) and \( j' \) be the combination with the highest ratio \( R_{ij} \).

b. Set \( S_i = S_i + e_j \)

**Step 4** If \( \beta_j(S) \geq F_j \) for all \( j \in J \) go to END, otherwise go to Step 2

**END**

### 6.2. Other alternatives

In this Section we will describe the five problem descriptions of the other alternatives, and the algorithms to determine the order-up-to levels.
6.2.1. Alternative 3SI
This model differs from the main-model because each product has its own required fill rate per location, instead of one aggregated fill rate per location. We therefore optimize one product at a time over all locations. It is the same as executing the algorithm of Alternative 3MI with $|I|$ equal to 1 executing multiple times, for each product one time. We start with optimizing all inventories for product one, then for product two, and so on.

**Problem**

$$C(\bar{s}) = \sum_{i=1}^{I} h_i \cdot P_i \cdot E[I_{i0}(\bar{s})] + \sum_{i=1}^{I} \sum_{j=1}^{J} h_{ij} \cdot P_i \cdot E[I_{ij}(\bar{s})]$$

s.t.

$$\beta_{ij}(\bar{s}_i) \geq F_{ij}, \quad \text{for all } i \in I, \text{ and all } j \in J$$

$$S_{ij} \in \mathbb{N}_0, \quad \text{for all } i \in I, \text{ and all } j \in J$$

Explanation: Minimize the total inventory investment under the constraint that at each location for every item the item fill rate is equal or greater than the desired item fill rate.

**Algorithm**

**Step 1**
Set $S_{ij} \geq \max\{\lambda_{ij} L_{ij}, 0\}$, for all $i \in I$, and all $j \in J$

For $i = 1$ to $I$ do

**Step 2**
Calculate $R_{ij}$ ($\Delta C_{ij}$ and $\Delta D_{ij}$), for all $j \in J$

**Step 3**

a. Let $j'$ be the location with highest ratio $R_{ij}$

b. Set $S_i = S_i + e_{j'}$

**Step 4**
If $\beta_{ij}(\bar{s}_i) \geq F_{ij}$ for all $j \in J$, go to next $i$, otherwise go to Step 2

Next $i$

END

6.2.2. Alternative 2MI
This model differs from the main-model because we only are allowed to optimize the central stock levels. All de-central locations have predetermined base stock levels (See Section 4.2.1), which is incorporated with the constraint $S_{ij} = S^p_{ij}$. The constraint forces the model to fix the order-up-to levels to the predetermined stock levels ($S^p_{ij}$). We optimize all items at the same time, but only at one (central) location.

**Problem**

$$C(\bar{s}) = \sum_{i=1}^{I} h_i \cdot P_i \cdot E[I_{i0}(\bar{s})] + \sum_{i=1}^{I} \sum_{j=1}^{J} h_{ij} \cdot P_i \cdot E[I_{ij}(\bar{s})]$$

s.t.

$$\beta_{j}(\bar{s}) \geq F_j, \quad \text{for all } i \in I, \text{ and all } j \in J$$

$$S_{i0} \in \mathbb{N}_0, \quad \text{for all } i \in I$$

$$S_{ij} = S^p_{ij}, \quad \text{for all } i \in I, \text{ and all } j \in J$$
Explanation: Minimize the total inventory investment under the constraint that at each location the aggregated fill rate is equal or greater than the desired fill rate. However, only the central stock is adjustable.

**Algorithm**

1. Set \( S_{i0} \geq \max\{\lambda_{i0}L_{i0}\}, 0\), for all \( i \in I \)
2. Calculate \( R_{i0} \), for all \( i \in I \)
3. a. Let \( i' \) be the item with the highest ratio \( R_{i0} \).
   b. Set \( S_{i0} = S_{i0} + e_0 \)
4. Calculate \( R_{ij} \), for all \( i \in I \)
5. If \( \beta_i(S_i) \geq F_i \) for all \( j \in J \) go to END, otherwise go to Step 2

END

6.2.3. **Alternative 2SI**

This model differs from the main-model because we only are allowed to optimize the central stock levels, and have fill rates for each individual product and location. All de-central locations have fixed base stock levels \( (S_{ij} = S_{ij}^p) \). We optimize all items in isolation.

**Problem**

\[
C(S) = \sum_{i=1}^{I} h_{i0} * P_i * E[I_{i0}(S)] + \sum_{i=1}^{I} \sum_{j=1}^{J} h_{ij} * P_i * E[I_{ij}(S)]
\]

s.t.

\[
\beta_{ij}(S) \geq F_{ij}, \quad \text{for all } i \in I, \text{ and all } j \in J
\]

\[
S_{i0} \in \mathbb{N}, \quad \text{for all } i \in I
\]

\[
S_{ij} = S_{ij}^p, \quad \text{for all } i \in I, \text{ and all } j \in J
\]

Explanation: Minimize the total inventory investment under the constraint that at each location for every item the item fill rate is equal or greater than the desired item fill rate. However, only the central stock is adjustable.

**Algorithm**

1. Set \( S_{i0} = 0 \), for all \( i \in I \)
2. For \( i = 1 \) to \( I \)
   2.1. Set \( S_{i0} = S_{i0} + e_0 \)
   2.2. If \( \beta_{ij}(S_i) \geq F_{ij} \) for all \( j \in J \) go to next \( i \), otherwise go to Step 2
3. Next \( i \)

END

6.2.4. **Alternative 1MI**

This model differs from the main-model because we have only one constraint for the fill rate at the central warehouse, \( \beta_0(S) \geq F_0 \). All de-central locations are not taken into consideration in the optimization. This is a multi-item, single location problem.

**Problem**
\[ C(S) = \sum_{i=1}^{I} h_{i0} \cdot P_i \cdot E[I_{i0}(S)] \]

s.t.
\[ \beta_0(S) \geq F_0, \quad \text{for all } i \in I \]
\[ S_{i0} \in \mathbb{N}, \quad \text{for all } i \in I \]

Explanation: Minimize the inventory investment at the central location under the constraint that the aggregate fill rate constraint is met for the central location.

**Algorithm**

**Step 1** Set \( S_{i0} \geq \max\{\lambda_{i0}L_{i0}\} \), for all \( i \in I \)

**Step 2**

Calculate \( R_{i0} (\Delta G_{i0} \text{ and } \Delta D_{i0}) \) for all \( i \in I \)

**Step 3**

a. Let \( i' \) be the item with the highest ratio \( R_{i0} \).

b. Set \( S_{i0} = S_{i0} + e_0 \)

**Step 4**

Recalculate \( R_{i0} \) for \( i = i' \)

**Step 5**

If \( \beta_0(S_{i0}) \geq F_0 \) go to END, otherwise go to Step 3

**END**

6.2.5. **Alternative 1SI**

This model differs from the main-model because we only optimize the central stock levels with the aggregated demand, and we optimize one item at a time. All de-central locations are not taken into consideration. We have again no constraints at the local stock points but only at the central location. This is a single-item, single-location problem. This results in a Newsboy problem which results in an optimal solution.

**Problem**

\[ C(S_{i0}) = \sum_{i=1}^{I} h_{i0} \cdot P_i \cdot E[I_{i0}(S_{i0})] \]

s.t.
\[ \beta_{i0}(S_{i0}) \geq F_{i0}, \quad \text{for all } i \in I \]
\[ S_{i0} \in \mathbb{N}, \quad \text{for all } i \in I \]

Explanation: Minimize the inventory investment at the central location under the constraint that the item fill rate constraint is met for all items at the central location.

**Algorithm**

**Step 1**

Set \( S_{i0} = 0, \ i \in I \),

For \( i=1 \) to \( I \)

**Step 2** Set \( S_{i0} = S_{i0} + e_0 \)

**Step 3** If \( \beta_{i0}(S_{i0}) \geq F_{i0} \) go to END, otherwise go to Step 2

Next \( i \)

**END**
6.3. Model implementation

The algorithms described in Section 6.1.2 and 6.2 are programmed in Excel VBA. Excel is probably not the most advanced programming tool and it has its limitations. However, there are some decent arguments to use this tool. The first reason is the prior knowledge of programming in Excel VBA. Furthermore, the program is also used for the preparation of data. Finally, this tool is available at Railpro and the easiest to use in practice.

6.4. Model verification and testing

We need to test whether the translation of our conceptual model consisting of the six alternative models is implemented correctly into Excel. Verification ensures that the software matches the concept model. For this all steps of the model are carefully analyzed and compared with the conceptual model. We also tested whether the model gives the right or reasonable results. The results are shown in Appendix D.

Evaluation

To test if the evaluation of a given situation is done correctly we compare the output to an existing example of a linear multi-echelon model proposed by Atan (2012). However, with specific input parameters we also can test characteristics of a distribution network. With this example we check the evaluation of the central location, the allocation of central backorders to the de-central locations. The application of the two-moment approximation, and calculating the expected inventory and outstanding backorders at the local stock points. Our model gave the exact same results.

Greedy approach

For the greedy part of the model we don’t have an example available. However, we can investigate some specific situations which will show us whether we receive the expected results. Some examples: when we have two identical products except for their cost price, the product with the lowest cost price should be in favor to stock. If the target fill rate for a location is met, the algorithm should stop adding stock for that location. When for all locations with demand for a specific product the target fill rate is met, it should stop adding stock at the central location. The first item that is added for a product can’t be at the central location because that will not increase the fill rate at local stock points. There should be a zero stock when there is no demand.

We also tested the first step of our greedy procedure in which we determine initial base stock levels. The results are in Appendix D. The results are the same for the single-item models, we only use the greedy procedure for Alternative 3SI. For the multi-item models the results are about 2-3% higher when initial base stock levels are used.
7. Practical case study
In this Chapter we show the results for the different models in the railway infrastructure environment at Railpro. We analyze the current situation of eight VOL-locations (numbered 1-8), and later include the demand for direct (failure) demand and Work packages at the central location. We include 542 SKU’s in the analyses, these are regarded as Failure items at the VOL-locations (See Section 3.2.2). We exclude the items that are measured in ‘meters’ because these SKU’s have really high demand rates due to their unit of measurement. First, we discuss the data collection and input data structure in Section 7.1. In Section 7.3 we present the results for the perspective of the total system. In Section 7.4 we execute some analysis to test the sensitivity of some input parameters.

7.1. Data collection
We now describe how we collect the data for the input parameters. We execute the analysis for items that are in the Failure assortment at VOL-locations, see also Section 3.2. The input parameters are represented in Table 5 and we will treat them in the order of presentation.

Table 5: Model input parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predetermined stock levels</td>
<td>$S_{ij}^P$</td>
</tr>
<tr>
<td>Demand rate</td>
<td>$\lambda_{ij}$</td>
</tr>
<tr>
<td>Lead-time</td>
<td>$L_{ij}$</td>
</tr>
<tr>
<td>Unit holding cost</td>
<td>$h_{ij}$</td>
</tr>
<tr>
<td>Cost price</td>
<td>$P_{ij}$</td>
</tr>
<tr>
<td>Target fill rate</td>
<td>$F_{ij}$</td>
</tr>
<tr>
<td>Aggregate target fill rate</td>
<td>$F_j$</td>
</tr>
</tbody>
</table>

7.1.1. Current base stock levels
The current base stock levels $S_{ij}^P$ are obtained from the current contracts that are in place. As described in Section 3.2. Railpro and the contractor negotiate about the assortment classification and the order-up-to level for all products. We use these lists from the contracts as input for the predetermined stock levels.

7.1.2. Demand
For the determination of the demand rates we have to forecast based on historical demand. We have demand data on the detail level of order lines. So, for each order line we have the order number, item number, quantity, delivery date, and warehouse/delivery location. However, due to the newness of the VOL-concept there is not much historical data on the withdrawals from the locations. We have four locations with 6 months of reliable data available, and four locations with only three months of data. Therefore, we will compare this data with historical demand at the central location for the years 2011 and 2012. We will use the maximum of the two. For the locations with 6 months of data, we have 80 order lines for 48 different items and in total 278 products. For the locations with 3 months of demand, there are 288 order lines for 148 items and in total 848 products. With expert knowledge of Railpro the central demand is filtered to approximate the withdrawals from the VOL-locations as close as possible. We end up with 4246 order lines.
To allocate the demand to one of the VOL-locations we assign all demand which have a delivery location that corresponds to a VOL-location to that location. 1,114 order lines have a delivery location that is currently a VOL-Location.

For this historical demand data we know that it is not the exact withdrawals from the VOL-locations and therefore the right direct demand from the central location. However, it is plausible that these data are of the right proportions.

7.1.3. Lead-times
We have different kinds of lead-times. The supplier lead-time from the supplier to the central location and the replenishment lead-times from the central location to the customer locations.

**Supplier lead-times (L_{00})**
As said earlier in Section 5.2.2 we know supplier lead-times are highly variable and our model is not capable of including variance in the lead-times. We therefore want a method to cope with this difference, for example using a lead-time that results in only 10% of the deliveries having a longer lead-time. However, according to the historical data it is not possible to determine the appropriate lead-time. The recorded moment of ordering and the moment of registering can differ from the actual moment. Lead times can be much longer than the normal supplier lead-time because of a large planning horizon. After discussion with the procurement people at Railpro it is decided to use the planned supplier lead-time that is present in the ERP system. These are the lead-times that the planners, purchasers, and inventory control software use.

**Replenishment lead-times to the customer (L_{ij})**
Lead-times for the replenishments from the local warehouses depends highly on the moment of ordering, because of the two deliveries per week. For the expected replenishment lead-times we assume an automated ordering system is in place. This will be the case within several months. When the ordering system is in place it takes on average one day to pick the order and make it ready for delivery. However, the delivery is on average (assuming a uniform demand during the week) about 2.5 days. Therefore, in total the average replenishment time is on average 3.5 days. Because we know this average and the maximum of 6 days, we will use a constant lead-time of 5 days to the customer sites.

