MASTER

Inventory pooling through lateral transshipments at a railway contractor

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Inventory pooling through lateral transshipments at a railway contractor

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ABSTRACT

This master thesis describes the implementation of an inventory pooling model that utilizes lateral transshipments. This model is used to determine the total system costs in three different inventory management scenarios for the company Strukton Rail Netherlands, which has several regional warehouses spread throughout the Netherlands. The three scenarios that are compared are: (1) the current situation, (2) a situation in which the inventory levels of the current situation are optimized and (3) a situation in which lateral transshipments are used to pool the inventory of several regional warehouses.
ACKNOWLEDGEMENT

In this report the results of my master thesis project of the master program Operations Management and Logistics are presented. This research project has been carried out at the SRX department of Strukton Rail Netherlands. I realize that completing this thesis would not have been possible without the support and guidance of others and I would like to take the opportunity here to thank these people.

I would like to thank my primary university supervisor Marco Slikker for this continuous support, insights and patience during this master thesis project. Marco has been incredibly helpful by providing extensive feedback and the opportunity for discussions about which paths to take.

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MANAGEMENT SUMMARY

The project on which we report in this thesis is performed at Strukton Rail Netherlands, which is part of the Strukton Group N.V.. Strukton Rail Netherlands operates in a business environment in which the way products and services are brought to the market is changing rapidly. To stay competitive within this changing market, Strukton Rail Netherlands is undergoing a reorganization in 2014/2015 in which a new organizational structure is introduced.

One of the goals that Strukton Rail Netherlands aims to achieve with this reorganization is improving the financial state of the company: in order to stay financially healthy it is important to SR NL to reduce unnecessary costs as much as possible. Everyone within the organization should contribute to this, for example by doing the job right the first time, being frugal with material and resources and offering ideas about the work and team. One of the reasons that costs have to be decreased is the shift by ProRail from Output Process Contracts (OPC) to less lucrative Prestatie Gericht Onderhoud (PGO, translation: Performance Based Maintenance) contracts. The main objective for which Strukton Rail is performing preventive and corrective maintenance is to ensure a high availability of the railway track. The performance of Strukton Rail Netherlands is judged by its customer ProRail based on the time it takes to restore functionality of the railway track after a failure occurs.

In order to provide quick maintenance to the railway infrastructure throughout all the contract regions that Strukton Rail Netherlands is responsible for, the company has ten regional warehouses spread throughout the country. Each of the warehouses holds an inventory of spare parts that are required to perform maintenance activities. Currently there is little to no coordination between the regional warehouses when it comes to inventory levels. This means that there is an opportunity to possibly reduce inventory holding costs by developing a way in which the regional warehouses work together more closely and coordinate their inventories.

One way of cooperating between these regional warehouses is through inventory pooling. This means that the inventory, or part of the inventory, is shared between the different warehouses. When one regional warehouse faces a demand while it is out of stock for the required item, the warehouse first checks if the demand can be satisfied through a lateral transshipment from another regional warehouse. In theory, when one includes the possibility of these lateral transshipments in the calculation of the base-stock levels, the base-stock levels should be lower while still being able to achieve the desired service level.

In this master thesis project a mathematical model has been implemented following Wong et al. (2005). This model describes a single echelon situation in which there are multiple locations (warehouses) and multiple items. The performance of a given base-stock level allocation is determined by calculating the average waiting time per location for an arbitrary item. Through the use of a greedy algorithm a (near) optimal base-stock allocation is determined. This is done by calculating per iteration of the greedy heuristic the ratio of the waiting time reduction to the increase in total system costs; the combination of item and location with the highest ratio receives an additional unit of stock. This process continues until the average waiting time per location is below the maximum average waiting time per location.

This model has been applied to the situation of Strukton Rail Netherlands, in which 3 regional warehouses and 5 different items were included. The model and its adaption are used to analyze three different scenarios: (1) the current situation, (2) situation without lateral transshipments but with optimized inventory allocation and (3) the situation in which lateral transshipments are used.

The main conclusions are that using lateral transshipments can prove beneficial for Strukton Rail Netherlands given the data that was available for this research. A cost reduction of roughly 50% could be achieved compared to the current (unoptimized) situation. Another important conclusion is that cost savings can be
achieved simply by optimizing the inventory levels per location individually. Even though the cost reductions here are significantly lower than when lateral transshipments are utilized, depending on the maximum average waiting times the cost savings can be as great as 40% compared to the current situation. The relation between model scenario and maximum average waiting time is presented in Figure 1.

The main recommendations for Strukton Rail Netherlands are that Strukton Rail Netherlands should seriously consider utilizing the concept of inventory pooling by allowing lateral transshipments to take place between the regional warehouses. However, in order to do so successfully, more accurate data is required. Therefore the next steps that Strukton Rail Netherlands has to take if it wishes to pursue the idea of inventory pooling through lateral transshipments are as follows: creating a company wide database with accurate data on item usage per location and supply lead times per item per location and creating a system to monitor the current inventory levels at each warehouse at any given point in time. This will allow the regional warehouses to communicate directly about the demands they are facing for the items and quickly establish whether lateral transshipments might be a solution for satisfying an immediate demand. Additionally, Strukton Rail has to be mindful of a clear communication with the procurement department so that it is aware that an item has been moved from one location to another. The procurement department can then communicate with the regional warehouses about whether or not replenishments are required and if so at which location(s). The more accurate the data on item demand and replenishment rates, the more accurate the mathematical model can determine the optimal base-stock level.

The most important recommendation regarding the scientific literature is researching the link between theoretical measurements for service levels and the practical service level measurements used in the railway industry. For instance, how can the availability of spare parts be translated to a workable measurement of the railway availability and which factors play a role in this? Scientific research can in this way contribute to creating a more reliable and efficient railway infrastructure that is used by many passengers and companies on a daily basis.
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In this report the results of the master thesis project on inventory pooling at Strukton Rail Netherlands are presented. Strukton Rail Netherlands is one of the contractors that (re)constructs and maintains part of the Dutch railway track for the railway network manager ProRail. An important aspect in this is having the right inventory at the right location so that the company is able to act quickly whenever a failure occurs. Currently there is little to no coordination between the different regional warehouses that Strukton Rail NL uses to store its spare part inventory. A mathematical model has been created which is used to determine the potential benefits of creating an inventory pooling system in which the inventories of spare parts are shared among the different warehouses with the goal of reducing the overall inventory levels.

1.1 THE DUTCH RAILWAY INDUSTRY

The railway industry is involved in transporting passengers or goods by way of vehicles running on rails, more commonly referred to as train transport. Railway vehicles are restricted in their movement in the sense that they have to move along existing railway tracks which usually consist of steel rails installed on ties and ballast. The carriages and wagons containing the freight or passengers are connected to form longer trains. The operations on the railway track are carried out by railway companies. These companies provide transport between train stations or freight customer facilities. The power for these operations is provided by locomotives which either draw electrical power or produce their own power, typically in the form of diesel engines.

The NS (Nederlandse Spoorwegen) is the principal passenger railway operator in the Netherlands. Freight services, which were previously also performed by a division of NS, NS Cargo, have merged with the German company DB Schenker. The network manager ProRail is responsible for the maintenance of the Dutch railway infrastructure, in order to do this ProRail has service contracts with several contractors. Each service contract runs for usually five years in a certain region of the country.

The supply chain involved in construction and maintaining the Dutch railway is structured as can be seen in Figure 2. In this supply chain ProRail uses contractors to (re)construct and maintain the railway track. These contractors rely on several suppliers for their material, the largest of which is RailPro. ProRail in turn provides the service of railway availability to passenger and freight transporters.
The next section will narrow the focus of this thesis to Strukton Rail Netherlands, which is one of the contractors used by ProRail for (re)constructing and maintaining the railway track in the Netherlands.

1.2 COMPANY DESCRIPTION STRUKTON

Strukton Rail B.V. (SR) is part of the Strukton Group N.V., which consists of four divisions: Civil Infrastructure, Worksphere, Integral Projects and Rail. The research project focusses on Strukton Rail, the remaining three divisions will first be briefly explained after which a closer look will be taken at Strukton Rail.

Strukton Civil Infrastructure develops, constructs and manages infrastructure projects on the international market. It handles large-scale works, which require a combination of skills, collaboration and innovation. Strukton Civil Infrastructure has various business units that together serve the entire construction chain.

Strukton Worksphere is involved in all areas of construction and can therefore take full responsibility for the design, realization, management and maintenance of buildings and building projects.

Strukton Integral Projects operates as a manager and investor in the field of public-private partnership in the Netherlands and Europe. It focuses on long-term, integrated contracts like DBFMO (Design, Build, Finance, Maintain, Operate) and maintenance and energy service contracts.

Strukton Rail consists of several business divisions: together these divisions offer a complete range of products and services in the field of railway infrastructure, railway vehicles and mobility systems in Europe. Their common goal is making railway transport more attractive. To attain this goal, Strukton Rail aims to provide solutions for its customers. The most important competences and specialties of SR are: track work, machines, asset management, energy systems and train systems. Strukton Rail has the mission to provide a safe and reliable rail system. Their measurement and monitoring systems prove, demonstrate and give insight into this system reliability. The goal of SR is to make rail transport an attractive option. It aims to do so with cross-border solutions in the field of rail infrastructure, railway vehicles and mobility systems. The vision of SR on attractive rail transport is: (1) aimed at the passenger; (2) safe, on time and reliable; (3) competitive with other transport modalities; (4) sustainable: energy-saving, environmentally friendly and adjusted to the environment.
Strukton Rail B.V. has organizations within The Netherlands, Sweden, Denmark, Italy, Germany and Belgium. Additionally, SR is a 50% shareholder in Eurailscout, a company that monitors the condition of the railway track in The Netherlands, Germany and France. The headquarters of SR are located in Utrecht (NL). In December 2014, the company has approximately 3.500 employees (Explanation Organizational Structure, 2014).

Figure 3 shows the organizational structure of Strukton Rail BV, in which the nine departments of which SR consists are depicted. The departments relevant for this research, which are Strukton Rail Netherlands, Strukton Systems, Strukton Rolling Stock and, are briefly discussed below. The departments outside of The Netherlands are excluded. Strukton Rail X will be discussed in more depth in section 1.2.2.

SR Netherlands

SR Netherlands is responsible for all railway related operations of SR in the Netherlands. This includes new constructions and/or maintenance activities concerning train, tram and metro tracks, cable work, catenary work, and/or installation operations on or nearby the track. SR Netherlands has several offices spread throughout the Netherlands. The largest customer is ProRail, the company that is responsible for the railway network in the Netherlands. SR Netherlands employs around 1.000 people at the start of 2014. Strukton Rail Netherlands is organizationally divided in maintenance activities and projects.

The maintenance activities focus on preventing breakdowns. Several monitoring and information systems help to do preventive and corrective maintenance. In doing this, SR Netherlands works closely with Strukton Systems (see below) and Strukton Rail X (see section 1.2.2). If, despite preventive measures, a breakdown occurs a nationwide 24 hours service organization is in place to achieve a quick recovery time of functionality.

In addition, SR Netherlands also executes multi-disciplined projects for ProRail and other clients, for example in the tram-metro business.
Strukton Systems

Strukton Systems is active within several specialized fields in the electrical market, both related to the railway track and outside of that (e.g. information systems at stations). Strukton Systems has four different Product Market Combinations (PMC) these are: Signaling & Security, Catenary, Energy Solutions, Telecom/Tunnel & Technical Installations. At the start of 2014 Strukton Systems employs 400 people, both nationally and internationally.

Strukton Rolling Stock

Strukton Rolling Stock operates internationally and provides technological solutions for the implementation of complete electrical and electronic vehicle systems. The organization consists of four departments: (1) Maintenance, responsible for maintenance of passenger rolling stock and locomotives. (2) Service Center, develops, manufactures, installs and overhauls electrical and mechanical system solutions that are applicable in the railway environment and or rolling stock. (3) Technology, provides engineering and systems integration of the actuators with a focus on reducing energy consumption, actuators, train management systems and fleet management systems. (4) Engineering, focusses on all engineering activities within Strukton Rolling Stock and mostly supports the other departments. At the start of 2014, Strukton Rolling Stock employs 90 people.

1.2.2 STRUKTON RAIL X

Strukton Rail X (SRX), as the European service centrum, supports the different divisions of Strukton Rail in several countries. SRX is involved in the following topics: business development and innovation, railway technology, engineering, securing and developing of knowledge assets and procurement. As well as quality control, occupational health & safety and the environment. SRX translates technical know-how into maintenance concepts, management systems and management organizations. Building on the practical knowledge and experiences Strukton Rail has acquired over the years.

Strukton Rail X manages, rents out, operates and maintains a large part of the railway machinery of Strukton Rail. To achieve a high productivity in short track loads (period of time in which the railway track cannot be used), Strukton Rail possesses High Output Equipment such as renewal trains, ballast cleaners and a catenary renewal train. Partially due to the increasing amount of international activities, Strukton Rail is focusing more and more on smart logistic solutions that lead to more efficient methods of working. Strukton Rail is an acknowledged rail transporter with large capacities, which brings significant advantages when it comes to bringing material to the worksite. The entire fleet of machinery is maintained at the internationally certified technical service in Zutphen. The national welding department is located in Utrecht. Approximately 300 people are employed by the SRX department at the start of 2014.