7.1.4. Holding costs
For inventory control calculations within Railpro a percentage of 25% on the cost price (VGP) is used, the cost price is determined by the moving average price method. This percentage is build up from three different costs factors, the interest, cost for storage (space) and the obsolescence risk. For the interest the Weighted Average Cost for Capital (WACC) is used. For storage and obsolescence risk the numbers that are used at the financial department are used. These numbers are not public and therefore not represented in this report. The sum of these three factors is between 20%-25%. For practicality reasons and easy interpretation of the results we will use the percentage of 25% that Railpro use for their inventory control at the moment. The percentage of 25% is used only for the central location. For stocks at customer locations we know that the percentage is a bit higher because of the handling/transportation and the risk (although this is minor because items can be shipped back to the central location). From the business case of the VOL-concept it is estimated that transportation and handling costs for
moving goods from the central to the local warehouse is about 4% of the cost price. Charging 25% on this extra investment results in 1% extra holding costs, therefore a percentage of 26% is used at the local stock points. Because this percentage is a rough estimate we will test the sensitivity in Section 7.4.4.

7.1.5. Unit cost price (VGP)
The cost price is determined by the moving average price method (VGP). These values are extracted from the ERP system.

7.1.6. Fill rates
The (aggregate) fill rates of a stock point (or an assortment within a stock point) are determined by negotiation with the customer. See Section 3.2.

7.2. Modelling issues
As a starting point for Alternative 1 and Alternative 2 we have the current stock levels that are determined in the agreements between Railpro and the customers. When we evaluate the current stocks (without central stock) we see that without central stock the VOL-locations are far from their desired performance, see Table 6. And when we add excessive stock to the central location still the performance of the total system is far too low, see Table 7. This is caused by the imbalance between demand and inventory at the local warehouses. This is likely because we used historical data where demand was an order to the VOL-location instead of a withdrawal from the location, see also Section 7.1.2. So it is possible that we have demand for items that are not stocked. If there is demand at the local warehouse without any inventory, it is impossible to get the fill rate above zero.

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>B_(S)</th>
<th>C_(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>0.00%</td>
<td>€ 0</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>76.93%</td>
<td>€ 30,418</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>37.92%</td>
<td>€ 8,323</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>82.28%</td>
<td>€ 38,281</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>8.00%</td>
<td>€ 23</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>55.87%</td>
<td>€ 11,090</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>69.24%</td>
<td>€ 9,152</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>100.00%</td>
<td>€ 2,055</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>58.38%</td>
<td>€ 14,531</td>
</tr>
<tr>
<td>Total system</td>
<td>70.25%</td>
<td>€ 113,873</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>B_(S)</th>
<th>C_(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>100.00%</td>
<td>€ 49,701,398</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>82.51%</td>
<td>€ 33,949</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>77.21%</td>
<td>€ 8,604</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>95.21%</td>
<td>€ 53,961</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>16.64%</td>
<td>€ 24</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>66.64%</td>
<td>€ 11,255</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>75.83%</td>
<td>€ 10,162</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>100.00%</td>
<td>€ 2,058</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>71.89%</td>
<td>€ 16,933</td>
</tr>
<tr>
<td>Total system</td>
<td>81.66%</td>
<td>€ 49,838,345</td>
<td></td>
</tr>
</tbody>
</table>

To overcome the problem of the imbalance between inventory and demand we have two choices. The first one is deleting the demand for which no stock is available. The second is to add some stock for the positions where the minor stock causes an infeasible solution. We choose the second option because adding stock is most realistic compared to the desired situation, we therefore use this method in the remainder of this analysis. It is more realistic because when Railpro observe an imbalance between demand and stock at the VOL-location, they will discuss this with the customer and add some stock and record this in the agreements. In total we have 595 combinations of item/location that have a positive demand rate, 157 of
these satisfy the criteria of zero stock. We add stock according to a single-location, single-item base stock model (the same as Alternative1SI, however for a local stock point). It is assumed the central location can always deliver.

So, from now on we will use the data with the added stock for the further analyses. For each item that has a positive demand rate and a base stock level of zero we determine a base stock level based on the above procedure. We use these adapted base stock levels both for Alternative1 (SI/MI) and Alternative2 (SI/MI). For the first one it is not necessary to reach the target fill rate (only central). However, it is more realistic that there is stock for demand at the VOL-locations.

### 7.3. Results

In this analysis we compare the six alternative models with each other. We evaluate them on the two performance measures we determined in Section 5.2.1, the system aggregate fill rate and the total system costs. In the tables that are presented, 'central' represents the central locations, de-central locations are numbered 1-8. \( F_j \) is the target fill rate, \( \beta(S) \) is the aggregate fill rate for location \( j \in J \), and \( C_j(S) \) are the inventory costs for location \( j \in J \). The first results are in Table 8. The detailed results, with results for each location are in Appendix F. It is shown that the multi-item models perform better than the single-item models. Alternative3 performs the best and Alternative1 is the worst. However, the fill rate is also much lower for the models with low costs, but they are all above the target level of 95%.

#### Table 8: Comparison of six different models

<table>
<thead>
<tr>
<th>Alternative</th>
<th>( \beta(S) )</th>
<th>( C(S) )</th>
<th>savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.93%</td>
<td>€ 243,352</td>
<td></td>
</tr>
<tr>
<td>1MI</td>
<td>98.02%</td>
<td>€ 165,929</td>
<td>-34%</td>
</tr>
<tr>
<td>2SI</td>
<td>98.48%</td>
<td>€ 216,670</td>
<td>-11%</td>
</tr>
<tr>
<td>2MI</td>
<td>95.47%</td>
<td>€ 145,447</td>
<td>-42%</td>
</tr>
<tr>
<td>3SI</td>
<td>97.20%</td>
<td>€ 118,094</td>
<td>-51%</td>
</tr>
<tr>
<td>3MI</td>
<td>95.04%</td>
<td>€ 39,426</td>
<td>-84%</td>
</tr>
</tbody>
</table>

All results are more or less what we expected. However, the results of Alternative2SI are a little bit surprising, incorporating the VOL-locations does not help that much to lower the inventory costs. We therefore represent the results for Alternative2SI in Table 9.

#### Table 9: Results for alternative2SI

<table>
<thead>
<tr>
<th>Location</th>
<th>( F_j )</th>
<th>( \beta_j(S) )</th>
<th>( C_j(S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>39.86%</td>
<td>€ 67,513</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>99.02%</td>
<td>€ 34,843</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>98.70%</td>
<td>€ 8,875</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>98.82%</td>
<td>€ 55,225</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>96.99%</td>
<td>€ 292</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>99.12%</td>
<td>€ 11,265</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>98.86%</td>
<td>€ 15,124</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>100.00%</td>
<td>€ 2,058</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>97.14%</td>
<td>€ 21,066</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td>98.50%</td>
<td>€ 216,260</td>
</tr>
</tbody>
</table>
It is likely that these results are caused by the current customer stocks. However, we would like to investigate this a little bit more, so prevent ourselves for rejecting this alternative while the results depend on this specific situation. It is possible that with some slight adaptations to the customer stocks this model will perform much better. We investigate the costs for the inventory at the central location. If we look at the items that contribute most to the costs, they have a high cost price and/or have a long supplier lead-time (6-12 months). See Table 10. For example look at the second product that is on average demanded about 0.25 times every month at the VOL-locations. This demand comes from one location that has one item on stock. Due to the low decentralized stock and the long supplier lead-time, the central stock is relatively high.

Table 10: Material that contribute most to the high central costs for Alternative 2SI

<table>
<thead>
<tr>
<th>Material</th>
<th>VGP</th>
<th>$S_0$</th>
<th>$L_0$</th>
<th>$h_0$</th>
<th>$\lambda_0$</th>
<th>$F_1$</th>
<th>Costs (central)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€ 2,380</td>
<td>11</td>
<td>1.84</td>
<td>25%</td>
<td>1.21</td>
<td>95%</td>
<td>€ 5,221</td>
</tr>
<tr>
<td>2</td>
<td>€ 3,745</td>
<td>8</td>
<td>11.99</td>
<td>25%</td>
<td>0.25</td>
<td>95%</td>
<td>€ 4,686</td>
</tr>
<tr>
<td>3</td>
<td>€ 983</td>
<td>25</td>
<td>4.14</td>
<td>25%</td>
<td>2</td>
<td>95%</td>
<td>€ 3,643</td>
</tr>
<tr>
<td>4</td>
<td>€ 847</td>
<td>30</td>
<td>8.97</td>
<td>25%</td>
<td>1.46</td>
<td>95%</td>
<td>€ 3,581</td>
</tr>
<tr>
<td>5</td>
<td>€ 863</td>
<td>24</td>
<td>6.90</td>
<td>25%</td>
<td>1.38</td>
<td>95%</td>
<td>€ 3,131</td>
</tr>
<tr>
<td>6</td>
<td>€ 2,416</td>
<td>8</td>
<td>11.99</td>
<td>25%</td>
<td>0.25</td>
<td>95%</td>
<td>€ 3,023</td>
</tr>
<tr>
<td>7</td>
<td>€ 3,286</td>
<td>7</td>
<td>11.96</td>
<td>25%</td>
<td>0.33</td>
<td>95%</td>
<td>€ 2,543</td>
</tr>
<tr>
<td>8</td>
<td>€ 2,454</td>
<td>5</td>
<td>11.99</td>
<td>25%</td>
<td>0.17</td>
<td>95%</td>
<td>€ 1,854</td>
</tr>
<tr>
<td>9</td>
<td>€ 2,750</td>
<td>7</td>
<td>8.97</td>
<td>25%</td>
<td>0.50</td>
<td>95%</td>
<td>€ 1,832</td>
</tr>
<tr>
<td>10</td>
<td>€ 2,339</td>
<td>5</td>
<td>11.99</td>
<td>25%</td>
<td>0.17</td>
<td>95%</td>
<td>€ 1,768</td>
</tr>
</tbody>
</table>

The results that we have retrieved till now reveal that the saving potentials range from 11%-84%, (Table 9). Furthermore, we see that the necessary adaptations to the predetermined base stock levels that we propose in Section 7.2 give feasible solutions. However, as Table 10 show there are many predetermined base stock levels that are far from optimal and therefore highly influence the results.

### 7.4. Sensitivity of parameters

In this Section the sensitivity of the different parameters is discussed. In 7.4.1 we will discuss how much the results differ for different number of locations. The sensitivity of the demand rates are discussed in Section 7.4.2. Section 1.1.1 is about the supplier and replenishment lead-time. Section 1.1 is about the results when we request different values for the target fill rate.

#### 7.4.1. Number of locations

The test on the number of locations is carried out to give insight in the saving potential for different sizes of the VOL-concept. We first analyze the development of the costs when we add the locations one by one. The results are in Figure 12. Not surprisingly the distances between the different models become bigger as the number of locations grew. Notice that the developments of the lines are due to the order in which the locations are added. However, it gives some insight in the saving potential for different sizes. Next, we create ‘twin’-locations for all locations. With this method we create 24 locations, 3 times the original size. The results are in Figure 13. We observe that all alternatives more or less follow a linear pattern.
7.4.2. Demand rates

In this Section we will discuss the sensitivity of the demand rates, which we will do this in two ways. First, we differ all demand rates with the same percentage (80%-120%). For each iteration we recalculate the demand rate and we optimize all base stock levels and evaluate the system, the effects are in Figure 14 and Figure 15. For the fill rate we observe that the expected fill rates are closer to the target fill rate which is normal because when the demand is low, sometimes one unit will result in a fill rate of 99%. When the demands increase, this overstocking will have a minor influence. The system cost increase which is also normal because we need more stock to prevent us from stock outs. The 6 different models show different values when we change the amount of demand. However, the differences between the models mostly remain. We can conclude that different demand rates influence our outcomes of the alternatives, but do not harm the results.

Next, we vary each demand rate with a random number. We assign a random variation of -50%/-+50% to each demand. There are many products/locations that have no demand. On average only 20% of the items has observed demand. Therefore we adapt these zero demand rates with four different scenarios, in all scenarios we change the zero demand into a yearly demand that is randomly determined between zero and two. In the first scenario we assign a random demand rate for 12.5% of the item. In the second case we assign random demand for 25% of the item. In the third for 50% of the item. And the last scenario we assign demands for 50% of the items. Because there is a tradeoff between calculation time and accuracy, we did take the average of 10 runs for each model. As can be seen in Figure 16 and Figure 17 when 9-10 runs are included the line flattens out.
The results are shown in Table 11 to Table 14. For all scenario's and alternatives the multi-item models are performing better than the single-item models. In all scenarios, Alternative two performs better than one, and three better than two. The results indicate that the performance of Alternative2 (SI/MI) is highly influenced by the predetermined stock levels. The more demand we create, the better this alternative performs compared to the other alternatives.

Table 11: Zero demand not changed (1)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>β(S)</th>
<th>C(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.85%</td>
<td>€ 239,714</td>
</tr>
<tr>
<td>1MI</td>
<td>97.89%</td>
<td>€ 165,217</td>
</tr>
<tr>
<td>2SI</td>
<td>98.35%</td>
<td>€ 220,966</td>
</tr>
<tr>
<td>2MI</td>
<td>95.47%</td>
<td>€ 146,834</td>
</tr>
<tr>
<td>3SI</td>
<td>97.09%</td>
<td>€ 117,247</td>
</tr>
<tr>
<td>3MI</td>
<td>95.04%</td>
<td>€ 39,720</td>
</tr>
</tbody>
</table>

Table 12: Zero demand changed for 12.5% items (2)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>β(S)</th>
<th>C(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.87%</td>
<td>€ 309,348</td>
</tr>
<tr>
<td>1MI</td>
<td>98.00%</td>
<td>€ 207,947</td>
</tr>
<tr>
<td>2SI</td>
<td>98.35%</td>
<td>€ 274,534</td>
</tr>
<tr>
<td>2MI</td>
<td>95.47%</td>
<td>€ 182,658</td>
</tr>
<tr>
<td>3SI</td>
<td>97.11%</td>
<td>€ 177,125</td>
</tr>
<tr>
<td>3MI</td>
<td>95.00%</td>
<td>€ 39,720</td>
</tr>
</tbody>
</table>

Table 13: Zero demand changed for 25% items (3)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>β(S)</th>
<th>C(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.93%</td>
<td>€ 362,856</td>
</tr>
<tr>
<td>1MI</td>
<td>98.10%</td>
<td>€ 250,603</td>
</tr>
<tr>
<td>2SI</td>
<td>98.35%</td>
<td>€ 323,583</td>
</tr>
<tr>
<td>2MI</td>
<td>95.42%</td>
<td>€ 217,283</td>
</tr>
<tr>
<td>3SI</td>
<td>97.22%</td>
<td>€ 231,393</td>
</tr>
<tr>
<td>3MI</td>
<td>95.00%</td>
<td>€ 82,039</td>
</tr>
</tbody>
</table>

Table 14: Zero demand changed for 50% items (4)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>β(S)</th>
<th>C(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.96%</td>
<td>€ 459,800</td>
</tr>
<tr>
<td>1MI</td>
<td>98.25%</td>
<td>€ 335,548</td>
</tr>
<tr>
<td>2SI</td>
<td>98.37%</td>
<td>€ 408,202</td>
</tr>
<tr>
<td>2MI</td>
<td>95.53%</td>
<td>€ 290,798</td>
</tr>
<tr>
<td>3SI</td>
<td>97.31%</td>
<td>€ 328,144</td>
</tr>
<tr>
<td>3MI</td>
<td>95.01%</td>
<td>€ 127,793</td>
</tr>
</tbody>
</table>

Figure 18: Randomly assigned demand rates
We have to conclude that the results of alternative 1 and 2, are influenced by the relatively high predetermined customer stock. However, in all Scenarios the multi-item model still performs much better than the single-item model. Alternative three performs best, followed by alternative two. Even when there would be much more demand, savings can be up to 72%, see Table 15.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cost 1 SI</th>
<th>Savings 1 SI</th>
<th>Cost 2 SI</th>
<th>Savings 2 SI</th>
<th>Cost 3 SI</th>
<th>Savings 3 SI</th>
<th>Cost 4 SI</th>
<th>Savings 4 SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>€ 239,714</td>
<td>€ 309,348</td>
<td>€ 362,856</td>
<td>-31%</td>
<td>€ 369,800</td>
<td><strong>-27%</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>€ 165,217</td>
<td>-31%</td>
<td>€ 207,947</td>
<td>-33%</td>
<td>€ 250,603</td>
<td>-31%</td>
<td>€ 335,548</td>
<td>-27%</td>
</tr>
<tr>
<td>3</td>
<td>€ 220,966</td>
<td>-8%</td>
<td>€ 274,534</td>
<td>-11%</td>
<td>€ 323,583</td>
<td>-11%</td>
<td>€ 408,202</td>
<td>-11%</td>
</tr>
<tr>
<td>4</td>
<td>€ 146,834</td>
<td>-39%</td>
<td>€ 182,658</td>
<td>-41%</td>
<td>€ 217,283</td>
<td>-40%</td>
<td>€ 290,798</td>
<td>-37%</td>
</tr>
<tr>
<td>5</td>
<td>€ 117,247</td>
<td>-51%</td>
<td>€ 177,125</td>
<td>-43%</td>
<td>€ 231,393</td>
<td>-36%</td>
<td>€ 328,144</td>
<td>-29%</td>
</tr>
<tr>
<td>6</td>
<td>€ 39,720</td>
<td>-83%</td>
<td>€ 58,952</td>
<td>-81%</td>
<td>€ 82,039</td>
<td>-77%</td>
<td>€ 127,793</td>
<td>-72%</td>
</tr>
</tbody>
</table>

7.4.3. Lead times
This Section describes the sensitivity of the lead-time parameter. We will evaluate both the supplier lead-time and the replenishment lead-time. The former represents the assumption that the supplier can always supply with the constant lead-time. The latter one is about the constant delivery time between the central warehouse and the local stock points. We test the sensitivity in the same way as we did for the arrival rates of the demand.

Supplier lead-time
For the supplier lead-times we use the planned lead-times that are in the ERP system and used by the current inventory control system and the purchasers. However, we know that lead-times can differ over time and therefore we will execute an analysis on the supplier lead-times. We optimize each time we change the lead-time. The results are in and Figure 19 and Figure 20, and not surprisingly the results are similar as for the analysis on the demand rate. This test does not harm our results.
Replenishment lead-time

For the replenishment lead-time we have used a constant lead-time of 5 days. However, this is a conservative estimation. And the number of replenishment per week isn’t fixed and can be adapted when considerable inventory holding costs savings can be realized. In this analysis we test whether the length of the replenishment lead-time will have a major impact on the results. The results are in Table 16 and Figure 21-Figure 22.

Table 16: System costs for different replenishment lead-times

<table>
<thead>
<tr>
<th></th>
<th>½ day</th>
<th>1 day</th>
<th>2 days</th>
<th>3 days</th>
<th>4 days</th>
<th>5 days</th>
<th>7 days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1SI</strong></td>
<td>€ 243,119</td>
<td>€ 242,944</td>
<td>€ 242,594</td>
<td>€ 241,897</td>
<td>€ 241,550</td>
<td>€ 240,862</td>
<td></td>
</tr>
<tr>
<td><strong>1MI</strong></td>
<td>€ 165,553</td>
<td>€ 165,397</td>
<td>€ 165,086</td>
<td>€ 164,467</td>
<td>€ 164,160</td>
<td>€ 163,549</td>
<td></td>
</tr>
<tr>
<td><strong>2SI</strong></td>
<td>€ 194,449</td>
<td>€ 195,400</td>
<td>€ 196,850</td>
<td>€ 204,832</td>
<td>€ 207,753</td>
<td>€ 216,260</td>
<td>€ 234,403</td>
</tr>
<tr>
<td><strong>2MI</strong></td>
<td>€ 143,329</td>
<td>€ 143,315</td>
<td>€ 143,368</td>
<td>€ 143,532</td>
<td>€ 143,741</td>
<td>€ 144,203</td>
<td>€ 146,225</td>
</tr>
<tr>
<td><strong>3SI</strong></td>
<td>€ 103,832</td>
<td>€ 105,551</td>
<td>€ 107,137</td>
<td>€ 111,826</td>
<td>€ 115,329</td>
<td>€ 118,094</td>
<td>€ 121,203</td>
</tr>
<tr>
<td><strong>3MI</strong></td>
<td>€ 37,463</td>
<td>€ 37,828</td>
<td>€ 38,229</td>
<td>€ 38,690</td>
<td>€ 39,121</td>
<td>€ 39,426</td>
<td>€ 40,120</td>
</tr>
</tbody>
</table>

The total system costs for Alternative1 (SI/MI) decline when the replenishment lead-time increases. The replenishment lead-time is not incorporated in the optimization for alternative one, because we limit ourselves to the central location. However, the replenishment lead-time is incorporated in the evaluation of all alternatives, and when the replenishment lead-time increases the average stock will decline.

For the other multi-item models, the increase in holding costs is about €3,000 between having a lead-time of 0.5 days or 7 days. For the two other single-item models the costs increase with about 20% which is a considerable increase. We can conclude that a different replenishment lead-time will not harm our results. To say more about what the optimal replenishment lead-time would be, the transportation costs should be included in the analysis.

7.4.4. Local holding costs

As described in Section 7.1.4, the local holding costs percentage is a rough estimate. Therefore we will execute a sensitivity analysis on this parameter. For this analysis we use base stock levels of zero. The results are in Table 17 and Figure 23. When interpreting the results it is good to have in mind that for Alternative 1 and 2 (SI/MI) the local stocks do not change. What we can observe is that the saving potential for Alternative3 (SI/MI) becomes bigger when the local holding cost percentage increase. These results therefore do not harm our results.
Table 17: Total annual costs for different local holding costs percentages

<table>
<thead>
<tr>
<th>Alternative</th>
<th>25%</th>
<th>26%</th>
<th>27%</th>
<th>28%</th>
<th>29%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>€ 235,736</td>
<td>€ 241,550</td>
<td>€ 247,365</td>
<td>€ 253,179</td>
<td>€ 258,993</td>
</tr>
<tr>
<td>1MI</td>
<td>€ 158,709</td>
<td>€ 164,160</td>
<td>€ 169,610</td>
<td>€ 175,061</td>
<td>€ 180,511</td>
</tr>
<tr>
<td>2SI</td>
<td>€ 210,539</td>
<td>€ 216,260</td>
<td>€ 221,981</td>
<td>€ 227,702</td>
<td>€ 233,423</td>
</tr>
<tr>
<td>2MI</td>
<td>€ 138,925</td>
<td>€ 144,203</td>
<td>€ 149,481</td>
<td>€ 154,759</td>
<td>€ 160,037</td>
</tr>
<tr>
<td>3SI</td>
<td>€ 115,312</td>
<td>€ 118,094</td>
<td>€ 121,740</td>
<td>€ 124,323</td>
<td>€ 127,333</td>
</tr>
<tr>
<td>3MI</td>
<td>€ 38,201</td>
<td>€ 39,426</td>
<td>€ 40,602</td>
<td>€ 41,854</td>
<td>€ 43,100</td>
</tr>
</tbody>
</table>

7.4.5. Only withdrawals from VOL locations
Demand from the years 2011-2012 can be an overestimation of the demand. People at Railpro think there could be ‘project’ demands in this data. We therefore will also execute the analysis with the demand data that is the exact data from the VOL-locations. This is the data we have also included when determining the demand rates in Section 7.1.2., which is six months of data for half of the VOL-locations and three months of data for the other four locations. The results are in Table 18. Compared to the results in Table 8 the savings potentials are even bigger for Alternative 3, which is likely due to the lower demand rates. This effect is already explained in Section 7.4.2.

Table 18: Only VOL demand

<table>
<thead>
<tr>
<th>Alternative</th>
<th>β(S)</th>
<th>C(S)</th>
<th>savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>99.50%</td>
<td>€ 181,182</td>
<td>-19%</td>
</tr>
<tr>
<td>1MI</td>
<td>98.55%</td>
<td>€ 145,922</td>
<td>-6%</td>
</tr>
<tr>
<td>2SI</td>
<td>98.93%</td>
<td>€ 170,229</td>
<td>-6%</td>
</tr>
<tr>
<td>2MI</td>
<td>96.07%</td>
<td>€ 136,869</td>
<td>-24%</td>
</tr>
<tr>
<td>3SI</td>
<td>96.90%</td>
<td>€ 54,638</td>
<td>-70%</td>
</tr>
<tr>
<td>3MI</td>
<td>95.08%</td>
<td>€ 17,370</td>
<td>-90%</td>
</tr>
</tbody>
</table>

7.4.6. Determine all customer inventories
In several analyses we have executed the predetermined stock points seems to have a major impact on the results. Therefore, we will test what the results will look like when the VOL-locations are controlled by a Single-Echelon Single-Item model. This is the same model we use
for Alternative1SI and for the modelling issues we mentioned in Section 7.2. The results are in Table 19. Compared to the results in Table 8 the savings for Alternative 3 are smaller, for the other alternatives the possible savings are higher. This is again the effect of predetermined base stock levels on the performance of the models. When we determine the stock levels instead of using the stock levels from the contracts, the levels are more in line with the demand rates.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>( \beta(S) )</th>
<th>( C(S) )</th>
<th>savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.03%</td>
<td>€ 151,062</td>
<td></td>
</tr>
<tr>
<td>1MI</td>
<td>97.16%</td>
<td>€ 74,140</td>
<td>-51%</td>
</tr>
<tr>
<td>2SI</td>
<td>97.06%</td>
<td>€ 123,971</td>
<td>-18%</td>
</tr>
<tr>
<td>2MI</td>
<td>95.68%</td>
<td>€ 60,754</td>
<td>-60%</td>
</tr>
<tr>
<td>3SI</td>
<td>97.20%</td>
<td>€ 118,094</td>
<td>-22%</td>
</tr>
<tr>
<td>3MI</td>
<td>95.04%</td>
<td>€ 39,426</td>
<td>-74%</td>
</tr>
</tbody>
</table>

7.4.7. Efficient frontiers

This Section shows some efficient frontiers. It is worthy to know how the costs develop during the optimization process. These pictures give some insight in the questions about different fill rates and corresponding costs. The efficient frontiers are in Figure 24 to Figure 27. For Alternative 1 (SI/MI) we do not show an efficient frontier because for these models the optimization goal is different from the evaluation.
7.5. Direct demand and work packages

In all the previous analyses we isolated the demand stream of replenishments to the VOL-locations from the other demand streams. In this Section we will extend the analyses by adding the two streams of direct demand (Failure demand at the central location) and Work packages, as we announced in Section 3.1.1. In the current practice at Railpro all demand streams are controlled together (Section 3.1). The results of Section 7.3 can probably raise the question to isolate the control for replenishment demand from the other streams to save inventory costs. However, splitting the demand at the central location will influence the pooling effect between the three demand streams, what would probably cause a higher increase in costs than the savings of the coordinated control for the replenishment demand. To investigate these situations, a whole new research design would be needed because in the 'current practice' there are no differentiated service levels for the different demand streams. Nevertheless, we can gain some insight into the costs and availability when we include the demand streams of direct Failure demand and Work packages into our model.