The research presented in this report has been conducted under the supervision of the head of the Operations & Purchase department within Strukton Rail X. A more detailed organizational structure of Strukton Rail X (SRX) is presented in Figure 4.
**1.2.3 PROBLEM CONTEXT**

Strukton Rail Netherlands operates in a business environment in which the way products and services are brought to the market is changing rapidly. To stay competitive within this changing market Strukton Rail Netherlands is currently undergoing a reorganization in which a new organizational structure is introduced. The reorganization brings a new business strategy that focusses primarily on the following (Strukton Rail NL Reorganization Special, 2014).

- Strengthen the position of SR NL on the safety ladder.
- Use knowledge and expertise within Strukton Rail NL as a means to company growth.
- Earn the status of “best railway contractor”.
- Realize the financial return requirement.

This research is in line with the fourth goal, because in order to stay financially healthy it is important to SR NL to reduce unnecessary costs as much as possible. Everyone within the organization should contribute to this, for example by doing the job right the first time, being frugal with material and resources and offering ideas about the work and team. One of the reasons that costs have to be decreased is the shift from OPC to less lucrative PGO contracts, which is elaborated upon in section 2.6.

SR NL has recently started Lean Six Sigma (LSS) projects that aim to do the following:

- Reduce working capital
- Improve procurement power
- Reduce failure costs
- Increase labor productivity
Each goal has its own project team that consists of members from different backgrounds with the company. The first step in these projects is mapping the business processes in its current form, and then, by following the LSS approach (George & George, 2003) reduce waste within these processes, making them more effective and efficient. The LSS approach recognizes eight different types of waste: waiting, unnecessary stock keeping, transport, overproduction, unused talent, not doing the job right the first time, unnecessary movements, superfluous process steps.

The research project described in this document focusses on optimizing the trade-off between reducing unnecessary stock and maintaining the required service level towards the customer. This research project is thereby pursuing the same goal as the “Reduce working capital” project. However, while information may be exchanged between the projects, this research is conducted independent from the projects currently already in motion within Strukton Rail.

1.2.4 STRUCTURE OF THE REPORT

This report consists of seven chapters. In the second chapter the current situation of the inventory policy of Strukton Rail NL is described. Chapter three contains the research design that has been followed during the execution of this project. The fourth chapter discusses the scientific model that was used to analyze potential benefits of using lateral transshipments. Chapter five discusses how the scientific model has been implemented in Matlab. In chapter six the data from Strukton Rail Netherlands is used as model input in order to determine the performance of Strukton Rail NL in three different scenarios. Finally, in chapter seven answers to the research questions, conclusions and recommendations are presented.
This chapter describes the current situation of the inventory management within Strukton Rail Netherlands. It will be done by describing the following aspect of SR NL: the maintenance activities, physical flow of material within the supply chain, information flow within the supply chain, the control structure, current inventory policies, service contracts with customers and service level agreements with suppliers. In addition, a brief description of the required data and relevant performance aspects will be given.

2.1 MAINTENANCE ACTIVITIES

The preventive and corrective maintenance is primarily focused on realizing a high function availability of the railway infrastructure by effective maintenance management and regular functionality inspections.

2.1.1 PREVENTIVE- AND CONDITION BASED MAINTENANCE

The new PGO contracts which focus on the performance of the maintenance contractor have shifted the focus from corrective (OPC contracts) to preventive- and condition based maintenance (see section 2.6 for more on service contracts). One way to achieve this is by measuring and monitoring those components most susceptible to failure. This is exactly what the railway condition monitoring system POSS (Preventief Onderhoud- en Storingsdiagnosesysteem Strukton, English: Preventive Maintenance and Fault Diagnosis System Strukton) does for the moving parts of the railway. Strukton developed the POSS system to optimally perform its maintenance contracts. The aim is to contribute to optimally reliable, available, maintainable and safe railways. POSS continuously and remotely monitors the condition of essential assets in the railway infrastructure and rolling stock. If points along the track use more power than usual, this could be an indication of a potential problem. This is generally the start of a failure. POSS immediately issues a warning signal or alarm. The rail infrastructure manager or maintenance engineer can then intervene and avert any disruption.

It allows for condition-based maintenance, where repairs are performed before failure but only when necessary. Maintenance frequency can be reduced as a result, which leads to lower operating costs. POSS also provides trend information from measurements for further analysis on the nature of breakdowns. This helps to assure that recurring breakdowns can be reduced to a minimum. This again leads to lower operating costs. POSS makes it possible to check the condition and quality of objects after commissioning, maintenance and repair work. It is therefore a useful tool for quality assurance. Finally, the event data is converted into information for different user roles, from management to engineer.

In addition to POSS, Strukton Rail utilizes inspections and the services of Eurailscout (a company which has inspection trains and of which Strukton Rail B.V. owns 50% of the shares) to monitor the status of the railway track. Together with manual inspections, POSS and Eurailscout provide the data input for the asset management system of Strukton Rail. This data is analyzed by maintenance engineers and the results of these analyses are used as input for the planning of maintenance activities. It is, however, impossible to perfectly predict failures and as a result of this corrective maintenance actions are still required.
2.1.2 CORRECTIVE MAINTENANCE

Whenever, despite preventive- and condition based maintenance actions, a failure occurs Strukton Rail is required to perform corrective maintenance actions. Strukton Rail distinguishes two types of failures: urgent and non-urgent (Interview LSS project manager, 2014). Urgent failures means that functionally of the railway is in jeopardy and require immediate attention since functionality has to be restored as soon as possible. Non-urgent failures do not threaten railway functionality and do not require immediate attention.

In the service contracts with ProRail, six categories of urgent failure are distinguished with increasing required response times (5-30 min, 31-60 min, etc.). The service contract specifies how many failures per category are allowed on a yearly basis. Financial bonuses can be earned if the number of failures are lower than the agreed amount, however, higher amounts result in financial penalties. This incentivizes Strukton Rail to keep the number of failures and response times very low. Further details about service contracts are unavailable due to confidentiality reasons.

2.2 PHYSICAL FLOW OF MATERIAL

The physical flow of material in the supply chain of Strukton Rail is depicted in Figure 5. As can be seen, the supply chain consists of multiple suppliers and a limited number of regional warehouses (RW).

Strukton Rail uses multiple suppliers for the material that its operations require. The most notable supplier is RailPro, which supplies material for an estimated 34% of procurement spending from SR.

The regional warehouses are spread throughout the Netherlands in such a way that they can cover the four contract regions: North-East, South, Randstad-North and Randstad-South. Each of these contract regions consists of one or more contracts, these contracts will be discussed further in section 2.6.

The inventory stored in the local warehouses of Strukton Rail is split up in three different types of inventory: failure spare parts, working stock and hazardous material, there is no overlap between these categories.
Failure spare parts are the parts that are required for restoring functionality after an item fails. Working stock are the generic goods that are kept in larger quantities and are used for multiple jobs, some examples are nuts and bolts, gloves, etc. Hazardous material such as fuel, batteries, welding material is stored in a separate locked container at the local warehouse. Additionally there are containers spread throughout the Netherlands in which some stock is kept as well, however, it is often unclear how much this is (Figure 6).

In the current situation, the inventory levels in the regional warehouses is not, or very minimally, centrally coordinated. The central procurement department, which receives the purchasing requests of all the regional warehouses, is the central entity that executes some form of coordination. When the procurement department receives a purchasing request of one of the regional warehouses, it checks if the material is available within the organization. It could be that the material is stored in a different regional warehouse, or that the material was intended to be used for a different project or repair job but has remained unused and was returned to a regional warehouse without booking it back into the inventory. If the material is available within the organization, then it is transported to the regional warehouse that made the purchasing request. If it is not available, then a purchasing order is placed at one of the suppliers. Transshipments are only executed for excess amount of stock at a location, this means that transshipments only take place when the supplying RW has more items than the set base-stock level. This possible transshipment is depicted in Figure 5 with the dotted line between RW1 and RW2, transshipments between other combinations of regional warehouses has been left out of the image for the sake of clarity.

The items used by Strukton Rail can be divided into five categories depending on where in the supply chain the products are stored and by whom. These categories are as follows:

1. Railstock: an inventory collection of items which are difficult to acquire but of which the availability should be well organized in order to be able to resolve failures and restore functionality as quickly as possible. Railstock is a collaboration between ProRail, several contractors among which Strukton Rail and Voestalpine Railpro.
2. Common items: are not kept in stock by Strukton Rail. However, an availability agreement has been made about these items with RailPro. This agreement typically specifies a delivery lead time of one day. If, for whatever reason, no such agreement has been made about a common item then this item is placed in the Railstock.
3. Regionally specific items: are kept in stock by Strukton Rail. Certain items are only used in the maintenance of railway in specific regions so those items are only kept in stock in those regions. If the delivery lead time of a regionally specific item is too long, then an agreement is sought with the supplier and the item will be kept in stock at the supplier.
4. Failure spare parts: are kept in stock by Strukton Rail according to a \((S-1,S)\) inventory policy, as further discussed in section 2.5. These failure spare parts are the same as mentioned earlier in the section on types of inventory at the local warehouse level.

5. Working stock: can be divided into two subcategories: single items and bulk items. Both are kept in stock by Strukton Rail. The inventory policy for these items is further discussed in section 2.5. This working stock is the same as mentioned earlier in the section on types of inventory at the local warehouse level.

Figure 7 shows a schematic overview of the five inventory categories and how they relate to the regional division in the three sub-categories of failure spare parts, working stock and hazardous material.

![Figure 7 Inventory categories](image)

### 2.3 INFORMATION FLOW

The information flow within the supply chain of Strukton Rail, related to the inventory of the regional warehouses, is depicted in Figure 8. The process starts at the regional warehouse, where there are three different forms for the three types of inventory. Additionally, the execution department and the job preparation/engineering department can also place procurement requests at the procurement department.

The daily usage of failure spare parts (FSP) is accounted for by the mechanics who fill in the daily usage form, the same goes for the break bulk material in the working stock (WS). The inventory level of the hazardous material (HM) is checked on a weekly basis by the regional warehouse supervisor. The three forms are checked by the regional warehouse supervisor and subsequently sent to the procurement department. The procurement department then checks in the MetaCom database (the Enterprise Resource Planning system) if the material is available internally, if so a transshipment between regional warehouse is executed. In case the material is not available, then a purchasing order is placed at the supplier. The supplier in turn sends information to the procurement department about whether or not the order is accepted, the availability of the part and the lead time. This information is passed on to the regional warehouse. Finally, the inventory levels at the regional warehouse can be updated in MetaCom by the procurement department and by the regional
warehouse. In the current situation the registering of the incoming flows to the warehouses is monitored quite well. However, outgoing flows are not always correctly booked into the system, which in turn can lead to incorrect inventory levels.

![Figure 8 Information Flow in Supply Chain SR NL](image)

### 2.4 CONTROL STRUCTURE

The descriptions of the physical and information flows reveal a regional control structure with limited centralized coordination. Where most of the decisions related to inventory control are made at the regional level. Most notably deciding on the reorder point and order up to level. This is done by a regional team consisting of a mechanic, the regional contract manager, production manager and warehouse supervisor. The reason that the teams differ per region is that the materials used are not necessarily the same in each region, however, there is a large overlap.

The central procurement department performs the limited centralized coordination in the current situation. This department has an overview of the inventory levels per regional warehouse and can, when necessary, make the decision to transport goods from one regional warehouse to another. However, this is done on a case by case operational level. Transshipments are not a core strategic part of the current inventory control policies, meaning that the control parameters (reorder point and order up to level) are chosen without considering the option of transshipments.

### 2.5 INVENTORY POLICIES

The different types of inventory are being managed by different inventory policies.

The failure spare parts are monitored on a daily basis and for every used part a purchasing order is requested, this is the \((S-1,S)\) policy. The order up to level \((S)\) has been determined by the regional team discussed in the section on control structure.

Material in the working stock is split up in two categories, single items (break bulk) and bulk material. The single items is done according to a \((s,S)\) policy. In which the reorder level \((s)\) and order up to level \((S)\) are determined by the aforementioned regional team. The usage of bulk goods is not registered on a daily basis,
instead the regional warehouse supervisor checks the bins every day and makes a judgment call if any new material has to be ordered and if so how many.

The inventory level of the hazardous material in the containers is checked on a weekly basis by the regional warehouse supervisor. If the inventory level is below a certain amount then new material is ordered up to a predetermined level, this implies a \((R,s,S)\) policy. In which the review period \((R)\) is one week, and the reorder point \((s)\) and the order up to level \((S)\) are determined by the previously mentioned regional team.

### 2.6 SERVICE CONTRACTS

Strukton Rail Netherlands currently uses two different types of service contracts with the customers, Output Process Contracts (OPC) and Prestatie Gericht Onderhoud (PGO, translation: Performance Based Maintenance). OPC used to be the standard up until a few years ago, when PGO contracts were introduced. Currently the organization is still in the transition phase between the two types of contracts, this means that in certain regions the old output process contracts are still in use while other regions have already switched to PGO contracts. Eventually OPC will disappear completely and all contracts will be PGO contracts. The two types of service contracts will be discussed briefly in the following sections.

#### 2.6.1 OUTPUT PROCESS CONTRACTS

The output process contracts that Strukton Rail Netherlands works with are characterized by a very specific description of the service requirements by the customer. The customer would make a complete and very detailed description of the services they would require and all SR NL would have to do is make sure that these services are provided. The description would include exactly which materials to use, when to perform maintenance at which location, etc. This means that all the necessary research to come to this description was the responsibility of the customer. The customers, most notably ProRail, came to the conclusion that maintenance is not part of their core business and that this is not the way to achieve the optimal cost/performance ratio and this lead to the introduction of PGO contracts.

#### 2.6.2 PGO

In PGO contracts, the customer describes the functionality they would like to have realized and it is up to the contractor to make a proposal during the tender phase as to how they would do this and what it would cost. This places the required research and engineering efforts under the responsibility of the contractor. Compared to OPC contracts the PGO contracts are substantially less lucrative, on average PGO contracts yield 40% less revenue than OPC contracts (Interview LSS project manager, 2014). This is also one of the reasons that inventory costs have to be reduced.

#### 2.6.3 KEY PERFORMANCE INDICATORS

The performance of Strukton Rail Netherlands is determined by looking at several Key Performance Indicators (KPI) as set by the customer. Since ProRail is by far the largest customer in the Netherlands, this section will focus on how ProRail judges the performance of SR NL on a quarterly basis. First it is important to look at the four most important goals for ProRail, since the service contracts with the operators exist to contribute to attaining these goals.

- A safe railway: zero preventable accidents, reducing the number of red light passes, reducing the number of risky and unsecured railway crossings and creating criteria for a safe work environment.
- Reliable railway: zero preventable failures, more and better preventive maintenance actions and better analyses of recurring failures.
• Punctual railway: further increase of punctuality and reduction of failure, achieving a train timetable that is feasible, improve the railway performance together with the transporter organizations.

• Sustainable railway: achieve a reduction in energy consumption of 30% by 2020, climb to the highest step of the CO2-performance ladder, apply more innovative railway technology and increase the sustainability of all core business processes.

The performance indicator that is most influenced by inventory levels is availability. If the right material is kept in stock this means that functionality can be restored as soon as possible, meaning the impact on the train timetable is as low as possible.

2.7 SERVICE LEVEL AGREEMENTS WITH SUPPLIERS

At the end of 2014, Strukton Rail has one Service Level Agreement (SLA) with a supplier, being RailPro. This section will briefly discuss the main points of this SLA.

The reasons for developing an agreement about the service level of RailPro towards Strukton Rail are as follows. It is essential for Strukton Rail to have access to material and services to perform function restoring maintenance actions on short term and sometimes unannounced. Considerable financial penalties are issued by the customer of Strukton Rail (ProRail) whenever the time limit is exceeded. RailPro is willing to keep certain materials on stock and take the necessary organizational measures to be able to meet the demand from Strukton Rail.

In the SLA, RailPro has agreed to deliver failure- and maintenance related material with a fixed lead time of one day (Interview Purchaser SRX, 2014), for material with an order value of up to confidential amount,-(SLA Voestalpine RailPro, 2014). In the agreement two performance measures are used: service level and delivery reliability. The product portfolio is split up in two categories: (1) the common trade assortment consisting of approximately 1500 product codes and (2) the remaining product codes which are not frequently used, this is presented in Table 1.

<table>
<thead>
<tr>
<th>Assortment Category</th>
<th>Method of measuring</th>
<th>Measuring frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service level of common trade assortment</td>
<td>% of delivered order lines on the requested date</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Delivery reliability of remaining assortment</td>
<td>% of delivered order lines on the confirmed date</td>
<td>Quarterly</td>
</tr>
</tbody>
</table>

Table 1 Service Level Agreement: Goal, Measuring Method & Frequency

Measuring per order line means that if on a single day only one order of 100 products of the same product code are ordered and only 90 products can be delivered on the requested date the service level is 0% for that day. The agreed upon service levels between RailPro and Strukton Rail NL are confidential and are therefore excluded from this document.

At the end of 2014, Strukton Rail receives a discount on the material ordered at RailPro. However, this discount increases if RailPro fails to meet the agreed upon service level and decreases if RailPro achieves the agreed upon service level or exceeds it.
2.8 PERFORMANCE

In this section the most relevant indicators of Strukton Rail’s maintenance activities related inventory performance will be briefly discussed.

2.8.1 SERVICE LEVEL

The service level performance measure of Strukton rail will first be discussed in the practical manner in which it is maintained within the organization and then a link will be made with a performance measure that can be used in a theoretical sense. The practically achieved service levels of Strukton Rail can be split up in two main parts: (1) the achieved railway availability and (2) the acquired penalty costs of failure or bonuses.

Railway availability is measured by ProRail on the basis of occurrences that negatively impact the train schedule. ProRail expresses unavailability in the number of (weighted) hours of failure time (unplanned unavailability) (Strukton Rail NL performance Report by ProRail, 2014). For the measurement of the duration of the unavailability the function recovery time of the ProRail traffic control is used, not the times registered by the contractor itself. Additionally, only the recovery time in which railway usage was scheduled is included in this calculation. The planned decommissioning time is therefore not included, however, any amount of time exceeding this planned downtime is included. It is irrelevant which specific trains have been hindered. To give a weight to the severity of the failure occurrence, the recovery time is related to the number of railway zones that have been impacted and to the railway section value (ranging from 1 to 15). An occurrence that has led to a temporary speed limitation is treated the same way as a complete stop in the schedule. However, the temporary speed limitation can receive a lower weight.

The data required for the availability analysis is therefore the unplanned downtime of the railway track as measured by ProRail, the scheduling of the railway usage, the railway zone in which the failure occurred and finally the section value of the area where the failure happened. This calculation is executed and owned by ProRail Traffic Control. Performance reports are created by ProRail on a quarterly basis and send to the contractors.

The penalty costs or bonuses that are involved with the performance are related to the function recovery time of the railway. If the total amount of time agreed up for function recovery is exceeded, financial penalties are issued by ProRail, the same goes for any excess per failure categories as discussed in section 2.1.2. Bonuses can be earned by having fewer failures per category. No exact figures are known related to the penalties or bonuses due to confidentiality reasons.

2.8.2 INVENTORY HOLDING COSTS

The management of Strukton Rail uses an inventory cost percentage of 20% of the item value, how exactly this 20% has been determined is unknown, since it is just a percentage that has been estimated by the management of Strukton Rail based on conventional management theories. There are, however, reasons to believe this estimate is too high due to the low depreciation rate of the material in stock (Interview Purchaser SRX, 2014). This low depreciation rate comes from the fact that contracts run for usually at least 5 years per region, during this time the same parts will be used. Also different regions use the same parts, this together with the long contract times means the chance of obsolescence is quite low. Nevertheless, since this percentage is currently used in the organization it will also be used in the inventory holding cost calculations made in this report.
3 RESEARCH DESIGN

This chapter will briefly go over the research design for this master thesis project.

3.1 PROBLEM DEFINITION

The reorganization within Strukton Rail Netherlands and the shift from OPC to PGO contracts brings focus to the reduction of waste within the organization. One important waste aspect is unnecessary inventory: Strukton Rail NL has to make a constant trade-off between the level of inventory of its failure spare parts versus the high requirements of service level in terms of functionality (availability) of the railway track.

3.2 SCOPE

This project focuses on reducing the inventory levels at the local warehouses using a more centralized coordination of material, under a certain service measure constraint that has to be achieved towards the customer. The scope is limited to the Maintenance department of Strukton Rail, this means that the department Projects is left out of scope. The focus in this research is on the failure spare parts inventories at the level of local warehouses within Strukton Rail, as depicted in Figure 9. The reason for this is that, when compared to the other two types of inventory, failure spare parts account for the highest capital investments.

Figure 9 Research scope in supply chain

The literature on inventory management discusses two types of theoretical models that could apply to the situation of Strukton Rail Netherlands, described by e.g. Caglar et. al (2004) and Wong et. al (2006):

- A two echelon system: centralized warehouse with regional warehouses
- Inventory pooling by making use of lateral transshipments between regional warehouses

Because a separate centralized warehouse would most likely take over the role of the main supplier (i.e. RailPro), in this research it was chosen to focus on the use of lateral transshipments between the current regional warehouses.
3.3 RESEARCH QUESTIONS

This section discusses the research questions that have been formulated based on the given problem definition and project scope. A main research question has been formulated, which is supported by several sub questions.

Main research question

Would inventory pooling, by allowing lateral transshipments between the regional warehouses, improve the performance of the inventory control for failure spare parts, in terms of costs and service level, compared to the current situation of Strukton Rail Netherlands?

Sub research questions

1. What is the structure and performance of the current inventory policy of Strukton Rail Netherlands?
2. Which key performance indicators have to be considered in the situation of Strukton Rail Netherlands?
3. What is the most appropriate scientific model that can be used to analyze the situation of Strukton Rail Netherlands?
4. What is the performance level of the optimized current inventory policy?
5. What is the performance level of the inventory policy in which the use of lateral transshipments is allowed between the regional warehouses?
6. How do the performance levels of the inventory policies with and without lateral transshipments compare to each other?

The first sub research question has already been partly answered in chapter 2, regarding the structure of the inventory policies. The second research question has been answered in section 0.

3.4 RESEARCH METHODOLOGY

The research methodology used in this research project is developed by Mitroff et al. (1974), as depicted in Figure 10. Bertrand and Fransoo (2002) have created an overview of the quantitative model-based research methodologies in the field of operations management based on the work of Mitroff et al. (1974). The model of Mitroff et al. (1974) consists of four phases, which together form the research approach for the field of operational research.

![Figure 10 Research methodology Mitroff et al.](image-url)
The first phase is conceptualization, a conceptual model is made of the problem and system that is being studied. Decisions are made about which variables need to be included and which theoretical model is appropriate for the given situation. Part of the conceptualization has already been done in the process of creating this research proposal.

The next phases are creating and solving a quantitative model which defines relationships between the variables. “The scientific model must be presented in formal, mathematical terms, such that either mathematical or numerical analysis is possible, or computer simulation can be carried out. Thus researchers in this field must be well educated in mathematical analysis, numerical analysis or computer science. In case computer simulation is used as research tool, knowledge is also needed about experimental design and statistical analysis. The scientific quality of the research is mainly determined by the ‘optimality’ of the result, given the scientific model. In case of normative research, ‘optimality’ pertains to the extent to which the result can be proven to be the best possible solution for the problem given. In case of descriptive research, ‘optimality’ pertains to the extent to which the results can be proven to give the exact characteristics of the process given.” (Bertrand and Fransoo, 2002). In this research two mathematical models will be created. One capable of evaluating and optimizing the performance of the current inventory control within Strukton Rail and one that extends this model with inventory pooling through the use of lateral transshipments between the regional warehouses. This means three scenarios will be reviewed: (1) the current situation, (2) the optimized current situation and (3) the situation in which lateral transshipments are possible. These three model scenarios are depicted in Figure 11 and Figure 12, the latter in which the dotted line represents the possible lateral transshipments. The red rectangle shows the single echelon scope of this research project.

The final phase is implementation, this research project will not include the actual implementation of the lateral transshipment system at Strukton Rail Netherlands. Instead the results of the models (current situation
and the extension with lateral transshipments) will be analyzed and summarized. Part of this is a comparison of the performances of the three scenarios. Based on these results, conclusions and recommendations will be made towards Strukton Rail NL.

3.5 DELIVERABLES

During the research project the following deliverables have been created:

- A mathematical model of the current situation and the situation extended with lateral transshipments, formulated in such a way that optimization is possible.
- Determination of the right parameters for the scientific models described above.
- The results of the model analyses including a comparison of the performances of three scenarios (current situation, optimized current situation, situation in which lateral transshipments are possible) by using the two mathematical models described above.
- Conclusions and recommendations for Strukton Rail Netherlands.
- Recommendations for further research related to this master thesis project.
This chapter discusses the requirements of the theoretical model that will be used in order to answer part of the research questions. The requirements for the model originate from the situation of Strukton Rail and from the aim of this research project, which are aligned in this case. The result of the literature review (van Kaathoven, 2014), which was created prior to this master thesis project, will then be used as a basis for selecting the most appropriate model. After a model has been selected, a more in depth look will be taken in order to ensure and argue that it is a viable choice. Next a description of the model implementation will be presented along with any limitations this brings along.

In order to answer the research questions as posed in the previous chapter the model needs to be able to describe three different scenarios, as previously discussed in section 3.4:

- Scenario 1: The current situation of Strukton Rail.
- Scenario 2: An optimized version of the current situation, without use of lateral transshipments.
- Scenario 3: The situation in which lateral transshipments are used to pool the company’s inventory.

### 4.1 MODEL REQUIREMENTS

This section will discuss the requirements the theoretical model will have to fulfill. These requirements are based on the situation of Strukton Rail Netherlands. When it comes to the management of spare part inventories it often comes down to finding the right balance between inventory holding costs and costs of downtime (unavailability), this is also the case for Strukton Rail. A certain agreed upon service level has to be reached towards the customer while at the same time minimizing inventory holding costs. Figure 13 illustrates the tradeoff between the two key performance indicators that occurs in this situation.