We incorporate the demand streams by creating two new 'local warehouses' for these demand streams. In this way of analyzing we create some dedicated stocks for the demand streams of Direct demand and Work packages. It is better to use a model with priority rules by using a threshold-based rationing policy, however our analysis is a relatively simple method to gain some understanding of the rough savings potentials. A threshold-based rationing rule stops fulfilling demand for some stream(s) if the on hand stock drops below a certain level.

For this investigation we will only evaluate both models (SI/MI) of Alternative 3, because we are not dealing with predetermined customer stocks and we need local warehouses for the differentiation of target fill rates. In Section 7.5.1 we treat the demand stream of Direct failure demand. Section 7.5.2 is about the Work packages. In Section 0 we incorporate both demand streams into the model.

7.5.1. Direct demand

In this Section we will extend the analysis by adding the direct failure demand at the central location. We first deal with the data input, thereafter the results are presented.

Data input

The input data for the unit cost price is the same as before. The holding costs percentage is 25%, the same as for the local warehouse.

Demand data

The historical demand that we will use to determine the demand rates of direct demand, is all data from the years 2011-2012 that not assigned to a VOL-location in Section 7.1.2. All demands that are delivered somewhere else then at one of the VOL-locations are included in the demand stream of direct failure demand. This results in 3,132 order lines.

Lead-times to location direct demand.

In reality this lead-time is zero, because the inventory is located in the same central warehouse. To have an easy calculation of the performance for these locations we separate this location from the central warehouse with a lead-time of 1E-20.
Target fill rate
For the direct demand in Hilversum the percentage of 96% is used for the target fill rate. Railpro promises this percentage to its customers for items that are in the Trade assortment (See Section 3.1.2).

Results
Single-item
To investigate the influence of including direct demand at the central location, we first determine what amount of stock we need when we isolate the stream of direct demand. For this we use the single-item, single-location model that we also use for alternative 1SI. The results are in Table 20. Together with the inventory that we need for the VOL-locations (Section 7.3) we have the total system costs if we optimize both streams in isolation.

When we determine the inventory for these two demand streams together, we end up with the results that are presented in Table 21. The results can be compared with the results for only the replenishment demand in Table 41. The system costs when we optimize both demand streams together are about €40,000 less than when we optimize them separately, a large pooling potential is present with these two demand streams.

Multi-item
For the multi-item case we do the same analysis as for the single-item case. The results are in Table 22 and Table 23. The results for the replenishment demand only are present in Table 44. Also in the multi-item case there are savings possible with the pooling effect, however they are much smaller than in the single-item case. This is according to our expectations, in single-item models each item need to be available with a certain percentage. Therefore, there is much overstocking resulting in higher costs, especially for the low volume/high cost price items. Higher volumes will reduce the percentage of overstocking.
Table 22: Optimization for each stream in isolation (3MI)

<table>
<thead>
<tr>
<th></th>
<th>$F_i$</th>
<th>$\beta_i(S)$</th>
<th>$C_i(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOL-locations</td>
<td>95%</td>
<td>95.04%</td>
<td>€ 39,426</td>
</tr>
<tr>
<td>Direct demand</td>
<td>96%</td>
<td>96.00%</td>
<td>€ 42,395</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td></td>
<td>€ 81,821</td>
</tr>
</tbody>
</table>

Table 23: Alternative 3MI with direct demand

<table>
<thead>
<tr>
<th>Location</th>
<th>$F_i$</th>
<th>$\beta_i(S)$</th>
<th>$C_i(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>79.38%</td>
<td>€ 17,681</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>95.08%</td>
<td>€ 3,428</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>95.18%</td>
<td>€ 389</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 15,098</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>97.69%</td>
<td>€ 18</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>95.61%</td>
<td>€ 258</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>95.11%</td>
<td>€ 3,713</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>99.73%</td>
<td>€ 4</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>95.07%</td>
<td>€ 5,254</td>
</tr>
<tr>
<td>Direct</td>
<td>96%</td>
<td>96.00%</td>
<td>€ 26,399</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td>95.58%</td>
<td>€ 72,242</td>
</tr>
</tbody>
</table>

7.5.2. Work packages

In this Section we will add the demand for work packages at the central location to replenishment demand. We first deal with the data input thereafter the results are presented.

Data input

Demand data

For the work packages we have historical demand for ten months (1-3-2013 to 29-1-2014). From these data we can analyze the structure of the work packages. For the amount of order lines, Failure items etc.

Lead-times to location ‘work packages’

This is the same case as for the direct demand. We therefore use a lead-time of 1E-20.

Target fill rate

For the Failure items in the work packages the average number of items in a work package is 2.12 units, where the total average is 11.2 units (4-6 order lines). The total packages need to be delivered with a package fill rate of 95%. We therefore have determined to have 2 Failure items together available with a percentage of 98% which is approximately 99% per item.

Results

For the work packages we execute the same analyses as for the direct demand.

Single-item

Results for the single-item case are in Table 24 and Table 25. Results for only replenishment demand are in Table 41. We observe that the savings potential is much smaller than for the direct demand. This is likely due to the larger difference in target fill rates.
Table 24: Optimization for each stream in isolation (3SI)

<table>
<thead>
<tr>
<th>Location</th>
<th>( F_j )</th>
<th>( \beta_j(S) )</th>
<th>( C_j(S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOL-locations</td>
<td>95%</td>
<td>97.20%</td>
<td>€ 118,094</td>
</tr>
<tr>
<td>Work packages</td>
<td>99%</td>
<td>99.39%</td>
<td>€ 103,967</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td></td>
<td>€ 222,061</td>
</tr>
</tbody>
</table>

Table 25: Alternative 3SI with work packages included

<table>
<thead>
<tr>
<th>Location</th>
<th>( F_j )</th>
<th>( \beta_j(S) )</th>
<th>( C_j(S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>87.00%</td>
<td>€ 81,138</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>97.85%</td>
<td>€ 6,965</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>98.04%</td>
<td>€ 973</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>97.42%</td>
<td>€ 37,966</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>97.96%</td>
<td>€ 269</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>96.71%</td>
<td>€ 255</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>97.22%</td>
<td>€ 8,362</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>99.62%</td>
<td>€ 4</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>97.94%</td>
<td>€ 11,127</td>
</tr>
<tr>
<td>Direct</td>
<td>99%</td>
<td>99.38%</td>
<td>€ 45,264</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td>98.61%</td>
<td>€ 192,322</td>
</tr>
</tbody>
</table>

Multi-item

Results for the multi-item case are in Table 26 and Table 27. The results can be compared with the results in Table 44, which shows the results for the replenishment demand only. For the multi-item models the savings are even bigger than for the direct demand. This is not surprisingly because multi-item models especially perform well in situations with high target fill rates.

Table 26: Optimization for each stream in isolation (3MI)

<table>
<thead>
<tr>
<th>Location</th>
<th>( F_j )</th>
<th>( \beta_j(S) )</th>
<th>( C_j(S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOL-locations</td>
<td>95%</td>
<td>95.04%</td>
<td>€ 39,426</td>
</tr>
<tr>
<td>Work packages</td>
<td>99%</td>
<td>99.00%</td>
<td>€ 59,788</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td></td>
<td>€ 99,214</td>
</tr>
</tbody>
</table>

Table 27: Alternative 3MI with work packages included

<table>
<thead>
<tr>
<th>Location</th>
<th>( F_j )</th>
<th>( \beta_j(S) )</th>
<th>( C_j(S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>83.62%</td>
<td>€ 19,525</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>95.15%</td>
<td>€ 3,418</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 346</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>95.10%</td>
<td>€ 15,857</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>97.72%</td>
<td>€ 18</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>95.06%</td>
<td>€ 256</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>95.14%</td>
<td>€ 3,775</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>99.83%</td>
<td>€ 4</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>95.22%</td>
<td>€ 5,469</td>
</tr>
<tr>
<td>W. packages</td>
<td>99%</td>
<td>99.00%</td>
<td>€ 40,489</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td>97.39%</td>
<td>€ 89,157</td>
</tr>
</tbody>
</table>
7.5.3. Direct demand and work packages

Now we add both direct demand and work packages to the model. We now have included all three demand streams. Analyses are again executed for the single- and multi-item case.

Single-item

Results are in Table 28 and Table 29. Results for the isolation optimization are the combined results of Table 20 and Table 24. We observe that the pooling effect of the three demand streams together have a potential of 25%.

<table>
<thead>
<tr>
<th>Location</th>
<th>$F_i$</th>
<th>$\beta_i(S)$</th>
<th>$C_i(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOL-locations</td>
<td>95%</td>
<td>97.20%</td>
<td>€ 118,094</td>
</tr>
<tr>
<td>Direct demand</td>
<td>96%</td>
<td>97.69%</td>
<td>€ 120,524</td>
</tr>
<tr>
<td>Work packages</td>
<td>99%</td>
<td>99.39%</td>
<td>€ 103,967</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td></td>
<td>€ 342,585</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>$F_i$</th>
<th>$\beta_i(S)$</th>
<th>$C_i(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>86.87%</td>
<td>€ 117,368</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>98.24%</td>
<td>€  6,970</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>98.14%</td>
<td>€  973</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>97.59%</td>
<td>€ 35,256</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>98.06%</td>
<td>€  270</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>97.18%</td>
<td>€  257</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>97.21%</td>
<td>€  8,587</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>99.65%</td>
<td>€      4</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>98.27%</td>
<td>€ 11,144</td>
</tr>
<tr>
<td>Direct demand</td>
<td>96%</td>
<td>98.17%</td>
<td>€ 42,432</td>
</tr>
<tr>
<td>W. packages</td>
<td>99%</td>
<td>99.34%</td>
<td>€ 38,551</td>
</tr>
<tr>
<td>Total system</td>
<td>98.50%</td>
<td></td>
<td>€ 261,811</td>
</tr>
</tbody>
</table>
**Multi-item**

Results are in Table 30 (Combined results of Table 22 and Table 26) and Table 31. For the multi-item case we can save about 20% by pooling the three demand streams together.

<table>
<thead>
<tr>
<th>Location</th>
<th>$F_{ij}$</th>
<th>$\beta_i(S)$</th>
<th>$C_i(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOL-locations</td>
<td>95%</td>
<td>95.04%</td>
<td>€ 39,426</td>
</tr>
<tr>
<td>Direct demand</td>
<td>96%</td>
<td>96.00%</td>
<td>€ 42,395</td>
</tr>
<tr>
<td>Work packages</td>
<td>99%</td>
<td>99.00%</td>
<td>€ 59,788</td>
</tr>
<tr>
<td>Total system</td>
<td></td>
<td></td>
<td>€ 141,609</td>
</tr>
</tbody>
</table>

We can conclude that pooling of the three demand streams together can save inventory costs of between 25% and 20% for the single-item case and multi-item case respectively. For both the single- and multi-item case the service is higher when we optimize all streams together. This is due to the fact that the demands at the local-warehouses are smaller compared to the demand for the isolated control. This results in more overstocking and therefore the fill rates are higher.
8. Conclusions and recommendations

This last Chapter discusses the main conclusions and recommendations that are the results of this research project. The research question that was formulated in Section 4.1 was the following:

“What is the most suitable inventory model to supply spare parts in a (semi-)coordinated way, and what is the improvement potential in terms of cost savings and performance?”

With the sub-questions to answer this question formulated as follows:
1. What is a useful classification of parts with respect to inventory control?
2. What is the current structure and control of stock points?
3. What are relevant Key Performance Indicators (KPI’s) of the VOL-locations?
4. Which inventory model is most suitable in an uncoordinated situation?
5. Which inventory model is most suitable in a semi-coordinated situation?
6. Which inventory model is most suitable in a coordinated situation?
7. What are the improvement potentials compared to the ‘current’ situation?

Now we will discuss the conclusions and recommendations. Some directions for further research are discussed as well.

8.1. Conclusions

Below are the main conclusions that are based on this research project. We will follow the order of the sub-questions.

The model that we have used has the assumption of a one-for-one replenishment strategy. And many spare parts models have this assumption according to Van Oostrum (2013). Therefore, the current distinction between Bulk and Failure items (Section 3.2) is a useful product classification to use in spare parts inventory control. This is not only a useful classification for this research but also in the practical situation of Railpro, because this is a main distinction in the way different SKU’s are controlled (Section 3.2.2.).

The current structure and control of the rail infrastructure supply chain shows a starting point to search for improvements. However, the complexity with multiple players and different contracts can impede the practical implementation of a improved inventory control model (Chapter 2). Railpro does not take into account the different demands steams they face, there is no differentiated service for the different demand streams or any priority rules (Section 3.1). When service levels are differentiated, pooling these demand streams together can save inventory costs of between 25% and 20% for the single-item case and multi-item case respectively (Section 7.5).

In the rail infrastructure industry the consequences of not having an item available to repair the system (rail track) highly depends on the urgency of the failure. It is therefore difficult to determine a general service measure that is applicable to this situation. However, according to the current contracts between Railpro and the contractors, an aggregate fill rate measure is a relevant performance measure.
The developed model consisting of three alternatives is a useful tool in answering the main research question. Each alternative has a different scope of available information and control. In the first alternative, control is possible at the central location without any information of the rest of the supply chain. In the second alternative control of the central location is possible with additional information available from the stock points downstream in the supply chain. In the third alternative the central location and the downstream stock points can both controlled with the same information as in the second alternative (Section 4.2). All three alternatives are used with both a single-item and a multi-item approach which shows large differences in the results.

For the multi-item models we needed the assumption that all items have the same criticality. It is questionable to which extend this assumption is justified. We will come up with some solutions to this in the recommendations and model extensions.