Figure 13 Tradeoff between Stock level and Unavailability Costs

#### 4.1.1 SERVICE LEVEL

Since Strukton Rail uses a time based measurement (as discussed in section 2.8.1) to determine its achieved service level, it makes sense to attempt to incorporate this in a theoretical model as well. Therefore, a measurement that is based on the time it takes to respond to material requirements of a failure would be the preferred choice. This makes it possible to apply the output of the theoretical model to a practical performance measurement that can be used in the day to day operations of Strukton Rail Netherlands.

Aiming for a high service level typically means that the resulting total unavailability costs are low. Unavailability costs are costs that occur when a required item is not available in stock. These costs could...
Consist of many elements, some of which are: emergency supply costs, loss of production, penalty costs. However, in this research it is chosen to relate service level solely to the time it takes before a part is available for maintenance activities. This is done in order to make sure there is no unclear overlap between service level measures and the related costs which will be part of the second KPI.

4.1.2 SYSTEM COSTS

The drawback of aiming for a high service level is that it often requires high inventory levels as well. Since inventory holding costs are an important performance aspect of Strukton Rail (as seen in section 2.8.2), these costs should also be taken into account in the theoretical model. Other costs that will play a role in the situation of Strukton Rail Netherlands as presented in this thesis will be the costs of lateral transshipments and the costs for supplying parts when all inventory locations are out of stock, these costs will be called emergency supply costs.

Therefore, in this research the system cost KPI is focused on inventory holding costs, emergency supply costs and lateral transshipment costs.

4.1.3 MODEL CRITERIA

To make a final model selection from these different models available in the literature, criteria had to be formulated. These criteria are based on the position of Strukton Rail Netherlands in its supply chain, the key performance indicators it uses and wide selection of maintenance material Strukton Rail Netherlands stores in its warehouses. In order to be a suitable model it has to fulfil the following:

1. Single-Echelon structure, since the Netherlands is a reasonably small country and suppliers of Strukton Rail are based within the Netherlands it would not make sense to setup an inventory system with more than one echelon. For example in a two-echelon structure a main warehouse would be created, which would often be redundant next to the warehouses of the suppliers.

2. A time based measure of service level performance. Since Strukton Rail’s performance is measured in the time it takes to restore functionality. It makes the most sense to select a model of which the performance is linked to time as well.

3. A multi-item approach would be preferred, since the maintenance activities of Strukton Rail require a large of number of different items which all impact the same service performance measure and since research has shown that using a multi-item approach can greatly reduce inventory holding costs compared to a single-item approach.

4.2 RELEVANT LITERATURE

In order to select an appropriate model from the existing literature on spare part inventory management a literature study has been conducted (Van Kaathoven, 2014). In this literature review first a look has been taken at maintenance management in general, after which the scope was narrowed to spare part inventories and then the literature review further zoomed in on two types of inventory systems: (1) two-echelon inventory systems and (2) single-echelon lateral transshipment inventory systems. This section will briefly summarize the findings of the literature review.

Maintenance management focusses on guaranteeing the reliability of industry assets during uptime and aim to reduce downtimes related to maintenance and repair. Three different maintenance policies have been distinguished and discussed, namely: corrective-, preventive- and condition based maintenance. To judge the performance of a maintenance policy certain maintenance performance measures are used. The main ones such as availability and “mean time before failure” have been discussed. In addition, some performance
measures related to the railway industry have been elaborated upon in light of the remainder of this master thesis project. An important finding regarding these often empirical railway performance measures is that they are often difficult to link to the more theoretical performance measures used in the scientific literature.

The review of literature on spare part inventories highlights the unique aspects that have to be taken into account when designing inventory policies around them. A more in-depth look at the time aspects of unplanned breakdowns is given. When considering spare part inventory policies, the trade-off between unavailability costs and inventory holding costs is one of the more important aspects to take into account. Several spare part characteristics are discussed: criticality, specificity, demand and value. The spare part categorization according to Huiskonen (2001) based on these characteristics provides guidelines on how to deal with spare parts based on their specificity and level of criticality.

The remainder of the literature review focuses on taking a more in-depth look at several single- and two-echelon inventory systems, highlighting the important aspects for each.

4.3 MODEL SELECTION

After a brief review of several inventory systems that belong to the aforementioned category the selection was narrowed down to two primary candidates that could be applied to the situation of Strukton Rail.

The first, from Wong et al. (2005) describes a single-echelon, multi item lateral transshipment spare part inventory system of which the performance measure is based on mean aggregate waiting times. The second, from Reijnen et al. (2009), discusses a single-echelon, single item spare part inventory system in which regional warehouses from which lateral transshipments are possible are restricted by time windows and transshipments are sent directly to the customer instead of the regional warehouse.

Both the papers of Wong et al. (2005) and Reijnen et al. (2009) describe an inventory model with a single echelon structure with a service performance level measured in time. However, the model of Wong et al. (2005) uses a multi-item approach as opposed to the single-item approach of Reijnen et al. (2009). For this reason the choice has been made to apply the model of Wong et al. (2005) to the situation of Strukton Rail.

This section will provide further arguments as to why the model of Wong et al. (2005) is appropriate in the situation of Strukton Rail. This will be done in two steps. First, reviewing how the theoretical performance measures used in the paper relate to the practical performance measures used by Strukton Rail. Second, arguing why the assumptions made in the theoretical model apply well enough to the situation of Strukton Rail.

4.3.1 PERFORMANCE MEASURES

This section will briefly go over how the performance is measured by Wong et al. (2005) in their paper. These measures can, as discussed earlier, be split up into two categories: costs and service level.

The costs that are included in the model of Wong et al. (2005) are the following: (1) inventory holding costs per item that is kept in inventory, (2) transshipment costs for moving an item from the warehouse which has the item in stock to the warehouse which faces the requirement for that item and (3) emergency supply costs for procuring an item when none of the warehouses have it in stock at the time of failure. The goal here is to minimize the total of these costs while simultaneously meeting the service related performance goal.

The service related performance is measured in the average waiting time per request for a required item. This average waiting time is measured per warehouse location and each location has a maximum level for this average waiting time which should not be exceeded.
ASSUMPTIONS

4.3.2

Wong et al. (2005) make several assumptions that are critical for the model and its analysis. This section will discuss these assumptions and explain whether or not they apply to the situation of Strukton Rail NL and will serve to justify the chosen model.

Assumption 1: Failures occur according to Poisson processes with constant rates. Wong et al. (2005) justify this assumption by stating that since for expensive technical systems failure rates are low in general, and through the use of lateral transshipments or emergency supplies the failure times are never long. The constant rates assumption comes from the argument of Wong et al. (2005) that the expensive technical systems operate at a more or less constant rate. Furthermore they assume that failures per item for the whole set of technical systems occur according to a Poisson process, which is a common assumption in the literature on spare parts inventory models. This assumption is often justified by the fact that lifetimes of parts are exponential. Another way to justify this assumption, in case of non-exponential lifetimes, applies if the set of systems is so large that the combined failure processes approach a Poisson process.

In the case of Strukton Rail NL, the system can be seen as the railway network or a subsection of this network. The assumption that failure times are never long is a valid one since it is the main priority of Strukton Rail NL to restore functionality of the railway as quickly as possible. The assumption regarding constant rates can also be justified since the railway network is used according to a reasonably constant schedule set by companies such as the Nederlandse Spoorwegen (NS). Items used in the creation and maintenance of the railway are typically subject to high quality standards and preventive maintenance is performed on a regular basis, making it reasonable to assume that low failure rates apply in the situation of Strukton Rail.

Assumption 2: All parts are repairable and there is no condemnation. Wong et al. (2005) make this assumption to assure that the inventory positions at the locations are kept at a constant level. A constant inventory position can also be obtained if: (1) items are consumable and one for one procurement is performed, such as in an (S-1,S) inventory policy; or (2) there is condemnation for repairable parts and for each condemned part a new part is procured immediately.

In the situation of Strukton Rail NL, certain parts can be repaired and in certain cases this is also the option that is chosen, however, it is also possible that repairable parts are condemned upon failure and replaced by newly procured parts. The third possibility is that parts are never worth repairing and are always replaced by new parts. This means that the main assumption of no condemnation is violated, however, the alternative assumptions mentioned in the previous paragraph do apply. For the parts that cannot be repaired, or are not worth repairing, one for one replenishment is performed and alternative assumption (1) is justified. For the parts that are repairable, but in some cases condemned anyway, alternative assumption (2) applies in the case of Strukton Rail NL.

Assumption 3: Lateral transshipments are faster and cheaper than emergency supplies. Wong et al. (2005) make this assumption to ensure that lateral transshipments are always preferred over an emergency supply.

In the situation of Strukton Rail NL it is reasonable to assume that a lateral transshipment from one regional warehouse to another is cheaper than ordering an emergency supply from a supplier such as RailPro. The items in the regional warehouses are already owned by SR NL and ordering a new item from a supplier while there is an item available at a different regional warehouse would always be more expensive. Because SR NL operates in set regions within the small country of the Netherlands and most of the suppliers are also located within the Netherlands, the time it takes to deliver an item with a lateral transshipment or an emergency supply will not differ greatly. However, time can be saved by having a speedy lateral transshipment process within the organization of SR NL, opposed to the (expedited) procurement process.
**Assumption 4:** Failed parts are returned to the warehouse that fulfilled the demand. Similar to assumption 2, this assumption is also made to ensure that the inventory positions at the locations remain constant. For example, if warehouse A has a demand for an item which is supplied by warehouse B through a lateral transshipment. The item that failed at A is sent to warehouse B for repair. Or, in case of an unrepairable or condemned item, warehouse B immediately procures a new item.

For Strukton Rail NL, this is something that should be considered if it decides to include lateral transshipments in its spare parts inventory strategy. Currently the warehouse which uses a part simply procures a new one and since there are currently no lateral transshipments the assumption only applies in part.

**Assumption 5:** Repair lead-times are exponential. This assumption is made by Wong et al. (2005) to allow them to evaluate the situation with the use of Markov processes. However, as mentioned by Wong et al. (2005), Alfredsson and Verrijdt (1999) have made a similar assumption in their paper and after analyses conclude that there is almost no change in steady-state behavior when the exponential repair lead-times are replaced with deterministic or lognormal times.

Strukton Rail either repairs or procures the items used for maintenance. Procuring an item typically takes a deterministic lead-time that is agreed upon in advance with the supplier in the service level agreement.

**Assumption 6:** Complete pooling is applied. This assumption needs to be agreed upon between the cooperating warehouses. An alternative option is to introduce threshold levels for inventory positions under which the warehouses do not have to be the source for a lateral transshipment. However, these threshold levels and their determination are not included in the model by Wong et al. (2005) and can be considered as a possible extension.

Since the regional warehouses of Strukton Rail NL are all part of the same organization there should be no difficulties justifying the assumption that all warehouses will share their entire inventory of the items considered in this situation.

**Assumption 7:** Inventory costs dominate. This assumption places the focus of the model on determining the optimal inventory levels, rather than improving the use of lateral transshipments or emergency supplies.

This assumption is somewhat justified by the description of the research problem in this master thesis project, which focusses on reducing inventory holding costs while at the same time maintaining a required service level towards the customer.

In conclusion, most of the assumptions apply in the case of Strukton Rail Netherlands. The first assumption, regarding the Poisson failure rates is the one that is the most difficult to justify since it would require an analysis of the data regarding the demand for spare parts within each of the locations of Strukton Rail. However, as will be discussed further in section 6.1.1, the availability of the data regarding the spare part items is very limited. This makes it impossible to perform any meaningful analysis.
In this chapter an in depth look will be taken at the mathematics of the model by Wong et al. (2005). First the evaluation procedure is defined, after which the greedy optimization procedure is explained.

### 4.4.1 Evaluation Procedure

In the system discussed in Wong et al. (2005) several items \(i \in \{1, 2, \ldots, I\}\) and multiple warehouses \(j \in \{1, 2, \ldots, J\}\) are considered. Item \(i\) fails at warehouse \(j\) with rate \(m^i_j\). \(M^i_j = \sum_{i=1}^I m^i_j\) denotes the total failure rate at warehouse \(j\). It is assumed that \(\sum_{i=1}^I m^i_j > 0\) \(\forall i\) and \(M^i_j > 0\) \(\forall j = 1, \ldots, J\). \(S^i_j\) is the number of spare item \(i\) warehouse \(j\) has and \(S^i_{tot} = \sum_{j=1}^J S^i_j\) is the total number of items \(i\) that the warehouses share.

The time it takes to transship an item \(i\) from warehouse \(k\) to warehouse \(j\) is denoted as \(TL^i_{kj}(= TL^i_{jk})\). Since multiple warehouses could be the source for the lateral transshipment, the closest neighbor sourcing rule is applied. In case of equal distance a choice is made with equal probabilities.

Furthermore it is assumed that complete pooling is applied, i.e. warehouses offer their entire available inventory when there is a lateral transshipment request from another warehouse.

If no item is available at any of the warehouses, an emergency supply is initiated. This means either an expedited repair or an order at a third party supplier or OEM. The average time an emergency shipment of item \(i\) takes is denoted as \(TE^i\).

A failed item \(i\) is repaired or delivered with rate \(\mu^i\). It is assumed that if an item fails and a replacement is provided by warehouse \(j\) the failed item returns to warehouse \(j\) as well. This assumption ensures that the number of items \(i\) on stock plus the number of items \(i\) in repair (or on order) at warehouse \(j\) always equals \(S^i_j\).