The three alternatives show clear differences in the results and show that with the ‘current practice’ of the uncoordinated situation(Alternative1) and for the semi-coordinated situation of alternative 2 it is not possible to ensure the target fill rate agreements with the customers. In both situations it depends on the customer stocks whether the fill rates are attainable.

With the comparison of the six alternative models it is revealed that inventories within the supply chain can be reduced by 84% compared to ‘current practice’ while the target fill rates are met. It should be remarked that for the models with the lowest costs, the fill rates are lower compared to the other models. The case study shows that the multi-item approach is superior to the single-item approach in all three alternatives. Available information about the customer inventories can decrease inventories with 10%-38%. When the central and local warehouses are optimized together system inventory costs can drop by 49%-84%. We will stress that these exact numbers are only valid for the given situation and based on the input parameters. However, from the sensitivity analyses of the input parameters we can conclude that most results are insensitive for different input values. The results of Alternative 2 for both Single-item and Multi-item are sensitive for the predetermined stock levels/ demand rates. When the base stock levels are high compared to the demand rates this result in high local costs. When the base stock levels are low this results in high central costs or an infeasible solution, because the target fill rates cannot be reached.

For the issue of demand rates with zero stocks in Alternative 2 (Section 7.2)we can conclude that this influence both the results of Alternative 1 and 2. The situation we created by adding stock for these items is more according to a practical situation, however it misrepresent the actual performance of these alternatives because with the current base stock levels, the performance is much lower and it gives solutions that are infeasible.

Determining starting value’s for models that cope with calculation problems in Excel, due to extremely small probabilities, do influence the results. For the multi–item models costs (and performance) are higher when we determine positive starting base stock levels compared with starting with base stock levels of zero.
Overall we can conclude that we have developed a model that gives clear insights into the saving potentials for the rail infrastructure industry. And these potentials are worth to further investigate how these insights can be used in practice.

8.2. Recommendations

In this Section we describe the main recommendations, possible model extensions, and directions for further research.

8.2.1. Main recommendation

The developed inventory control models are useful to evaluate given base stock levels for example to investigate the feasibility of predetermined stock levels when a new location is added to the VOL-concept.

The output of the models is based on the available information. The more reliable this information is the more reliable the output of the control models will be. The data about the demand rates can highly influence the results. An administration of failure demand or installed base management can increase this reliability, also returns are important when determining demand rates. Furthermore, it could be useful to think about the registration of different order for inventory control purposes. Registration of the demand stream, contract region, stock point etc. can likely increase the performance.

For the multi-item models we made the assumption that all items have the same criticality. However, as discussed in Section 5.2.2 there are some items that are strategic to the contractors. We recommend analyzing the different criticalities of the products, this should be done in cooperation with the contractors (and ProRail). If there are some products with higher criticality we recommend first determining the base stock levels for these items, and letting the model start with these values. If there is a broader classification in two or three classes, then it might be useful to extend the model as we will describe later.

The models we developed for coordinating the supply chain show remarkable cost savings between the different alternative control mechanisms. And combined optimization of the different demand streams shows a large savings potential compared to the isolated optimization. It is therefore recommended to investigate if isolating the demand stream of replenishment to the VOL-locations will cause a higher increase in costs than the savings of the coordinated control for the replenishment demand. Or the model can be extended mended to use a combined (all demand streams) optimization approach. A threshold-based rationing rule should be implemented at the central location, this rule stops fulfilling demand for some stream(s) if the on hand stock drops below a certain level. This threshold-based rationing rule should also be implemented if it is decided not to use a coordinated control of the supply chain.

In the system we analyzed there are multiple parties. The contractors determine (in cooperation with Railpro) the stock levels for the local warehouses and Railpro determines the central stock. If it is decided to use the kind of models we use in Alternative 3, all inventories need to be determined together. Therefore, to implement a coordinative model there should be some kind of agreement on who is determining the stock levels, and who has to pay for the inventory.
The replenishment lead-time, which is in the control of Railpro, has no large influence on the results. The influence on the inventory costs is clear and can be compared with different transportation costs for determining the optimal length of the replenishment lead-time.

In this research we investigated the supply chain at the downstream site of Railpro. This shows large savings potentials when information is shared and the system control centrally. For the upstream supply chain information sharing and coordination can likely bring costs savings as well.

### 8.2.2. Model extensions

The models that we have developed can realize large savings. However, the models have their limitations in the assumptions that are needed or the saving potential. Therefore we describe some model extensions that are possible and will improve the performance of the model.

- In our model we assume a one-for-one replenishment policy for all locations. For the decentralized locations this was reasonable. However, for the central locations it is likely that there is batching. It is possible to include central batching into the model, see for example Kranenburg and Van Houtum (2013).

- Currently only products that have a demand process according to a Poisson process fit into the model. This requires exponential inter arrival times and an order size of one. To extend the number of products that can be incorporated and/or to have a better fit a Compound Poisson distribution can be used to describe the demand pattern. A compound distribution is a distribution where the orders arise according to a Poisson arrival process, but orders will be of different sizes.

- To determine the steady state distribution for the outstanding orders at the local stock points, we used a two-moment fit to the Poisson distribution or Negative Binomial Distribution. However, there are more distributions that can be used for this fit, or the exact method can be used as in Wong et al. (2007). According to Adan et al. (1995) there are four kinds of distributions that can be fitted. These are the Geometric, Binomial, NBD, and Poisson, where most of the time a mixture of two distributions is used. A better fit for this distribution will give a better approximation for the steady state distribution.

- If there are different levels of criticality (high-medium-low) and these are related to different mean waiting time constraints. For example high critical items need to be available immediately, medium items within one hour and low critical items within one day. Then the model can be extended with time-based aggregate fill rates as developed in Van Sommeren (2007).

- The model we have developed does not include the option for lateral or emergency shipments. The option of emergency shipments is relatively easy to implement, however it requires an extra assumption that the central location can always deliver. More information can be found in Basten and Van Houtum (2013). The option for lateral and emergency shipments can also be added, however then the whole model will change and become much more complex as shown in Kranenburg and van Houtum (2009). For an extensive overview of inventory models that include transshipments we refer to Paterson et al. (2011).
8.2.3. Further research
During the development and implementation of the different alternatives and the greedy procedure we faced some issues which we will discuss and recommend to do further research on.

- For evaluating Alternative 2 we have local warehouses that face demand but have no inventory. We chose the option to add demand for these locations according to a single-location single-item model. However, there might be better options to make the alternative suitable for comparison.

- Due to calculation problems in Excel we start the greedy approach with initial base stock levels. This calculation problem might occur when demands become so high the difference between the cumulative probabilities of a base stock level of one or zero is not observable. We therefore start the algorithm by setting all base stock levels at an ‘efficient solution’, this will be $S_{ij} \geq \max\{[λ_{ij}L_{ij}], 0\}$. However, there might be better starting solutions or options to cope with this issue.

- In our greedy approach it is needed to re-calculate all $R_{ij}$ after each change in the system base stock levels. Because after each iteration it might be possible that one of the $R_{ij}$ values is not valid anymore. This is possible if an item is added at some location and for that location the target fill rate is attained. Then all $R_{ij}$ values for that location should be zero. And the same holds for the central location when all target fill rates at locations with demand for item $I$ are met, then the $R_{i0}$ for that item should be zero. And the same holds when the ratio not need to be zero, but the distance is smaller than the previous calculation $\Delta D_{ij}$ (change in distance). Maybe there is a solution where it is not needed to update all $R_{ij}$ after each iteration which can decrease the computation time.
Literature


## Appendices

### A. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>Alternative 1, Single-Item</td>
</tr>
<tr>
<td>1MI</td>
<td>Alternative 1, Multi-Item</td>
</tr>
<tr>
<td>2SI</td>
<td>Alternative 2, Single-Item</td>
</tr>
<tr>
<td>2MI</td>
<td>Alternative 2, Multi-Item</td>
</tr>
<tr>
<td>3SI</td>
<td>Alternative 3, Single-Item</td>
</tr>
<tr>
<td>3MI</td>
<td>Alternative 3, Multi-Item</td>
</tr>
<tr>
<td>ATB</td>
<td>Order request created by the ERP system</td>
</tr>
<tr>
<td>BBM</td>
<td>BovenBouw Materialen</td>
</tr>
<tr>
<td>BEA</td>
<td>Document that specifies at which company a product should be ordered</td>
</tr>
<tr>
<td>EOQ</td>
<td>Economic Order Quantity</td>
</tr>
<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
</tr>
<tr>
<td>ETM</td>
<td>Elektro Technische Materialen</td>
</tr>
<tr>
<td>FCFS</td>
<td>First Come First Served</td>
</tr>
<tr>
<td>HSL</td>
<td>High Speed Line</td>
</tr>
<tr>
<td>KPI's</td>
<td>Key Performance Indicators</td>
</tr>
<tr>
<td>M&amp;I</td>
<td>Marketing and Innovation</td>
</tr>
<tr>
<td>NBD</td>
<td>Negative Binomial Distribution</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>OPC</td>
<td>Output Process Contract</td>
</tr>
<tr>
<td>PGO/PBC</td>
<td>Performance Based Contracts</td>
</tr>
<tr>
<td>SKU</td>
<td>Stock Keeping Unit</td>
</tr>
<tr>
<td>SLS</td>
<td>Supply, Logistics and Service</td>
</tr>
<tr>
<td>SPC</td>
<td>Product specification</td>
</tr>
<tr>
<td>VGP</td>
<td>Moving Average Price</td>
</tr>
<tr>
<td>VMI</td>
<td>Vendor Managed Inventory</td>
</tr>
<tr>
<td>VOL</td>
<td>Voorraad Op Locatie / Inventory At Location</td>
</tr>
</tbody>
</table>
B. Organization chart Railpro
C. Notation

$\mathbb{N}_0$ The set of all integer values including 0

$Z^*$ $\max(Z,0)$ for any variable $Z$

$I$ Set of Stock Keeping Units(SKU's), numbered $i=1,2,\ldots,|I|$

$J$ Set of local stock points, numbered $j=1,2,\ldots,|J|$

$J^0$ The union of location 0 with the collection $J$

$\lambda_{ij}$ Demand rate for item $i \in I$ at stock point $j \in J$ following a stationary Poisson distribution.

$L_{ij}$ Deterministic lead-times to stock point $j \in J$ from its supplier for product $i \in I$

$D_{ij}$ Average demand during the lead-time-Poisson $(L_{ij}\lambda_{ij})$.

$h_{ij}$ Percentage for holding item $i \in I$ on stock for one year at stock point $j \in J^0$ and in the pipeline to its successors

$P_i$ The cost price of item $i \in I$

$F_{ij}$ Target fill rate at local stock point $j \in J$ for product $i \in I$, expected fraction of demand that is delivered immediately upon request

$F_j$ Target aggregate fill rate at local stock point $j \in J$

$S^P_{ij}$ Predetermined order up to level for item $i \in I$ at stock point $j \in J$. These are stock levels that are agreed on in the contracts between the customer and Railpro

$S_i$ (Row)Vector with order up to levels for all locations for item $i \in I$

$S_0$ (Column)Vector with order up to levels for all items for location 0

$S$ All base stock levels represented in a $|I| \times |J|$ matrix

$Z_{ij}(S_i)$ Level of outstanding orders at stock point $j \in J$ for item $i \in I$

$C(S)$ Long-run expected costs per unit time, dependent on $S$

$C_j(S)$ Expected costs for location $j$, dependent on $S$.

$C^j_{ij}(S)$ In-transit holding cost for item $i \in I$ between the central location 0 and $j \in J$

$\beta_i(S_i)$ Expected fill rate for item $i \in I$ at location $j \in J^0$

$\beta_j(S)$ Expected aggregated fill rate for location $j \in J^0$

$e_j$ (Row)Vector with size $|J^0|$ with the $j$-th element equal to 1 and all other elements equal to 0.

$\Delta C_{ij}(S)$ Increase in cost when one unit of item $i \in I$ is added at stock point $j \in J^0$

$\Delta D_{ij}(S)$ Decrease in distance to the target fill rate when one unit of item $i \in I$ is added at stock point $j \in J^0$

$R_{ij}(S)$ Ratio between decrease in distance and increase in holding costs

$I_{ij}(S_i)$ Average stock on hand at stock point $j \in J^0$ for item $i \in I$

$B_{ij}(S_i)$ Average back orders at stock point $j \in J^0$ for item $i \in I$

$B^j_{ij}(S_{ij})$ Average back orders for item $i \in I$ at the central stock point, due to demand from location $j \in J$

$\lambda_{i0} = \sum_{j=1}^{|J|} \lambda_{ij}$

$\lambda_j = \sum_{i=1}^{|I|} \lambda_{ij}$
D. Model testing

Below are the results for the tests described in Section 6.4. First, the evaluation is tested. Thereafter some tests for the greedy approach are executed.

Evaluation

To test if the evaluation of a given situation is done correctly we compare the output to an existing example of a linear multi-echelon model (Atan, 2012). However, with specific input parameters we also can test characteristics of a distribution network. The input parameters are as in Table 32.

Table 32: Input parameters evaluation test

<table>
<thead>
<tr>
<th>Demand</th>
<th>( \lambda )</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-times</td>
<td>((L_0, L_1))</td>
<td>((0.25, 0.25))</td>
</tr>
<tr>
<td>Unit holding cost</td>
<td>((h_0, h_1))</td>
<td>((0.25, 0.5))</td>
</tr>
<tr>
<td>Base-stock levels</td>
<td>((s_0, s_1))</td>
<td>((5, 5))</td>
</tr>
</tbody>
</table>

The evaluation results for a linear situation are in Table 33. These are exactly the same as in the example.

Table 33: One location with a demand rate of 16

<table>
<thead>
<tr>
<th>J</th>
<th>EB0</th>
<th>EI0</th>
<th>VB0</th>
<th>Ezi</th>
<th>Vzi</th>
<th>a</th>
<th>Pi</th>
<th>Ri</th>
<th>EI1</th>
<th>EB1</th>
<th>( \beta_{ij} )</th>
<th>( W_{\beta_{ij}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.41</td>
<td>1.41</td>
<td>0.91</td>
<td>4.41</td>
<td>4.90</td>
<td>0.02</td>
<td>0.89</td>
<td>39.24</td>
<td>1.22</td>
<td>0.22</td>
<td>0.55</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Now we will test whether the distribution situation is also modelled correctly. We test this with the situation of two identical locations with each having a demand rate of 8 and the parameters as in Table 32. Results are in Table 34

Table 34: Both locations have a demand rate of 8

<table>
<thead>
<tr>
<th>J</th>
<th>EB0</th>
<th>EI0</th>
<th>VB0</th>
<th>Ezi</th>
<th>Vzi</th>
<th>a</th>
<th>Pi</th>
<th>Ri</th>
<th>EI1</th>
<th>EB1</th>
<th>( \beta_{ij} )</th>
<th>( W_{\beta_{ij}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.41</td>
<td>1.41</td>
<td>0.91</td>
<td>2.21</td>
<td>2.33</td>
<td>0.03</td>
<td>0.95</td>
<td>39.24</td>
<td>2.84</td>
<td>0.04</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>2</td>
<td>0.41</td>
<td>1.41</td>
<td>0.91</td>
<td>2.21</td>
<td>2.33</td>
<td>0.03</td>
<td>0.95</td>
<td>39.24</td>
<td>2.84</td>
<td>0.04</td>
<td>0.92</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Results for two different locations are in Table 35.

Table 35: Two locations with demand rates of 8 and 16 respectively

<table>
<thead>
<tr>
<th>J</th>
<th>EB0</th>
<th>EI0</th>
<th>VB0</th>
<th>Ezi</th>
<th>Vzi</th>
<th>a</th>
<th>Pi</th>
<th>Ri</th>
<th>EI1</th>
<th>EB1</th>
<th>( \beta_{ij} )</th>
<th>( W_{\beta_{ij}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.52</td>
<td>0.58</td>
<td>3.50</td>
<td>2.51</td>
<td>2.73</td>
<td>0.04</td>
<td>0.92</td>
<td>28.47</td>
<td>2.57</td>
<td>0.08</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>2</td>
<td>1.52</td>
<td>0.58</td>
<td>3.50</td>
<td>5.01</td>
<td>5.89</td>
<td>0.04</td>
<td>0.85</td>
<td>28.47</td>
<td>0.95</td>
<td>0.96</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Greedy approach

For the greedy approach we will test whether we can generate some logical output to test the functioning of the algorithm. Some examples: when we have two identical products except for their cost price, the product with the lowest cost price should be in favor to stock.

Table 36: Test greedy approach

<table>
<thead>
<tr>
<th>Material</th>
<th>VGP</th>
<th>S0</th>
<th>L0</th>
<th>h0</th>
<th>( \lambda_0 )</th>
<th>Fi</th>
<th>Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>13</td>
<td>1</td>
<td>0.25</td>
<td>8</td>
<td>0.95</td>
<td>0.94</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>19</td>
<td>1</td>
<td>0.25</td>
<td>8</td>
<td>0.95</td>
<td>0.99</td>
</tr>
</tbody>
</table>
for location 1 to 10 is zero when we add the first item at location 0. This is not the case in any iteration.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>$\sum_{j=1}^{J} S_{ij}$</th>
<th>$S_{i0}$</th>
<th>$\sum_{j=1}^{J} S_{ij} = 0$ and $S_{i0} = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 37: Results for not first adding central stock

We also checked whether the algorithm stops adding units at locations where the target fill rate is already met. This is indeed the case.

We also tested the influence of the initial base stock levels when starting the greedy procedure. For this situation, for which we used the data from the practical case study, the differences are small 2-3%.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>$\delta(S)$</th>
<th>$C(S)$</th>
<th>$\delta(S)$</th>
<th>$C(S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1SI</td>
<td>98.93%</td>
<td>€ 243,352</td>
<td>98.93%</td>
<td>€ 243,352</td>
</tr>
<tr>
<td>1MI</td>
<td>97.70%</td>
<td>€ 161,723</td>
<td>98.02%</td>
<td>€ 165,929</td>
</tr>
<tr>
<td>2SI</td>
<td>98.48%</td>
<td>€ 216,670</td>
<td>98.48%</td>
<td>€ 216,670</td>
</tr>
<tr>
<td>2MI</td>
<td>95.67%</td>
<td>€ 141,109</td>
<td>95.47%</td>
<td>€ 145,447</td>
</tr>
<tr>
<td>3SI</td>
<td>97.20%</td>
<td>€ 118,094</td>
<td>97.20%</td>
<td>€ 118,094</td>
</tr>
<tr>
<td>3MI</td>
<td>95.06%</td>
<td>€ 38,821</td>
<td>95.04%</td>
<td>€ 39,426</td>
</tr>
</tbody>
</table>

Table 38: Difference between initial base stock levels or starting at zero.
E. Analysis of demand distribution per period

For every inventory control model a certain probability distribution is used to describe the item demand. This is because the demand is stochastic. For spare parts inventory management most models assume a Poisson distribution. In this appendix we describe how the spare parts at Railpro are analyzed. Because we do not have enough data per location we will test on the aggregate level.

Poisson distribution

Because spare parts most of the time have infrequent moment of demand and low order quantities the Poisson distribution fits well in this situation. Also the origin of the demand grounds this choice. The demand for spare parts is caused by a failure, where failure behavior is well described by the negative exponential distribution. Then the number of defects in a certain period is Poisson distributed.

Goodness of fit test

For the analysis of this test demand data for the period 2011-2012 is used. For the moment of demand we use the desired delivery date. This can be different from the actual moment of ‘failure’. However, it the best possible method, which will not harm the results.

To determine whether the demand follow a Poisson distribution we use all demand data we have for the 555 Failure items that are stored in one of the VOL-locations. For 316 of the 555 items we have registered demand in the period 2011-2012. We should mention that we test on the moments of demand and not on the demand itself. It could be that the demand per demand moment is more than one unit, what is indeed the case in our dataset.

The Chi-square goodness-of-fit test (Montgomery & Runger, 1999) is used to test the fit between the Poisson distribution and the registered demand. With the following hypothesis, we will try to reject $H_0$ in favor of $H_1$. If we fail in rejecting the null hypothesis, we cannot say it is not from a Poisson distribution and therefore it is reasonable to say that the data is from a Poisson distribution.

$H_0$: demand data is from a Poisson distribution

$H_1$: demand data is not from a Poisson distribution

We used a significance level of 5%. This means that the chance of rejecting the hypothesis of rejecting $H_0$ is smaller than 5%. The categories within the goodness-of-fit test are the number of demands per month (1, 2, 3, .., 6). The number of month in which this number of demands occur are the observations in each category. In the literature there is much disputation about the minimum number of observations per category, ranging from 2 to 5 observations. We therefore conducted several test with different boundaries on the minimal observations per category.

Results

For the 316 items there are in total 1522 moments of demand. So, we have some products with up to 45 demands in two year, but also hundred product that only have one moment of demand. Only the first 25 items have the required number of observations. From this sample there are 24(96%)
where the null hypothesis could not be rejected. For the total population with different minimal observations per category, the number of rejections range from 6(2%) to 88(24%).

**Conclusion**

We can conclude that the Poisson distribution is a well description of the number of demands per period. We could not have enough observations for all materials, this should be no problem because especially for very low demand items(1 or 2 in one year) the Poisson process has proven to be a good representation. As we mentioned earlier, this test was about the moment of demand. Therefore we also did a small test on the number of items that are demanded. This test give the same results.
### F. Results for all alternatives

#### Table 39: Alternative 1SI

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>β_(S)_j</th>
<th>C_(S)_j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>96.98%</td>
<td>€ 90,377</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>99.60%</td>
<td>€ 35,372</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>99.64%</td>
<td>€ 8,903</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>99.37%</td>
<td>€ 56,603</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>98.76%</td>
<td>€ 293</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>99.44%</td>
<td>€ 8,903</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>99.15%</td>
<td>€ 15,333</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>97.81%</td>
<td>€ 2,058</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>99.03%</td>
<td>€ 241,550</td>
</tr>
</tbody>
</table>

#### Table 40: Alternative 2SI

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>β_(S)_j</th>
<th>C_(S)_j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>39.86%</td>
<td>€ 67,513</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>99.02%</td>
<td>€ 34,843</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>98.70%</td>
<td>€ 8,875</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>98.82%</td>
<td>€ 55,225</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>96.99%</td>
<td>€ 292</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>99.12%</td>
<td>€ 8,875</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>98.86%</td>
<td>€ 15,124</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>100.00%</td>
<td>€ 2,058</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>97.14%</td>
<td>€ 21,066</td>
</tr>
</tbody>
</table>

#### Table 41: Alternative 3SI

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>β_(S)_j</th>
<th>C_(S)_j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>79.81%</td>
<td>€ 50,715</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>97.57%</td>
<td>€ 6,928</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>96.68%</td>
<td>€ 963</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>97.39%</td>
<td>€ 39,581</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>97.54%</td>
<td>€ 269</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>96.47%</td>
<td>€ 255</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>96.64%</td>
<td>€ 8,296</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>99.52%</td>
<td>€ 4</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>97.61%</td>
<td>€ 11,084</td>
</tr>
</tbody>
</table>

#### Table 42: Alternative 1MI

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>β_(S)_j</th>
<th>C_(S)_j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>95.00%</td>
<td>€ 22,447</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>99.40%</td>
<td>€ 34,425</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>99.57%</td>
<td>€ 8,895</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>97.17%</td>
<td>€ 48,750</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>98.92%</td>
<td>€ 292</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>99.42%</td>
<td>€ 11,261</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>98.70%</td>
<td>€ 14,989</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>100.00%</td>
<td>€ 2,058</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>97.29%</td>
<td>€ 21,043</td>
</tr>
</tbody>
</table>

#### Table 43: Alternative 2MI

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>β_(S)_j</th>
<th>C_(S)_j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>44.97%</td>
<td>€ 6,975</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>97.23%</td>
<td>€ 33,732</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>97.06%</td>
<td>€ 8,789</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 47,074</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>95.31%</td>
<td>€ 286</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>97.03%</td>
<td>€ 11,241</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>95.56%</td>
<td>€ 13,925</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>100.00%</td>
<td>€ 2,058</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 20,123</td>
</tr>
</tbody>
</table>

#### Table 44: Alternative 3MI

<table>
<thead>
<tr>
<th>Location</th>
<th>F_1</th>
<th>β_(S)_j</th>
<th>C_(S)_j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>0%</td>
<td>73.36%</td>
<td>€ 7,557</td>
</tr>
<tr>
<td>1</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 3,459</td>
</tr>
<tr>
<td>2</td>
<td>95%</td>
<td>95.09%</td>
<td>€ 396</td>
</tr>
<tr>
<td>3</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 17,836</td>
</tr>
<tr>
<td>4</td>
<td>95%</td>
<td>97.67%</td>
<td>€ 19</td>
</tr>
<tr>
<td>5</td>
<td>95%</td>
<td>95.81%</td>
<td>€ 259</td>
</tr>
<tr>
<td>6</td>
<td>95%</td>
<td>95.00%</td>
<td>€ 4,000</td>
</tr>
<tr>
<td>7</td>
<td>95%</td>
<td>99.80%</td>
<td>€ 4</td>
</tr>
<tr>
<td>8</td>
<td>95%</td>
<td>95.02%</td>
<td>€ 5,897</td>
</tr>
</tbody>
</table>

Total system

- **Table 40: Alternative 2SI**
  - Central: 98.50% € 216,260
  - Total system: 98.06% € 164,160

- **Table 41: Alternative 3SI**
  - Central: 97.20% € 118,094
  - Total system: 95.55% € 144,203

- **Table 42: Alternative 1MI**
  - Central: 99.03% € 241,550
  - Total system: 98.06% € 164,160

- **Table 43: Alternative 2MI**
  - Central: 98.50% € 216,260
  - Total system: 95.55% € 144,203

- **Table 44: Alternative 3MI**
  - Central: 99.03% € 241,550
  - Total system: 98.06% € 164,160
G. Syntax optimization model alternative 3MI