The performance of the system is measured with the maximum level of average waiting time per request for a ready to use item at warehouse \(j\) which is denoted by \(W^i_j\).

The total system costs consist of holding costs, transshipment costs and emergency shipment costs. A holding cost \(CH^i\) is counted for each spare part of item \(i\). The transshipment cost depends on the locations between which the lateral transshipment is executed. For item \(i\), a lateral transshipment cost \(CT^i\) is counted for each distance unit (measured in time) between the two warehouses involved in the transshipment. A cost \(CE^i\) is counted for each part coming from the emergency supply procedure.

The objective in this problem situation is to find a stocking policy \(S\) under which the average total cost is minimized subject to the waiting time constraints of all warehouses.
$\beta^i_j$: fraction of demand for item $i$ at warehouse $j$ satisfied by warehouse $j$ itself

$\alpha^i_{jk}$: fraction of demand for item $i$ at warehouse $j$ satisfied by lateral transshipments from warehouse $k$ ($k \neq j$)

$\alpha^i_{jk} = \sum_{k=1,k \neq j}^J \alpha^i_{jk}$ fraction of demand for item $i$ at warehouse $j$ satisfied by lateral transshipment

$\theta^i_j$: fraction of demand for item $i$ at warehouse $j$ satisfied by emergency supplies

$W^i_j$: average waiting time per request for an item at warehouse $j$

$\beta^i_j + \alpha^i_j + \theta^i_j = 1$ for $i = 1, ..., I; j = 1, ..., J$. Note that since complete pooling is applied $\theta^i_j$ is the same for all warehouses so $\theta^i_j = \theta^i$ for all $i$.

The system behavior regarding an item $i$ is independent of the other items and can be described as a $J$-dimensional Markov chain. For each item $i$, state $x^i = (x^i_1, ..., x^i_J)$ is introduced. Where $x^i_j$ represents the physical stock for item $i$ at warehouse $j$ and $0 \leq x^i_j \leq S^i_j, x^i_j \in \mathbb{N}_0$. Furthermore, $x^i_j+ = (x^i_1, ..., x^i_{j-1}, x^i_j + 1, x^i_{j+1}, ..., x^i_J)$ and $x^i_j− = (x^i_1, ..., x^i_{j-1}, x^i_j - 1, x^i_{j+1}, ..., x^i_J)$ are defined.

There are four possible transitions in this Markov process, which are as follows:

Transition 1: a failure of item $i$ occurs at warehouse $j$ while $x^i_j > 0$; the state transition is $x^i \rightarrow x^i_j−$ and the transition rate is $m^i_j$. The demand for item $i$ at warehouse $j$ is satisfied by warehouse $j$ itself.

Transition 2: a failure of item $i$ occurs at warehouse $j$ while $x^i_j = 0$ and $x^i_k > 0$ for at least one warehouse $k \neq j$. Define $K = \{k | k \neq j, x^i_k > 0, T^i_{jk} \leq T^i_{jm} \forall m \neq j\}$. A warehouse $k \in K$ is selected as the source of the lateral transshipment with probability $1/|K|$. The state transition is $x^i_k \rightarrow x^i_k−$ and the transition rate is $m^i_j/|K|$. This represents a lateral transshipment from warehouse $k$ to warehouse $j$.

Transition 3: a failure of item $i$ occurs at warehouse $j$ while $x^i = 0$. An emergency supply is performed, the state remains $0$ and the transition rate is $m^i_j$.

Transition 4: the repair (or supply) of an item $i$ belonging to warehouse $j$ is completed. The state transition is $x^i \rightarrow x^i_j+$ and the transition rate is $(S^i_j - x^i_j)\mu^i$.

An example of a system with two warehouses sharing item $i$ is depicted in Figure 14. Warehouse One has a base stock level of 2 for item $i$ and Warehouse Two has a base stock level of 1.

Let $q_{x \rightarrow x'}$ denote the transition rate from state $x$ to state $x'$. All the defined transition rates will form an infinitesimal generator $Q$ of an irreducible continuous-time Markov Chain and $Q$ has the size of $N \times N$, where $N = \prod_{j=1}^J (S^i_j + 1)$ represents the total number of states in the Markov process. We define $\pi$ as the steady-state probability vector and $\pi$ is determined by solving $\pi Q = 0$.

The fraction of demands for item $i$ satisfied by emergency supplies is equal to the probability of being in state 0 and therefore $\theta^i = \pi_0$. To determine $\alpha^i_{jk}$, the fraction of demand for item $i$ at warehouse $j$ satisfied by transshipment from warehouse $k$, first the following has to be defined: $X^i_{jk} = \{x^i | x^i_j = 0, x^i_k > 0, x^i_m = 0 \text{ for all } m \neq j, m \neq k, TL^i_{jm} < TL^i_{jk}\}$ and $Y^i_{jk}(x^i) = \{m | m \neq j, m \neq k, x^i_m > 0, TL^i_{jm} = TL^i_{jk}\}$ for all $x^i \in X^i_{jk}$. Then $\alpha^i_{jk}$ can be determined using the following formula:

$$\alpha^i_{jk} = \sum_{x^i \in X^i_{jk}} 1/(1 + |Y^i_{jk}(x^i)|)\pi_xi.$$

Figure 14 Markov Chain for two locations one item
The expected waiting time for a lateral transshipment of item $i$ to warehouse $j$ is given by $D_j^i = \sum_{k=1,k\neq j}^l \alpha_{jk}^i TL_{kj}^i$. The fraction of the demand satisfied by local stock is equal to $\beta_j^i = 1 - \alpha_{jk}^i - \theta^i$. However, in reality it is unlikely that the lateral transshipment times between different locations are exactly the same. Then the fraction $\alpha_{jk}^i$ can easily be determined by the simplified formula: $\alpha_{jk}^i = \sum_{\chi^i \in \chi_{jk}}^l \pi_{\chi^i}$

In order to calculate the average waiting time, first the waiting time for an item $i$ at warehouse $j$ has to be calculated, by the following expression:

$$W_j^i(S_j^i) = \beta_j^i0 + \sum_{k=1,k \neq j}^l \alpha_{jk}^i TL_{kj}^i + \theta^iTE^i = D_j^i + \theta^iTE^i$$

Taking all the items together the average waiting time per item at warehouse $j$ for a given stocking policy can be calculated by taking the probability that an arbitrary part $i$ fails at location $j$ fails and multiplying this by the average waiting time for an item $i$, and summing this over all items. This is expressed in the following formula:

$$W_j(S) = \sum_{i=1}^l \frac{m_j^i}{M_j} W_j^i(S_j^i) = \sum_{i=1}^l \frac{m_j^i}{M_j} (D_j^i + \theta^iTE^i)$$

### 4.4.2 Optimization Procedure

Using the defined notation the optimization problem can be formulated as follows:

**Problem $P_0$:**

Minimize $Z(S) = \sum_{i=1}^l \sum_{j=1}^l (CH^i S_j^i + CT^i m_j^i D_j^i + CE^i m_j^i \theta^i)$

Subject to

$$W_j(S) \leq W_j^{\text{max}}, \quad j = 1, ..., J$$

$$S_{ij} \in \mathbb{N}_0, \quad i = 1, ..., I; \quad j = 1, ..., J$$

In this optimization problem $Z(S)$ is the system cost. This system cost is calculated adding up the three cost factors: holding costs, transshipment costs and emergency supply costs. The holding costs are calculated by multiplying the holding costs per item $CH^i$ with the base-stock levels per item and location $S_j^i$. The transshipment costs are calculated by multiplying the transshipment costs per item $CT^i$ with the demand per item per location $m_j^i$ multiplied by the average waiting time for a transshipment of item to a location $D_j^i$. The emergency supply costs are calculated by multiplying the cost of emergency supply per item $CE^i$ with the demand per item per location $m_j^i$ multiplied with the probability of having zero inventory at all locations for an item $\theta^i$.

The goal of this optimization procedure is to find stocking policy $S \in \mathcal{S}$ that minimizes the total costs, where $\mathcal{S}$ is the set of all feasible solutions for problem $P_0$.

Wong et al. (2005) have developed a solution procedure consisting of two steps. The first step generates an initial solution and the second step executes a local search process which tries to improve upon the initial solution by making small changes to it until a local minimum is reached. The following section will describe the generating of the initial solution in which the greedy approach is being used, since Wong et al. (2005) conclude this works best compared to the other options they have analyzed.

The greedy approach is an iterative procedure, it starts with $S$ as an empty vector and next, in each iteration one unit of stock is added into the system. This iterative process is ended when a feasible solution is reached. In each iteration a unit of stock is added for the item and location that gives the largest decrease in distance to the set of feasible solutions per extra unit of costs. Let $e_j^i=(0,...,0,1,0,...,0)$ denote a stocking policy with one
unit of stock for item $i$ and location $j$ and zero stocks for all other items and locations. For each solution $S$ the
distance to the set of feasible solutions is defined as $\sum_{j=1}^{I} (W_j(S) - W_{j}^{max})^+$ where $(a)^+ = \max(0, a)$. For
each combination of $i \in \{1, \ldots, I\}$ and $j \in \{1, \ldots, J\}$ the ratio $r_{j}^{i}(S)$ is calculated:

$$r_{j}^{i}(S) = \frac{\Delta W_{j}^{i}(S)}{\Delta Z_{j}^{i}(S)}$$

Where

$$\Delta W_{j}^{i}(S) = \sum_{j=1}^{I} (W_j(S) - W_{j}^{max})^+ - \sum_{j=1}^{I} (W_j(S + e^{i}_j) - W_{j}^{max})^+$$

and

$$\Delta Z_{j}^{i}(S) = Z(S + e^{i}_j) - Z(S)$$

One unit of stock is added for the item and location with the highest $r_{j}^{i}$. Formally this procedure can be written
as follows:

*Step 1:* Set the initial solution $S = 0$; calculate $W_j(0)$ for all locations $j$

*Step 2:* For all $i \in \{1, \ldots, I\}$ and $j \in \{1, \ldots, J\}$: calculate $\Delta W_{j}^{i}$, $\Delta Z_{j}^{i}$ and $r_{j}^{i}$.

*Step 3:* Let $i^*$ and $j^*$ be the combination with the highest $r_{j}^{i}(S)$. Set $S = S + e^{i*}_j$;

In case there is a combination of $i$ and $j$ for which $\Delta Z_{j}^{i} \leq 0$, this should receive priority.*

If $W_j(S) \leq W_{j}^{max}$ for all $j$ go to END; otherwise go to Step 2.

*END*

* This line was initially left out of the Matlab code. However, after performing sensitivity tests particularly
  pertaining to increasing the demand, this proved to be a necessary addition to the model. See section 6.3.2 for
  further information.
5 MATLAB IMPLEMENTATION

This chapter will go over some of the important parts of the Matlab code. The entire code consisting of 11 different functions can be found in Appendix 1. Before describing the Matlab code, the scope of the model will be discussed. Next the model as described by Wong et al. (2005) will be discussed. Afterwards the adaptations that were necessary to make this model viable for a situation in which there are no lateral transshipments are presented. The adapted model will be used to determine the performance of situations 1 and 2.

5.1 MODELING SCOPE AND ISSUES

The model for which the code has been created in Matlab consists of three locations and five items. Limiting the scope to three locations can be justified within Strukton Rail Netherlands since the regional warehouses can be separated into four clusters which each have a maximum of three regional warehouses, as further elaborated upon in section 6.1.2. Each location will have a maximum base-stock level of four per item. In the situation of Strukton Rail Netherlands this limitation is not unreasonable when the items with high value and reasonable low turnover rate are considered.

The number of items would ideally have been greater than five, however, a choice was made to create a smaller more workable model, instead of a larger model that might prove too difficult to complete. So due to the rapidly increasing complexity and computation duration of the model by Wong et al. (2005) when additional locations/items are taken into account, the created model can only be used for a situation with 3 locations and 5 different items which a maximum base stock level of 4 per location.

This means the base stock levels can range from \( S = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \) to \( S = \begin{bmatrix} 4 & 4 & 4 \\ 4 & 4 & 4 \\ 4 & 4 & 4 \\ 4 & 4 & 4 \\ 4 & 4 & 4 \end{bmatrix} \).

In this situation the greedy procedure takes approximately 2-5 minutes to complete, using a laptop with an Intel® Core™ i7-2630QM 2.00GHz processor and 4.0 GB Installed memory (RAM).
5.2 EVALUATION PROCEDURE

The evaluation procedure aims to calculate the waiting times per warehouse and the total system costs for a given base stock allocation. This calculation requires the use of five functions, the connections between these functions are shown in Figure 15. The purpose, input and output of each of the functions is briefly summarized in Table 2. A distinction can be made between the global input and the local input. The global input remains the same throughout one run of the model while the local input changes on every iteration. The global input for the model is:

- the demand matrix (m),
- the replenishment rate matrix (u),
- the lateral transshipment duration matrix (TL)
- the emergency shipment duration matrix (TE)
- the inventory holding costs (CH)
- the lateral transshipment costs (CT)
- the emergency supply costs (CE)

<table>
<thead>
<tr>
<th>Function name</th>
<th>Purpose</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>funRTV</td>
<td>Transforming a row or column number of the generator matrix Q to its corresponding inventory level vector.</td>
<td>Row or column number of generator matrix Q.</td>
<td>Physical level vector ($x_i$)</td>
</tr>
<tr>
<td>funVTR</td>
<td>Transforming an inventory level vector to its corresponding row or column number in the generator matrix Q.</td>
<td>Physical level vector ($x_i$)</td>
<td>Row or column number of generator matrix Q.</td>
</tr>
<tr>
<td>CalcWDE</td>
<td>For each item separately this function creates the generator matrix Q and subsequently calculates per item and per location the expected waiting time and the expected waiting time per lateral transshipment request. Additionally it calculates the probability of requiring an emergency supply.</td>
<td>item number (y), base-stock level matrix (S).</td>
<td>waiting times (w) per item per location, waiting time per lateral transshipment request (d) per item per location, probability of all locations having an inventory level of 0 (e).</td>
</tr>
<tr>
<td>CalcWZ</td>
<td>This function uses the CalcWDE function to created matrices in which all item and locations are put together. For a given base stock level (S) this results in three matrices: waiting time, lateral transshipment waiting time, emergency shipment probabilities. Using these three matrices the costs per item/location combination can be calculated.</td>
<td>base stock level (S), output from the CalcWDE function: [w],[d],[e].</td>
<td>for the input base stock level (S): Matrix (W) with waiting times for each combination of item and location, Matrix (Z) with costs for each combination of item and location.</td>
</tr>
</tbody>
</table>
CalcWJ calculates the average waiting times per location for a given inventory level allocation (S).

- base stock level (S),
- average waiting times per location [Wj]

<table>
<thead>
<tr>
<th>Table 2 Evaluation Procedure Matlab Functions</th>
</tr>
</thead>
</table>

Figure 15 shows the connections between the evaluation procedure functions. It is a very straightforward input output chain that results in the waiting times per location for a given base stock allocation (S). An arrow from function A to function B means that function A provides input for function B, the name of the input is presented on the arrows. The functions funRTV and funVTR assist the function CalcWDE.

The most important aspects regarding the Matlab implementation of these functions can be found in Appendix 1.
5.3 OPTIMIZATION PROCEDURE

This section describes the functions involved in executing the greedy procedure that aims to find the optimal inventory allocation. In order to do so it uses the evaluation procedure again for each iteration of the greedy procedure.

The optimization procedure requires the use of nine functions, the connections between these functions are shown in Figure 16. This figure is organized as follows. Each function is represented in a rectangle. The arrows from one function to another signify that the former function provides input for the latter. As can be seen, the function starts with the input for the greedy heuristic, which triggers the evaluation procedure which in its turn provides the input for the remainder of the optimization procedure. These iterations continue until the maximum average waiting time objective is met. The final output of the greedy heuristic is: the (near) optimal base-stock allocation matrix \([S]\), the corresponding achieved waiting times per location \([W_j]\) and the corresponding total costs.

![Figure 16 Overview functions Optimization Procedure](image)

The most important aspects of these functions will each be discussed in Table 3.

<table>
<thead>
<tr>
<th>Function name</th>
<th>Purpose</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>fune_yj</td>
<td>Support function, creates an empty 5x3 matrix with a 1 at item i and location j</td>
<td>• Item number (i), • Location number (j).</td>
<td>• Matrix of size 5x3 with all zeroes except for coordinate i,j.</td>
</tr>
<tr>
<td>Calc_deltaWy</td>
<td>Calculates the reduction in waiting time per location (j) when one item (i) is added. Calc_deltaWyj is used once at the start of the greedy procedure to create the initial matrix. For each following iteration Calc_deltaWy is used since adding an item only affects the waiting time for that particular item at the three locations, the rest of the matrix remains the same.</td>
<td>• base stock level (S), • Maximum waiting times per location, • For Calc_deltaWy: item number (i) .</td>
<td>• Matrix containing the change in waiting time per location when an item of stock is added.</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
<td>Inputs</td>
<td>Outputs</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Calc_deltaZy</td>
<td>Calculates the change in total costs when one item (i) is added. Calc_deltaZyj is used once at the start of the greedy procedure to create the initial matrix. For each of the following iterations Calc_deltaZy is used since adding an item only affects the costs for that particular item at the three locations, the rest of the matrix remains the same.</td>
<td>- base stock level (S),&lt;br&gt;- For Calc_deltaZy: item number (i).</td>
<td>- Matrix containing the change in total costs when an item of stock is added.</td>
</tr>
<tr>
<td>Calc_r_adj</td>
<td>Used by the greedy algorithm to determine where to add a unit of stock. The function calculates the ratio (r) by dividing the deltaW by deltaZ for each combination of item (i) and location (j) and puts this in matrix Ryj. If the inventory level of that combination is already at the maximum, the ratio is -1.</td>
<td>- base stock level (S),&lt;br&gt;- Matrix deltaWyj,&lt;br&gt;- Matrix deltaZyj.</td>
<td>- Matrix Ryj</td>
</tr>
<tr>
<td>Greedy</td>
<td>This function contains the actual greedy heuristic and is supported by all the functions that were discussed previously. The purpose of this function is to determine the base stock allocation matrix S which meets the maximum average waiting time requirements for the lowest total costs. For the current base stock allocation S the ratio (r) is calculated. The item and location combination with the largest ratio (r) receives an additional item of stock, this process repeats itself until all the average waiting times per location are below their assigned maximum.</td>
<td>- Maximum average waiting time per location</td>
<td>- Optimized base stock allocation matrix S&lt;br&gt;- Achieved expected waiting times per location&lt;br&gt;- Total costs</td>
</tr>
</tbody>
</table>

**Table 3 Optimization Procedure Matlab Functions**

The most important aspects regarding the Matlab implementation of these functions can be found in Appendix 2.
5.4 MODEL ALTERNATIVE SITUATIONS

In order to make the Matlab implementation of the model by Wong et al. (2005) suitable for the situations in which lateral transshipments are not allowed, a few changes have to be made. This section will briefly go over those changes.

In the function calcWDE, changes have to be made in the transition rates that lower the inventory level of a location. The demand rate for a location now only depends on its own inventory level, no matter what the inventory of the other locations is. Replenishment rates remain unaffected, so they can remain the same. Another element of this function is the calculation of the ratios of demand satisfied by other locations. These ratios are simply all set to equal zero. The last aspect in this function that needs to be changed is the probability of needing emergency supplies. Since lateral transshipments are no longer possible, this means that every time a demand occurs at a location when the inventory level of that location is zero, an emergency supply will be required. Therefore all states in which the inventory is zero need to count toward the probability of needing an emergency supply. For each location all these state probabilities are added up and placed the vector e which consists of the elements [e1 e2 e3] which, contrary to the original version of the model, do not need to be equal to each other. The values in this e vector are then used in the computation of the waiting times per location.
5.5 MODEL VERIFICATION

In this section the performance of the model will be verified by making changes in the input and determining whether the model behaves as it logically should. The base input that is used resembles the original data from Styrton Rail NL, however it has been rounded.

5.5.1 TEST 1: ONLY ONE LOCATION HAS DEMAND FOR AN ITEM

Table 4 shows the model input for a situation in which each item is only demanded by one location. A low maximum average waiting time is used to force the model to assign base-stock levels. All other input factors are kept the same.

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 0 1</td>
<td>3</td>
<td>€1,500.00</td>
<td>€5,000.00</td>
<td>€12,000.00</td>
<td>1 2 3</td>
</tr>
<tr>
<td>2</td>
<td>1 0 0</td>
<td>3</td>
<td>€1,000.00</td>
<td>€5,000.00</td>
<td>€7,500.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0 1 0</td>
<td>3</td>
<td>€800.00</td>
<td>€5,000.00</td>
<td>€6,000.00</td>
<td>0.0417</td>
</tr>
<tr>
<td>4</td>
<td>1 0 0</td>
<td>3</td>
<td>€800.00</td>
<td>€5,000.00</td>
<td>€5,000.00</td>
<td>0.00 0.03 0.07</td>
</tr>
<tr>
<td>5</td>
<td>0 1 0</td>
<td>3</td>
<td>€700.00</td>
<td>€5,000.00</td>
<td>€5,000.00</td>
<td>0.03 0.05 0.00</td>
</tr>
</tbody>
</table>

Table 4 Input for Verification Test One

The results of this first verification test are shown in Table 5. As was to be expected, the base-stock levels exactly represent the demand matrix used for this test.

<table>
<thead>
<tr>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Achieved Avg Waiting Time

0.041667 0.041667 0.041667

Table 5 Results of Verification Test One
5.5.2 TEST 2: ONE LOCATION WITH A LOW MAXIMUM AVERAGE WAITING TIME

The second verification test uses the input as shown in Table 6. Each location has a demand rate of one for each item, the replenishment rate for each item is two. Further it is important to note that only location one has a maximum average waiting time of 0.125 days (i.e. 3 hours), while the other two locations have a maximum average waiting time of one day.

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1 2 3</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 1,000.00</td>
<td>€ 5,000.00</td>
<td>€ 7,500.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 800.00</td>
<td>€ 5,000.00</td>
<td>€ 6,000.00</td>
<td>Max Avg Waiting Time</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 800.00</td>
<td>€ 5,000.00</td>
<td>€ 5,000.00</td>
<td>Transshipment Times</td>
</tr>
<tr>
<td>5</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 700.00</td>
<td>€ 5,000.00</td>
<td>€ 5,000.00</td>
<td>0.00 0.03 0.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 800.00</td>
<td>€ 5,000.00</td>
<td>€ 5,000.00</td>
<td>0.00 0.03 0.07</td>
</tr>
<tr>
<td>5</td>
<td>1 1 1</td>
<td>2</td>
<td>€ 700.00</td>
<td>€ 5,000.00</td>
<td>€ 5,000.00</td>
<td>0.00 0.03 0.07</td>
</tr>
</tbody>
</table>

Table 6 Input for Verification Test Two

The results for the second verification test are shown in Table 7. As one would expect, all the allocated inventory items go to location one. Due to the low lateral transshipment lead times, this also results in low average waiting times for location two and three.

<table>
<thead>
<tr>
<th>Item</th>
<th>Base-stock Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Achieved Avg Waiting Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.124632 0.157227 0.162744</td>
</tr>
</tbody>
</table>

Table 7 Results of Verification Test Two
The third verification test relates to increasing the lateral transshipment times between the locations. For this test all items are considered equal in all aspects, as can be seen in Table 8. Low maximum average waiting times and long transshipment times of two days, should result in high base-stock levels for all items/locations.

### Table 8 Input for Verification Test Three

<table>
<thead>
<tr>
<th>Location</th>
<th>Location</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

The results of the third verification test are presented in Table 9 and are what similar to what would be expected. All locations are required maintain a base-stock level of 2 or 3 for each item in order to ensure the maximum average waiting time requirements are met.

### Table 9 Results of Verification Test Three

<table>
<thead>
<tr>
<th>Location</th>
<th>Location</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Location</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Base-stock Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>
5.5.4 TEST 4: LOW INVENTORY HOLDING COSTS FOR ONE ITEM

The fourth test assumes all items have equal attributes, however, item five has significantly lower holding costs. With a relatively low holding cost, one would expect the greedy heuristic to prefer item five.

Test 4: Lower Holding Costs for Item 5

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>Max Avg Waiting Time</td>
</tr>
<tr>
<td>5</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 200.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>0.125 0.125 0.125</td>
</tr>
</tbody>
</table>

Table 10 Input for Verification Test Four

The results of the fourth verification test are presented in Table 11. These results are in line with the expectations, location one is assigned a base-stock level of three for item five.

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1  0.03 0.05</td>
</tr>
<tr>
<td>3</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1  0.07 0.05</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1  0.07 0.05</td>
</tr>
<tr>
<td>5</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 200.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>0.117149</td>
</tr>
</tbody>
</table>

Table 11 Results of Verification Test Four

Achieved Avg Waiting Time

0.117149 0.071759 0.114592
5.5.5 TEST 5: ONE LOCATION FAR AWAY FROM THE OTHER TWO

The fifth test assumes that one of the three locations is far away from the other two locations, which are relatively close to each other. The input for this test is presented in Table 12. The expected result in this case is that location one and two will mostly share their inventory, and thus one of the two locations will store most of the items. While location three has to maintain its own inventory since it for the most part cannot rely on lateral transshipments.

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,500.00</td>
<td>€ 5,000.00</td>
<td>€ 12,000.00</td>
<td>1 2 3</td>
</tr>
<tr>
<td>2</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 1,000.00</td>
<td>€ 5,000.00</td>
<td>€ 7,500.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 800.00</td>
<td>€ 5,000.00</td>
<td>€ 6,000.00</td>
<td>0.125 0.125 0.125</td>
</tr>
<tr>
<td>4</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 800.00</td>
<td>€ 5,000.00</td>
<td>€ 5,000.00</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1 1 1</td>
<td>3</td>
<td>€ 700.00</td>
<td>€ 5,000.00</td>
<td>€ 5,000.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 12 Input for Verification Test Five

The results of the fifth verification test are presented in Table 13. As can be seen, location two holds almost no inventory, while location 1 and 3 both hold at least one of each item in stock. This is in line with the expectations that were formulated previously.