Option Explicit
Sub Alternative3MI()
    'loops
    Dim a As Integer, i As Integer, i1 As Integer, j As Integer, j1 As Integer, x As Integer, y As Integer
    'number of products and locations included in the analysis
    Dim NP As Integer, NL As Integer
    NP = Sheets("All").Cells(3, 1) 'Number of Products
    NL = Sheets("All").Cells(3, 3) 'Number of Locations
    'input
    ReDim L(1 To NP, 0 To NL) As Double 'L0 is eerste kolom
    ReDim h(1 To NP, 0 To NL) As Double
    ReDim lambda(1 To NP, 0 To NL) As Double
    ReDim lambdaj(0 To NL) As Double
    ReDim Theta(1 To NP, 0 To NL) As Double
    ReDim VGP(1 To NP) As Double
    ReDim F(0 To NL) As Double
    ReDim d(1 To NP, 0 To NL) As Double 'Demand
    'output
    ReDim s(1 To NP, 0 To NL) As Double
    ReDim Ei(1 To NP, 0 To NL) As Double 'Expected Inventory
    ReDim EB(1 To NP, 0 To NL) As Double 'Expected backorders
    ReDim c(1 To NP, 0 To NL) As Double 'Costs
    ReDim ci(0 To NL) As Double 'Distance between fill rate and objective
    ReDim beta(1 To NP, 0 To NL) As Double 'Fill rate
    ReDim wbeta(1 To NP, 0 To NL) As Double 'Weighted fill rate
    ReDim wbeta1(1 To NP, 0 To NL) As Double 'Weighted fill rate when Si+ej
    ReDim dist(0 To NL) As Double 'Distance between actual fill rate and Fj
    ReDim dist1(0 To NL) As Double 'Distance between actual fill rate and Fj when Si+ej
    ReDim ddistance(1 To NP, 0 To NL) As Double
    ReDim dcost(1 To NP, 0 To NL) As Double
    ReDim r(1 To NP, 0 To NL) As Double 'Rij(Delta fill rate increase/Delta costs)
    ReDim Iteration(1 To 40000, 1 To 15) As Double 'logbook
    Dim cost As Double 'Total cost
    Dim distance As Double 'Total distance
    Dim aggregatefillrate As Double
    'evaluation
    Dim p As Double, EI02 As Double, EB02 As Double, VB0 As Double
    Dim EB0i As Double, EB0i2 As Double, VB0i As Double, EZi As Double, VZi As Double, Pi As Double, Ri As Double
    Dim Cx As Double, ax As Double, Combin As Double
    'Clear logbook
    If Sheets("all").CheckBox2 = True Then
For i = 1 To 6000
    For j = 0 To 10
        Sheets("I").Cells(i + 1, j + 1) = ""
    Next j
Next i
Else
End If

'All basestock levels zero
For i = 1 To NP
    For j = 0 To NL
        Sheets("All").Cells(i + 9, j * 6 + 3) = 0
    Next j
Next i

'Lambda0 is dependent on NL, Lambdaj is dependent on NP
For i = 1 To NP
    For j = 1 To NL
        lambda(i, 0) = lambda(i, 0) + Sheets("All").Cells(i + 9, 6 + j * 6)
    Next j
    Sheets("All").Cells(i + 9, 6) = lambda(i, 0)
Next i

For j = 1 To NL
    lambdaj(j) = 0
    For i = 1 To NP
        lambdaj(j) = lambdaj(j) + Sheets("All").Cells(i + 9, 6 + j * 6)
    Next i
    Sheets("All").Cells(8, j * 6 + 6) = lambdaj(j)
    lambdaj(0) = lambdaj(0) + lambdaj(j)
Next j

'Assign fill rates
Run ("fillrates")

'Fill arrays
For i = 1 To NP
    For j = 0 To NL
        s(i, j) = Sheets("All").Cells(i + 9, 3 + j * 6)
        L(i, j) = Sheets("All").Cells(i + 9, 4 + j * 6)
        h(i, j) = Sheets("All").Cells(i + 9, 5 + j * 6)
        lambda(i, j) = Sheets("All").Cells(i + 9, 6 + j * 6)
        d(i, j) = L(i, j) * lambda(i, j)
        F(j) = Sheets("All").Cells(8, 7 + j * 6)
        If lambda(i, 0) = 0 Then
            Else
            Theta(i, j) = lambda(i, j) / lambda(i, 0)
        End If
    Next j
    VGP(i) = Sheets("All").Cells(i + 9, 2)
Next i

'Set initial stocklevels
For i = 1 To NP

67
For j = 0 To NL
   Sheets("All").Cells(i + 9, j * 6 + 3) = WorksheetFunction.RoundDown(d(i, j), 0)
   s(i, j) = Sheets("All").Cells(i + 9, 3 + j * 6)
Next j
Next i

'Step 1
'Start evaluation
For i = 1 To NP
   'Central evaluation
   j = 0
   EI(i, j) = 0
   x = 0
   Do While x <= s(i, j)
      p = WorksheetFunction.Poisson(x, d(i, j), False)
      EI(i, j) = EI(i, j) + ((s(i, j) - x) * p)
      x = x + 1
   Loop
   beta(i, 0) = 0
   x = 0
   Do While x <= s(i, j) - 1
      p = WorksheetFunction.Poisson(x, d(i, 0), False)
      beta(i, 0) = beta(i, 0) + p
      x = x + 1
   Loop
   EI02 = 0
   x = 0
   Do While x <= s(i, j)
      p = WorksheetFunction.Poisson(x, d(i, j), False)
      EI02 = EI02 + ((s(i, j) - x) ^ 2) * p
      x = x + 1
   Loop
   EB(i, j) = d(i, j) - s(i, j) + EI(i, j)
   EB02 = d(i, j) + d(i, j) ^ 2 - 2 * s(i, j) * d(i, j) + s(i, j) ^ 2 - EI02
   VB0 = EB02 - EB(i, j) ^ 2
   c(i, 0) = VGP(i) * h(i, 0) * EI(i, 0) 'Centrale kosten
   wbeta(i, 0) = (lambda(i, 0) / lambdaj(0)) * beta(i, 0)
   'Local evaluation
   For j = 1 To NL
      If lambda(i, j) = 0 Then 'No demand = no fill rate
         betai(i, j) = 0
         EI(i, j) = s(i, j)
      Else
         EBoi = Theta(i, j) * EB(i, 0) 'central backorders due to local point i
         EZi = EBoi + d(i, j)
         VB0i = (Theta(i, j) ^ 2) * VB0 + Theta(i, j) * (1 - Theta(i, j)) * EB(i, 0)
         VZi = VB0i + d(i, j) 'Variance is equal to expectation for a Poisson distribution
         Cx = (VZi ^ 0.5) / EZi
         ax = Cx ^ 2 - (1 / EZi)
         'Expected inventory
         If ax < 0.002 Then 'Poisson
            EI(i, j) = 0
            x = 0
         Else
            Ei = Err(i, j) * d(i, j) 'expected inventory
            VZi = Ei + d(i, j) 'Variance is equal to expectation for a Poisson distribution
            Cx = (VZi ^ 0.5) / EZi
            ax = Cx ^ 2 - (1 / EZi)
            'Expected inventory
            If ax < 0.002 Then 'Poisson
               EI(i, j) = 0
               x = 0
         End If
      End If
   Next j
Next i
Do While x <= s(i, j)
    p = WorksheetFunction.Poisson(x, EZi, False)
    EI(i, j) = EI(i, j) + ((s(i, j) - x) * p)
    x = x + 1
Loop
beta(i, j) = 0
x = 0
Do While x <= s(i, j) - 1
    p = WorksheetFunction.Poisson(x, EZi, False)
    beta(i, j) = beta(i, j) + p
    x = x + 1
Loop
Else 'Poisson/NBD
    Pi = EZi / VZi 'Chance in individual experiment
    Ri = EZi * Pi / (1 - Pi) 'Number of successes until the experiment is stopped
    EI(i, j) = 0
    x = 0
    Do While x <= s(i, j)
        'Determine Combin
        Combin = 1
        For i1 = 1 To x
            Combin = Combin * ((i1 + Ri - 1) / i1)
        Next i1
        p = Combin * (Pi ^ Ri) * ((1 - Pi) ^ (x))
        EI(i, j) = EI(i, j) + (s(i, j) - x) * p
        x = x + 1
    Loop
    'Fill rate calculation
    beta(i, j) = 0
    x = 0
    Do While x <= s(i, j) - 1
        'Determine Combin
        Combin = 1
        For i1 = 1 To x
            Combin = Combin * ((i1 + Ri - 1) / i1)
        Next i1
        p = Combin * (Pi ^ Ri) * ((1 - Pi) ^ (x))
        beta(i, j) = beta(i, j) + p
        x = x + 1
    Loop
End If 'Poisson/NBD
wbeta(i, j) = (lambda(i, j) / lambdaj(j)) * beta(i, j)
End If 'no demand
c(i, j) = VGP(i) * h(i, j) * EI(i, j)
Next j
Next i
cost = 0
For i = 1 To NP
    For j = 0 To NL
        cost = cost + c(i, j)
    Next j
Next i
distance = 0
For j = 0 To NL
    betaj(j) = 0
    For i = 1 To NP
        betaj(j) = betaj(j) + wbeta(i, j)
    Next i
    dist(j) = F(j) - betaj(j)
    If dist(j) < 0 Then
        dist(j) = 0
    Else
    End If
    Sheets("All").Cells(8, j * 6 + 8) = betaj(j)
    distance = distance + dist(j)
Next j
For j = 0 To NL
    aggregatefillrate = aggregatefillrate + (betaj(j) * (lambdaj(j) / lambdaj(0)))
Next j
Sheets("All").Cells(5, 2) = distance
Sheets("All").Cells(6, 2) = cost

'a logbook
Iteration(1, 6) = cost
Iteration(1, 8) = distance
Iteration(1, 10) = aggregatefillrate

a = 1
Do While distance > 0
    'Step 2 Calculate Delta Cij, Dij. For all i and j
    For i = 1 To NP
        For j = 0 To NL
            If d(i, j) > 0 Then
                s(i, j) = s(i, j) + 1
            'Calculate Rij
            'Central evaluation
            EI(i, 0) = 0
            x = 0
            Do While x <= s(i, 0)
                p = WorksheetFunction.Poisson(x, d(i, 0), False)
                EI(i, 0) = EI(i, 0) + ((s(i, 0) - x) * p)
                x = x + 1
            Loop
            beta(i, 0) = 0
            x = 0
            Do While x <= s(i, 0) - 1
                p = WorksheetFunction.Poisson(x, d(i, 0), False)
                beta(i, 0) = beta(i, 0) + p
                x = x + 1
            Loop
            EI02 = 0
            x = 0
            Do While x <= s(i, 0)
                p = WorksheetFunction.Poisson(x, d(i, 0), False)
                EI02 = EI02 + ((s(i, 0) - x) ^ 2) * p
                x = x + 1
            Loop
            Iteration(1, 6) = cost
            Iteration(1, 8) = distance
            Iteration(1, 10) = aggregatefillrate
        Next j
    Next i
Loop

\[ EB(i, 0) = d(i, 0) - s(i, 0) + EI(i, 0) \]

\[ EB02 = d(i, 0) + d(i, 0)^2 - 2 * s(i, 0) * d(i, 0) + s(i, 0)^2 - EI02 \]

\[ VB0 = EB02 - EB(i, 0)^2 \]

\[ c1(i, 0) = VGP(i) * h(i, 0) * EI(i, 0) \] 'Centrale kosten

\[ wbeta1(i, 0) = \frac{\lambda(i, 0)}{\lambda_0} * \beta(i, 0) \]

If \( j = 0 \) Then

For \( y = 1 \) To NL

'Local evaluation

If \( \lambda(i, y) = 0 \) Then 'No demand = no fill rate

\[ \beta(i, y) = 0 \]

\[ EI(i, y) = s(i, y) \]

Else 'no demand

\[ EB0i = \Theta(i, y) * EB(i, 0) \] 'central backorders due to local point i

\[ EZi = EB0i + d(i, y) \]

\[ VB0i = (\Theta(i, y)^2) * VB0 + \Theta(i, y) * (1 - \Theta(i, y)) * EB(i, 0) \]

\[ VZi = VB0i + d(i, y) \] 'Variance is equal to expectation for a Poisson distribution

\[ Cx = (VZi^0.5) / EZi \]

\[ ax = Cx^2 - (1 / EZi) \]

'Expected inventory

If \( ax < 0.002 \) Then 'Poisson

\[ EI(i, y) = 0 \]

\[ x = 0 \]

Do While \( x <= s(i, y) \)

\[ p = \text{WorksheetFunction.Poisson}(x, EZi, \text{False}) \]

\[ EI(i, y) = EI(i, y) + ((s(i, y) - x) * p) \]

\[ x = x + 1 \]

Loop

\[ \beta(i, y) = 0 \]

\[ x = 0 \]

Do While \( x <= s(i, y) - 1 \)

\[ p = \text{WorksheetFunction.Poisson}(x, EZi, \text{False}) \]

\[ \beta(i, y) = \beta(i, y) + p \]

\[ x = x + 1 \]

Loop

Else 'Poisson/NBD

\[ Pi = (EZi / VZi) \]

\[ Ri = EZi * Pi / (1 - Pi) \]

\[ EI(i, y) = 0 \]

\[ x = 0 \]

Do While \( x <= s(i, y) \)

'Determine Combin

\[ \text{Combin} = 1 \]

For \( i1 = 1 \) To \( x \)

\[ \text{Combin} = \text{Combin} * ((i1 + Ri - 1) / i1) \]

Next \( i1 \)

\[ p = \text{Combin} * (Pi ^ Ri) * ((1 - Pi) ^ (x)) \]

\[ EI(i, y) = EI(i, y) + (s(i, y) - x) * p \]

\[ x = x + 1 \]