<table>
<thead>
<tr>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 13 Results of Verification Test Five

<table>
<thead>
<tr>
<th>Achieved Avg Waiting Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0897</td>
</tr>
<tr>
<td>0.1059</td>
</tr>
<tr>
<td>0.1240</td>
</tr>
</tbody>
</table>
In this chapter the implemented mathematical model and the data from Strukton Rail, as discussed in the following section, will come together. The results from this will form the basis for the answers to the research questions. The chapter is structured as follows. First the data collection will be discussed, in which attention is given to data availability and its consequences after which each input parameter is discussed individually. Next the performances for each of the three scenarios, as mentioned in paragraph 3.4 will be calculated using the model.

6.1 DATA COLLECTION

This section describes the data that that is required as input for the model by Wong et al. (2005) that has been described in the previous chapter. A brief elaboration on the availability of the data will be given, next an overview of the input parameters is presented and each of these parameters are discussed in more depth. Finally an overview of the collected data is given. This data will be used as a basis for the remaining results that are presented in this chapter.

6.1.1 DATA AVAILABILITY

The data that was available within the organization of Strukton Rail Netherlands that pertains to the items that can be included in the model is very limited. Current inventory levels are not known exactly per location, instead a nationwide total is given. Item usage due to corrective maintenance is registered as the number of items used per location per year, this means that any possible monthly or seasonal patterns in demand cannot be analyzed. Supply lead times are only known for items which fall under an existing service level agreement with RailPro. The supply lead times of other items are negotiated on a case by case basis and therefore have to be estimated. The costs and duration of emergency supplies are also not known and need to be estimated based on the regular cost and lead time. Each of these required assumptions will be discussed in the following section.
6.1.2 INPUT PARAMETERS

This paragraph will discuss the input data required by the model developed by Wong et al. (2005). The parameters used in the model are listed in Table 14 along with a brief description and unit measure. The following paragraphs will discuss how the data for each of the parameters has been collected and included in the model.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Parameter description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>Number of locations</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Number of items</td>
<td></td>
</tr>
<tr>
<td>CH(_i)</td>
<td>Inventory holding costs (\forall\ i)</td>
<td>€/unit/year</td>
</tr>
<tr>
<td>CT(_i)</td>
<td>Transshipment costs (\forall\ i)</td>
<td>€/day</td>
</tr>
<tr>
<td>CE(_i)</td>
<td>Emergency supply costs (\forall\ i)</td>
<td>€/day</td>
</tr>
<tr>
<td>(W_{\text{max}})</td>
<td>Maximum waiting time</td>
<td>days</td>
</tr>
<tr>
<td>(T_{L_{jk}})</td>
<td>Distance between warehouse (j) and (k) measured in time</td>
<td>days</td>
</tr>
<tr>
<td>TE(_i)</td>
<td>Emergency supply lead time (\forall\ i)</td>
<td>days</td>
</tr>
<tr>
<td>(\mu_i)</td>
<td>Repair/Procurement rate of item (i)</td>
<td>/day</td>
</tr>
<tr>
<td>(m_j^i)</td>
<td>Failure rate of item (i) at warehouse (j)</td>
<td>(/day)</td>
</tr>
</tbody>
</table>

Table 14 Input parameters

Number of Locations

Strukton Rail NL has, at the start of 2014, ten regional warehouses spread throughout the Netherlands. These regional warehouses can be divided into four clusters: North, South, North-West and South-West. Table 15 shows which regional warehouses belong to which cluster.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Warehouse location</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>Groningen, Meppel, Grou</td>
</tr>
<tr>
<td>South</td>
<td>Sittard, Venlo</td>
</tr>
<tr>
<td>North-West</td>
<td>Amsterdam, Breukelen, Almere</td>
</tr>
<tr>
<td>South-West</td>
<td>Alphen a/d Rijn, Zwijndrecht</td>
</tr>
</tbody>
</table>

Table 15 Clusters and their warehouses in the Netherlands

For the sake of limiting model complexity, not all ten regional warehouses will be analyzed together in the same model, instead the model will be used to analyze the cluster “North”. This means that the calculations in the model will be based on a situation in which there are three locations.

Number of Items

The items that will be included in the model need to fulfil a number of criteria. Reasonably low turnover speed, which results in low required inventory levels. An important aspect of the model by Wong et al. (2005) is that it rapidly becomes more complex when a new location is added or when the base-stock level of an item is increased. For this reason, and considering that the model will include three locations, items which require a base-stock level per location that is more than four will not be included in the model. This is based on the nationally aggregated inventory level, if this value was above 40 (on average 4 per warehouse location) the item was excluded from this analysis. Another important aspect for item selection is the economic value of an item. In order to make setting up a transshipment system financially feasible, it is necessary for the items to have a significant value in order for the benefits to outweigh the costs of transshipment.
A rough analysis of the item database of Strukton Rail NL, which includes aggregated inventory levels and turnover speeds of the items used throughout the Netherlands yields a list of items which may be useable in the model. In this initial rough analysis two cut-off values, related to the criteria discussed above were used: (1) cut-off for inventory level, since the base-stock level of the items cannot be higher than four per location and since there are ten locations, the cut-off value for aggregated inventory level is set at 40. (2) The second cut-off value relates to the value of the items, which is set to €1000 in regards to the purchasing costs of the item. Cutting off using the maximum inventory level reduces the number of items from 4721 to 2368. Cutting off at an item value of €1000 reduces the number of items from 4721 to 89. Combining the two cut offs results in that the initial list of 4721 items can be reduced to 25 items that could be used in the model.

The data that is available for these items is limited to the following: (1) the total inventory level in the whole country, not on an individual locations basis; (2) the item purchasing cost; (3) the total usage per item per location in the time period 2009-2014; (4) for those items that fall under the service level agreement with RailPro a lead time of 1 day can be counted on in at least 95% of the time, other items have lead times which are negotiated on a case by case basis.

The result of this limited available data is that assumptions and estimates have to be made in order to achieve a complete set of input data per item per location. Due to modeling limitations, see section 5.1, only five items can be used as input for the model that has been developed. These five items will be selected from the 25 items that were selected as viable options earlier. The selection criteria for these items are as follows: the items should be used by all three locations and the highest value items with high inventory holding costs should be included. Another consideration in selection these items is the supply lead time, for Strukton Rail it could be most interesting to look at items which do not fall under existing service level agreements, i.e. items that typically have a longer supply lead time.

Applying these criteria to the list of 25 items results in the selection of the following five items.

- Beacon
- Print, inlet
- Print, CPU,
- Print, amplifier for beacon
- Generator, pulse

The other items in the list could also be used as input for the model in exactly the same way. However, in this research project the choice has been made to focus on the items with the highest economic value since the goal is to determine whether or not introducing lateral transshipments might be feasible for Strukton Rail Netherlands.

**Inventory Holding Costs**

In 2015, Strukton Rail NL calculates the inventory holding costs per year as 20% of the purchasing costs of an item, as discussed previously in paragraph 2.8.2.

**Repair / Replenishment Rate of Items**

Since in the situation of Strukton Rail NL the inventory replenishments at the regional warehouses do not come from item repairs, from here on this parameter will be referred to as replenishment rate. The replenishment rate is directly related to the lead time given by the supplier. Some items are included in a service level agreement with RailPro, which means that in 95% of the cases the supply lead time is one day. In the remaining 5% of the cases the supply lead time is slightly longer. However, due to the urgency of repairs it is assumed it will never be much longer than one day. Resulting in a replenishment rate that is very close 1/day for an arbitrary case. Since this assumption might be wrong, the sensitivity of the model to replenishment rate
is tested for in section 6.3.1. Other items have varying lead times because they are negotiated on a case by case basis. This can vary from anywhere between 1 to 14 days (Interview Purchaser SRX, 2014). In order to make a reasonable assumption an average of 7 days will be used for items which have no known supply lead time.

**Demand Rate of Items**

The demand rate of items is influenced by many different factors, each depending on the item itself. Conditions such as weather, train routing and time schedules can all influence the amount of time it takes before an item fails and thus the amount of time it takes before a demand takes place. With the data available, the demand rate of the items is best estimated with the turnover speed. In the available data, the turnover speed is known per item per year for the last five years. Based on this an average turnover speed can be determined which can be converted to an average demand per item per day.

Since the data related to demand is very limited only a rough estimate can be made. This is done by taking the total of the item demand over the past five years and dividing that by 1825 days (=365*5). This is of course a very rough estimate but unfortunately all that the available data would allow for. The demand rate per item can be found in Table 16.

<table>
<thead>
<tr>
<th>Description</th>
<th>Code</th>
<th>Location 1 Meppel</th>
<th>Location 2 Grou</th>
<th>Location 3 Groningen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beacon</td>
<td>PU75020</td>
<td>0.006</td>
<td>0.006</td>
<td>0.020</td>
</tr>
<tr>
<td>Print, Inlet</td>
<td>PU75082</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Print, CPU</td>
<td>PU75078</td>
<td>0.003</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Print, amplifier for beacon</td>
<td>PU75072</td>
<td>0.002</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>Generator, pulse</td>
<td>PK07064</td>
<td>0.003</td>
<td>0.001</td>
<td>0.004</td>
</tr>
</tbody>
</table>

**Table 16 Demand rate per item per location**

**Lateral Transshipment Lead Time and Costs**

The lateral transshipment lead time is fixed amount of time that it takes to go from warehouse \( j \) to \( k \). For reasons of simplicity it is chosen to assume that the distances from \( i \) to \( j \) are the same as from \( k \) to \( j \). These times are shown in Table 17.

<table>
<thead>
<tr>
<th>Transshipment from/to</th>
<th>Distance</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groningen &lt;-&gt; Grou</td>
<td>71.7 km</td>
<td>47 minutes</td>
</tr>
<tr>
<td>Grou &lt;-&gt; Meppel</td>
<td>55.9 km</td>
<td>33 minutes</td>
</tr>
<tr>
<td>Meppel &lt;-&gt; Groningen</td>
<td>73.5 km</td>
<td>49 minutes</td>
</tr>
</tbody>
</table>

**Table 17 Transshipment travel times**

The costs of transshipment is included in the model by Wong et al. (2005) as a price of transshipping an item per unit of time, since distances between locations are measured in time as well. The transshipment cost will relate to: item handling (loading and unloading), transportation costs (e.g. fuel consumption) and the updating of the MetaCom system. The item and handling and information system updating will roughly be the same for any given transshipment activity, making the transportation costs the only element that varies with distance between the warehouses.
Up to a weight of 600kg RailPro calculates a price of €0.95 per km during regular working hours and a price of €1.39 during nights, weekends and holidays with a minimum of 35km per transport. Since many of products used by Strukton Rail come from RailPro these numbers will be used as a basis for the Transshipment costs used in this model. Because failures of items can occur at any time an average cost per km will be calculated. In order to do so an assumption is made that day time is from 06:00-18:00 and the remaining time of the day the night time rate will be used. This means 5*12 = 60 hours per week at a rate of €0.95 per km and 5*12+2*24 hours per week at a rate of €1.39 per km. This comes down to a weighted average price of €1.20 per km for a transshipment at an arbitrary point in time. The transport costs per hour as shown in Table 18.

<table>
<thead>
<tr>
<th>Transshipment from/to</th>
<th>Transport cost (=km*rate/km)</th>
<th>Road transportation duration</th>
<th>Cost per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groningen &lt;-&gt; Grou</td>
<td>71.7 km * 1.2 = €86.04</td>
<td>47 minutes = 0.783 hr</td>
<td>€110/hr</td>
</tr>
<tr>
<td>Grou &lt;-&gt; Meppel</td>
<td>55.9 km * 1.2 = €67.02</td>
<td>33 minutes = 0.550 hr</td>
<td>€122/hr</td>
</tr>
<tr>
<td>Meppel &lt;-&gt; Groningen</td>
<td>73.5 km * 1.2 = €88.20</td>
<td>49 minutes = 0.816 hr</td>
<td>€108/hr</td>
</tr>
</tbody>
</table>

Table 18 Transport costs per hour

The required material handling time is estimated at 1 hour per transshipment at a rate of €60/hr. This means that the total cost and time of the transshipment is as follows. The total costs of transshipments are shown in Table 19.

<table>
<thead>
<tr>
<th>Transshipment from/to</th>
<th>Transport cost (=km*rate/km)</th>
<th>Total duration</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groningen &lt;-&gt; Grou</td>
<td>71.7 km * 1.2 = €86.04</td>
<td>0.783 hr + 1 hr = 1.783 hr = 0.074 days</td>
<td>€170/hr = €4080/day</td>
</tr>
<tr>
<td>Grou &lt;-&gt; Meppel</td>
<td>55.9 km * 1.2 = €67.02</td>
<td>0.550 hr + 1 hr = 1.550 hr = 0.065 days</td>
<td>€182/hr = €4368/day</td>
</tr>
<tr>
<td>Meppel &lt;-&gt; Groningen</td>
<td>73.5 km * 1.2 = €88.20</td>
<td>0.816 hr + 1 hr = 1.816 hr = 0.076 days</td>
<td>€168/hr = €4032/day</td>
</tr>
</tbody>
</table>

Table 19 Total costs of Transshipment

Emergency Supply Lead Time and Costs

The emergency supply lead time is the time it takes for an emergency supply to arrive at the regional warehouses that requested it.