Loop

'Fill rate calculation

\[ \beta(i, y) = 0 \]

\[ x = 0 \]
Do While x <= s(i, y) - 1
'Determine Combin
Combin = 1
For i1 = 1 To x
    Combin = Combin * ((i1 + Ri - 1) / i1)
Next i1
p = Combin * (Pi ^ Ri) * ((1 - Pi) ^ (x))
beta(i, y) = beta(i, y) + p
x = x + 1
Loop
End If 'Poisson/NBD
wbeta1(i, y) = (lambda(i, y) / lambda(y)) * beta(i, y)
End If 'no demand
'Cost calculation
c1(i, y) = VGP(i) * h(i, y) * El(i, y)
Next y
'D Cost
dcost(i, 0) = 0
For j1 = 0 To NL
    dcost(i, 0) = dcost(i, 0) + (c1(i, j1) - c(i, j1))
Next j1
For y = 0 To NL
    beta1(y) = beta(y) + (wbeta1(i, y) - wbeta(i, y))
    dist1(y) = F(y) - beta1(y)
    If dist1(y) < 0 Then
        dist1(y) = 0
    Else
    End If
Next y
'D Distance
ddistance(i, 0) = 0
For j1 = 0 To NL
    distance(i, j) = distance(i, 0) + (dist(j1) - dist1(j1))
Next j1
'Rij
r(i, 0) = distance(i, 0) / dcost(i, 0)
Else 'j>0
'Local evaluation
If lambda(i, j) = 0 Then 'No demand = no fill rate
    beta(i, j) = 0
    El(i, j) = s(i, j)
Else 'No demand
    EB0i = Theta(i, j) * EB(i, 0) 'central backorders due to local point i
    EZi = EB0i + d(i, j)
    VB0i = (Theta(i, j) ^ 2) * VB0 + Theta(i, j) * (1 - Theta(i, j)) * EB(i, 0)
    VZi = VB0i + d(i, j) 'Variance is equal to expectation for a Poisson distribution
    Cx = (VZi ^ 0.5) / EZi
    ax = (Cx ^ 2) - (1 / EZi)
'Expected inventory
If ax < 0.002 Then 'Poisson
    El(i, j) = 0
    x = 0
    Do While x <= s(i, j)
\[ p = \text{WorksheetFunction.Poisson}(x, EZi, False) \]
\[ EI(i, j) = EI(i, j) + ((s(i, j) - x) * p) \]
\[ x = x + 1 \]
Loop
beta(i, j) = 0
x = 0
Do While x <= s(i, j) - 1
\[ p = \text{WorksheetFunction.Poisson}(x, EZi, False) \]
\[ beta(i, j) = beta(i, j) + p \]
\[ x = x + 1 \]
Loop
Else 'Poisson/NBD
\[ Pi = \frac{EZi}{VZi} \]
\[ Ri = EZi * Pi / (1 - Pi) \]
\[ EI(i, j) = 0 \]
\[ x = 0 \]
Do While x <= s(i, j)
'Determine Combin
\[ \text{Combin} = 1 \]
For i1 = 1 To x
\[ \text{Combin} = \text{Combin} * \frac{(i1 + Ri - 1) / i1}{(1 - Pi) ^ (x)} \]
Next i1
\[ p = \text{Combin} * (Pi ^ Ri) * ((1 - Pi) ^ (x)) \]
\[ EI(i, j) = EI(i, j) + (s(i, j) - x) * p \]
\[ x = x + 1 \]
Loop
'Fill rate /Distance
beta(i, j) = 0
x = 0
Do While x <= s(i, j) - 1
'Determine Combin
\[ \text{Combin} = 1 \]
For i1 = 1 To x
\[ \text{Combin} = \text{Combin} * \frac{(i1 + Ri - 1) / i1}{(1 - Pi) ^ (x)} \]
Next i1
\[ p = \text{Combin} * (Pi ^ Ri) * ((1 - Pi) ^ (x)) \]
\[ beta(i, j) = beta(i, j) + p \]
\[ x = x + 1 \]
Loop
End If 'Poisson/NBD
\[ wbeta1(i, j) = \frac{\lambda(i, j)}{\lambda(j)} * beta(i, j) \]
End If 'No demand
'Costs
\[ c1(i, j) = VGP(i) * h(i, j) * EI(i, j) \]
\[ dcost(i, j) = c1(i, j) - c(i, j) \]
'Distance
\[ beta1(j) = beta(j) - wbeta(i, j) + wbeta1(i, j) \]
\[ dist1(j) = F(j) - beta1(j) \]
If dist1(j) < 0 Then
\[ dist1(j) = 0 \]
Else
End If
\[ ddistance(i, j) = dist(j) - dist1(j) \]
'Rij
  r(i, j) = distance(i, j) / cost(i, j)
  End If ‘j=0
  s(i, j) = s(i, j) - 1
Else ‘d(i,0)>0
  End If ‘d(i,0)>0
  Next j
Next i

'Step 3a pick highest Rij
Dim max As Double
Dim indexi As Double
Dim indexj As Double
max = 0
indexi = 0
indexj = 0
For i = 1 To NP
  For j = 0 To NL
    If r(i, j) > max Then
      max = r(i, j)
      indexi = i
      indexj = j
    Else
    End If
  Next j
Next i

'Step 3b
i = indexi
j = indexj
s(i, j) = s(i, j) + 1
Sheets("All").Cells(i + 9, j * 6 + 3) = s(i, j)

'Start evaluation
i = indexi
'Central evaluation
EI(i, 0) = 0
x = 0
Do While x <= s(i, 0)
  p = WorksheetFunction.Poisson(x, d(i, 0), False)
  EI(i, 0) = EI(i, 0) + ((s(i, 0) - x) * p)
  x = x + 1
Loop
beta(i, 0) = 0
x = 0
Do While x <= s(i, 0) - 1
  p = WorksheetFunction.Poisson(x, d(i, 0), False)
  beta(i, 0) = beta(i, 0) + p
  x = x + 1
Loop
EI02 = 0
x = 0
Do While x <= s(i, 0)
  p = WorksheetFunction.Poisson(x, d(i, 0), False)
  EI02 = EI02 + ((s(i, 0) - x) ^ 2) * p
\[ x = x + 1 \]
Loop

\[ EB(i, 0) = d(i, 0) - s(i, 0) + EI(i, 0) \]

\[ EB0 = d(i, 0) + d(i, 0) \times 2 - 2 \times s(i, 0) \times d(i, 0) + s(i, 0) \times 2 - EI02 \]

\[ VB0 = EB0 - EB(i, 0) \times 2 \]

\[ c(i, 0) = VGP(i) \times h(i, 0) \times EI(i, 0) \text{ 'Centrale kosten'} \]

\[ \text{wbeta}(i, 0) = (\lambda(i, 0) / \lambda(j(0))) \times \beta(i, 0) \text{ 'Local evaluation'} \]

For \( j = 1 \) To \( NL \)
If \( \lambda(i, j) = 0 \) Then 'No demand = no fill rate
\[ \text{wbeta}(i, j) = 0 \]
\[ EI(i, j) = s(i, j) \]
Else
\[ EB0i = \Theta(i, j) \times EB(i, 0) \text{ 'central backorders due to local point i'} \]
\[ EZi = EB0i + d(i, j) \]
\[ VB0i = (\Theta(i, j) \times 2) \times VB0 + \Theta(i, j) \times (1 - \Theta(i, j)) \times EB(i, 0) \]
\[ VZi = VB0i + d(i, j) \text{ 'Variance is equal to expectation for a Poisson distribution'} \]
\[ Cx = (VZi \times 0.5) / EZi \]
\[ ax = Cx \times 2 - (1 / EZi) \]
'Expected inventory
If \( ax < 0.002 \) Then 'Poisson
\[ EI(i, j) = 0 \]
\[ x = 0 \]
Do While \( x <= s(i, j) \)
\[ p = \text{WorksheetFunction.Poisson}(x, EZi, False) \]
\[ EI(i, j) = EI(i, j) + ((s(i, j) - x) \times p) \]
\[ x = x + 1 \]
Loop

\[ \beta(i, j) = 0 \]
\[ x = 0 \]
Do While \( x <= s(i, j) - 1 \)
\[ p = \text{WorksheetFunction.Poisson}(x, EZi, False) \]
\[ \beta(i, j) = \beta(i, j) + p \]
\[ x = x + 1 \]
Loop
Else 'Poisson/NBD
\[ Pi = EZi / VZi \text{ 'Chance in individual experiment'} \]
\[ Ri = EZi \times Pi / (1 - Pi) \text{ 'Number of successes until the experiment is stopped'} \]
\[ EI(i, j) = 0 \]
\[ x = 0 \]
Do While \( x <= s(i, j) \)
'Determine Combin
\[ \text{Combin} = 1 \]
For \( i1 = 1 \) To \( x \)
\[ \text{Combin} = \text{Combin} \times (((i1 + Ri - 1) / i1) \times p) \]
Next i1
\[ p = \text{Combin} \times (Pi \times Ri) \times ((1 - Pi) \times (x)) \]
\[ EI(i, j) = EI(i, j) + (s(i, j) - x) \times p \]
\[ x = x + 1 \]
Loop
'Fill rate calculation
\[ \beta(i, j) = 0 \]
x = 0
Do While x <= s(i, j) - 1
'Determine Combin
Combin = 1
For i1 = 1 To x
  Combin = Combin * ((i1 + Ri - 1) / i1)
Next i1
p = Combin * (Pi ^ Ri) * ((1 - Pi) ^ (x))
beta(i, j) = beta(i, j) + p
x = x + 1
Loop
End If 'Poisson/NBD
wbeta(i, j) = (lambda(i, j) / lambdaj(j)) * beta(i, j)
End If 'no demand
c(i, j) = VGP(i) * h(i, j) * EI(i, j)
Next j
cost = 0
For i = 1 To NP
  For j = 0 To NL
    cost = cost + c(i, j)
  Next j
Next i
distance = 0
For j = 0 To NL
  betaj(j) = 0
  For i = 1 To NP
    betaj(j) = betaj(j) + wbeta(i, j)
  Next i
  dist(j) = F(j) - betaj(j)
  If dist(j) < 0 Then
    dist(j) = 0
  Else
  End If
  distance = distance + dist(j)
Next j
aggregatefillrate = 0
For j = 1 To NL
  aggregatefillrate = aggregatefillrate + (betaj(j) * (lambdaj(j) / lambdaj(0)))
Next j
'End evaluation
Sheets("All").Cells(5, 2) = distance
Sheets("All").Cells(6, 2) = cost
Sheets("All").Cells(7, 2) = aggregatefillrate

'Efficient frontier/logbook
i = indexi
j = indexj
'logbook
Iteration(a, 1) = a
Iteration(a, 2) = i
Iteration(a, 3) = j
Iteration(a, 4) = r(i, j)
Iteration(a, 5) = dcost(i, j)
Iteration(a, 6) = cost
Iteration(a, 7) = ddistance(i, j)
Iteration(a, 8) = distance
Iteration(a, 9) = s(i, 0)
Iteration(a, 10) = aggregatefillrate
a = a + 1
Loop

'logging
If Sheets("all").CheckBox2 = True Then
   For i = 1 To a
      For j = 1 To 10
         Sheets("I").Cells(i + 1, j) = Iteration(i, j)
      Next j
   Next i
Else
End If

Application.ScreenUpdating = True
End Sub
H. Scientific poster

Spare parts inventory planning in the Dutch railway infrastructure industry

By Jan van Oostrom

Introduction
Railpro is an independent service provider mainly serving the Dutch railway market. Carrying the right assortment and holding sufficient inventory to attain a high availability of products is an important business strategy for the company. In the last year they extend their service portfolio by taking over and managing the inventories of customers (VOL-concept). This raises the question whether there are better approaches of managing inventories in the supply chain.

“What is the most suitable inventory model to supply spare parts in a (semi-)coordinated way, and what is the improvement potential in terms of cost savings and performance?”

Method
To answer the research question we have developed a model consisting of three different alternative situations to investigate what the impact of sharing information and coordinated inventory control is. The upper element is the central location of Railpro in Hilversum. The lower elements are the VOL-locations (customers). Dotted lines are information about the demand, with D; the demand of location j that is faced by the central location. D; is the demand faced by VOL-location j. Solid lines are product streams with F; the target service for that stream. The red dots indicate that the stock levels at that location are in the scope of control and we can optimize them, otherwise they are fixed.

The optimization model is based on the model of Wong et al. (2007). However, with different performance measures. The objective is to minimize the total expected holding costs while the expected aggregate fill rates exceed the target fill rates for each location. A greedy approach is used including a two-moment approximation for the distribution of outstanding orders at the local warehouses. For the sensitivity analysis with random demand we use initial base stock levels to overcome calculation problems within Excel.

Results
Starting with initial base stock levels results in 2-3% higher costs for the multi-item models. A multi-item approach instead of a single-item approach can save 30-66% compared to a single-item approach. It is revealed that with a multi-echelon, multi-item model, inventories within the supply chain can be reduced by 84% compared to ‘current practice’ (single echelon, single-item).

<table>
<thead>
<tr>
<th></th>
<th>(S)</th>
<th>(C)</th>
<th>savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative 1 (Single)</td>
<td>€ 243,352</td>
<td>€ 298,932</td>
<td>-21%</td>
</tr>
<tr>
<td>Alternative 1 (Multi)</td>
<td>€ 268,729</td>
<td>€ 333,929</td>
<td>-24%</td>
</tr>
<tr>
<td>Alternative 2 (Single)</td>
<td>€ 236,679</td>
<td>€ 286,479</td>
<td>-21%</td>
</tr>
<tr>
<td>Alternative 2 (Multi)</td>
<td>€ 145,447</td>
<td>€ 175,547</td>
<td>-17%</td>
</tr>
<tr>
<td>Alternative 3 (Single)</td>
<td>€ 118,094</td>
<td>€ 130,394</td>
<td>-16%</td>
</tr>
<tr>
<td>Alternative 3 (Multi)</td>
<td>€ 39,426</td>
<td>€ 45,326</td>
<td>-13%</td>
</tr>
</tbody>
</table>

Sensitivity of the results
The sensitivity of several parameters is investigated. Different demand rates and supplier lead times have almost no impact on the differences between the models.

Creating random demand between 0-2 items/year for some items that have no demand does influence the results. Four different scenarios with different percentages of items are used (0%, 12.5%, 25%, and 50%).

Conclusions
Overall we can conclude that we have developed a model that gives clear insights into the saving potentials for the rail infrastructure industry. These potentials are worth to further investigate which model can be implemented in practice. Before implementation the aspects of multiple parties and interdependency between other demands streams should be investigated. Further scientific research can focus on an efficient starting solution. A time saving method for recalculation after each iteration of the greedy approach could be useful.