Emergency supplies are required when none of the regional warehouses has an item in stock for which there is a demand. The costs of an emergency supply is a fixed number per item that has to be supplied as an emergency. The model by Wong et al. (2005) assumes that emergency supplies are significantly longer and/or more expensive than lateral transshipments, so that lateral transshipments are always preferred.

Unfortunately there is no available data for the lead time nor the costs of emergency shipments, so an estimate has been made by the author of this report. The costs of emergency supplies are estimated to cost 50% more than regular item price and take half the regular lead time with a minimum of 1 day.

Maximum waiting time per location

Since the maintenance activities are urgent and should be performed as quickly as possible, the maximum average waiting time per location should be low. This goes for all locations where maintenance spare parts are stored. This research looks at the effect that different maximum average waiting times have on the base stock level and its corresponding total costs that result from the greedy heuristic. This is done with maximum average waiting time ranging from 1 hour to 2 days.
6.1.3 OVERVIEW OF ITEM/LOCATION SPECIFIC DATA

Table 20 presents an overview of the data that is specific to an item, a location or an item/location combination. Per item the price, lead time, demand rate per location, the replenishment rate and the inventory holding costs are given.

<table>
<thead>
<tr>
<th>Description</th>
<th>Code</th>
<th>Price €</th>
<th>Lead Time</th>
<th>1. Meppel</th>
<th>2. Grou</th>
<th>3. Groningen</th>
<th>Replenishment Rate</th>
<th>Inventory Holding Costs (€/item/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beacon</td>
<td>PU75020</td>
<td>7608</td>
<td>1</td>
<td>0.006</td>
<td>0.006</td>
<td>0.020</td>
<td>1</td>
<td>1521.6</td>
</tr>
<tr>
<td>Print, Inlet</td>
<td>PU75082</td>
<td>5029</td>
<td>7</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.142857</td>
<td>1005.8</td>
</tr>
<tr>
<td>Print, CPU</td>
<td>PU75078</td>
<td>3905</td>
<td>7</td>
<td>0.003</td>
<td>0.001</td>
<td>0.002</td>
<td>0.142857</td>
<td>781</td>
</tr>
<tr>
<td>Print, amplifier for beacon</td>
<td>PU75072</td>
<td>3768</td>
<td>7</td>
<td>0.002</td>
<td>0.001</td>
<td>0.005</td>
<td>0.142857</td>
<td>753.6</td>
</tr>
<tr>
<td>Generator, pulse</td>
<td>PK07064</td>
<td>3479</td>
<td>1</td>
<td>0.003</td>
<td>0.001</td>
<td>0.004</td>
<td>1</td>
<td>695.8</td>
</tr>
</tbody>
</table>

Table 20 Item/Location specific data
6.2 PERFORMANCES PER SITUATION

For the current situation, without any optimization, the base stock levels of all items at all locations are set to 1 for maximum average waiting times that are below one day. This is done because the shortest supply lead time of the items is one day for items 1 and 5 and 3.5 days for items 2, 3 and 4. For maximum average waiting times above 1 day, no stock is kept for items 1 and 5 and still one per item per locations for items 2, 3 and 4.

The maximum average waiting times are chosen to be the same for each of the locations because there is no good reason to make any distinction here. In order to illustrate the effect of the maximum average waiting times on the required base-stock levels and total system costs, several different computations have been done with maximum average waiting times ranging from 1 hour to 2 days. In the next paragraph a closer look will be taken at these results.

### Table 21 Model results for varying maximum average waiting times

Table 21 describes the behavior of the total costs for each of the three scenarios for different maximum average waiting times. For example, with a maximum average waiting time per location of 0.25 days (or 6 hours) the total costs for the current situation are €14,279.31, for the optimized current situation the costs are €12,915.52 and for the situation in which lateral transshipments are possible the costs are €4,786.52. Additionally the calculated average waiting times per location is shown.

### 6.2.1 PERFORMANCE COMPARISON BETWEEN THE THREE SITUATIONS

In this paragraph a comparison will be made of the performances of the three different situations. This will be done by taking a look at Figure 17 which is a graphical representation of the total system costs versus the maximum average waiting time for the three different situations.

Looking at this graph it is immediately clear the total system costs are the highest in the current situation, lower in the optimized current situation when the maximum average waiting time is 3 hours or above and significantly lower for the situation in which lateral transshipments can be utilized. These results reflect what could be expected according to the theory on lateral transshipments.
It is interesting to note that for the situation with lateral transshipments, small increases in the maximum average waiting time can mean large decreases in cost. This effect is illustrated in Figure 18 in which the maximum average waiting time is set against the cost reduction compared to the costs of the lowest maximum average waiting time of 1 hour. The red line that belongs to situation 3 rises much more rapidly compared to the blue line of situation 2, especially the first 20 hours. However as the maximum average waiting time rises, the effect disappears and both situations end up at a 92% and 88% reduction in total costs for scenario 2 and 3 respectively. This figure illustrates that small increases in maximum average waiting times can quickly result in large reductions in cost. In this graph the costs reductions are compared within the situations, the costs of situation 2 are compared to the costs of situation 2 with a maximum average waiting time of 1 hour, the same goes for situation 3. This explains why situation 2 can have a greater cost reduction percentage than situation 3, even though the actual cost of situation 3 are lower than the costs of situation 2.

Figure 17 Results - Total costs vs. Max. Avg. Waiting Times
Another interesting comparison is the costs reduction percentages of situation 2 and 3 versus the costs of situation one with the same maximum average waiting time. This comparison is visualized in Figure 19. It is interesting to note that the costs of situation 1 and 2 are the same for a maximum average waiting time of up to two hours, while the cost reductions of using lateral transshipments (situation 3) are directly noticeable. The dip in the graph at 24 hours can be explained by the fact that in the current situation the items 1 and 5 are no longer kept in stock, as explained previously in section 6.2. At a maximum average waiting time of 48 hours the costs of both scenario 2 and 3 are virtually the same: € 1,205.20 and € 1,180.92 respectively.

Figure 18 Cumulative cost reduction

Figure 19 Cost Reduction Percentages compared to Current Situation with same Max. Avg. Waiting Time
6.3 MODEL SENSITIVITY TESTS

In this section the model sensitivity will be tested. This is done by varying certain input elements of the mathematical model such as: demand, replenishment lead times, emergency supply times, while keeping the other input the same. Subsequently will be determined what the impact of this variation is on the base stock levels and/or on the performance regarding the KPI’s when the base stock levels are kept the same. The results will be compared to results discussed in section 6.2 for which the data of Strukton Rail Netherlands was used.

Figure 20 shows the base levels for the input parameters used in the model sensitivity tests.

<table>
<thead>
<tr>
<th>Item</th>
<th>Demand rate</th>
<th>Replenishment rate</th>
<th>Holding Costs</th>
<th>Transshipment Costs</th>
<th>Emergency Supply Costs</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.006</td>
<td>0.006</td>
<td>0.002</td>
<td>1</td>
<td>€ 1,521.60</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.001</td>
<td>0.003</td>
<td>0.143</td>
<td>€ 1,005.80</td>
<td>€ 4,160.00</td>
<td>Max Avg Waiting Time</td>
</tr>
<tr>
<td>3</td>
<td>0.003</td>
<td>0.001</td>
<td>0.002</td>
<td>€ 781.00</td>
<td>€ 4,160.00</td>
<td>0.125</td>
</tr>
<tr>
<td>4</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
<td>€ 753.60</td>
<td>€ 4,160.00</td>
<td>0.125</td>
</tr>
<tr>
<td>5</td>
<td>0.003</td>
<td>0.004</td>
<td>1</td>
<td>€ 695.80</td>
<td>€ 4,160.00</td>
<td>0.125</td>
</tr>
</tbody>
</table>

6.3.1 REPLENISHMENT RATE

Figure 21 shows the result of increasing and decreasing the replenishment rate within the model while keeping the remaining input data the same. Tests ranged from 0.05 to 20 times the original replenishment rate. A logarithmic scale is used to ensure the multiplication factors can all be visibly represented on the x-axis. As seen in Figure 21 the higher the replenishment rate, the lower the system costs, which makes perfect sense since higher replenishment rates mean less frequent out-of-stocks and lower waiting times. As can be seen, this effect behaves in a logarithmic fashion.
6.3.2 DEMAND RATE

Figure 22 and Figure 23 show the results of increasing and decreasing the demand rate within the model while keeping the remaining input data the same. Tests ranged from 0.05 to 20 times the original demand rate. Figure 22 shows that up until the original data (i.e. at multiplication factor = 1) there is no effect on the costs.

![Figure 22 Model Sensitivity to Demand Rate (Logarithmic scale)](image)

Figure 22 Model Sensitivity to Demand Rate (Logarithmic scale)

Figure 23 uses the same results as the previous figure, however, this time on a linearly scaled x-axis. This shows that multiplication factors greater than 1 have a linear effect on the increase of the system costs. This makes sense since higher demand equals the need for higher inventory levels (i.e. higher inventory holding costs) or if inventory levels do not increase, more frequent out-of-stocks and therefore a more frequent requirement for expensive emergency supplies.

![Figure 23 Model Sensitivity to Demand Rate (Linear scale)](image)

Figure 23 Model Sensitivity to Demand Rate (Linear scale)
A demand rate factor below 1 results in such small differences in demand rate that changes in price are not noticeable graphically. However, small cost reductions do occur (as seen in Table 22) due to fewer out of stocks and therefore fewer emergency supplies, albeit very slightly fewer.

While testing the sensitivity of the model to demand rate a mistake was found in the Matlab code. With greater demand rates, while keeping all other input the same, it can negative $\Delta Z_j$ can occur. This means that it adding an item $i$ at location $j$ actually both reduces the average waiting time and the total costs. These cases should always receive priority when it comes to selecting the best item/location combination in the greedy heuristic. A small addition to the Matlab code resolved this issue. However, this meant all previous results that had been found had to be checked again. The results presented in this document are all from the most correct version of the algorithm.

### Table 22 Demand rate factor vs. Costs

<table>
<thead>
<tr>
<th>Demand Factor</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>€ 4,758.18</td>
</tr>
<tr>
<td>0.1</td>
<td>€ 4,758.65</td>
</tr>
<tr>
<td>0.2</td>
<td>€ 4,759.82</td>
</tr>
<tr>
<td>0.4</td>
<td>€ 4,763.16</td>
</tr>
<tr>
<td>0.8</td>
<td>€ 4,773.68</td>
</tr>
<tr>
<td>1</td>
<td>€ 4,780.80</td>
</tr>
<tr>
<td>1.25</td>
<td>€ 5,540.77</td>
</tr>
<tr>
<td>2.5</td>
<td>€ 6,385.29</td>
</tr>
<tr>
<td>5</td>
<td>€ 7,898.25</td>
</tr>
<tr>
<td>10</td>
<td>€ 9,814.15</td>
</tr>
<tr>
<td>20</td>
<td>€ 14,692.93</td>
</tr>
</tbody>
</table>
Figure 24 shows the results of increasing and decreasing the lateral transshipment times within the model while keeping the remaining input data the same. Tests ranged from 0.05 to 100 times the original transshipment times. As can be seen, the costs follow a pattern that resembles a negative exponential curve. Small multiplications to the transshipment times result in great increases in the system costs, but at some point the effect disappears. In the case with this input this is around multiplication factor 40, at this point all item/location combinations have an inventory level of 1 which is enough to meet the maximum average waiting time of 0.125 days (i.e. 3 hours).
6.3.4  EMERGENCY SUPPLY COSTS

Figure 25 shows the result of increasing and decreasing the emergency supply costs within the model while keeping the remaining input data the same. Tests ranged from 0.05 to 20 times the original replenishment rate. The relationship between system costs and emergency supply costs is perfectly linear when the emergency supply costs are increased (or decreased) by the same rate for each of the items. For a given maximum average waiting time the heuristic always comes up with the same base-stock allocation, assuming all other input remains the same. This is due to the fact that the decisive performance indicator for the greedy heuristic is average waiting time and not costs. If, however, the emergency supply costs for one item is increased at a greater rate than the others, this item will receive a higher priority.

![Figure 25 Model Sensitivity to Emergency Supply Costs](image)
6.4 MODEL SCALING

The model created by Wong et al. (2005) has three scalable dimensions. This section will briefly go over the scalability of these three dimensions:

- The number of items
- The number of locations
- The maximum base-stock level per item/location

In its current form, as it is has been presented in this document so far, it is capable to process: 5 different items on 3 locations with a maximum base-stock level of 4 per item/location. The following three subsections discuss how the model should be altered such that it is capable of handling different dimension settings.

### NUMBER OF ITEMS

The number of items is the dimension that is the most scalable of the three. The evaluation functions, as in Chapter 5, are performed per item separately and are then put together in one matrix that includes all item/locations combinations. The number of items can be varied by simply changing the number of items over which these functions are run. In its current form the functions are performed over #items=1:5, changing this number (5) allows for the use of a different number of items. Of course, the input matrices and vectors have to reflect the new number of items as well. It should be noted that adding items greatly increases the computation time. For instance, using the basic data that was used for sensitivity tests (see section 6.3) and adding an item number 6 which is slightly cheaper in all regards than item 5, impacts the computation time as can be seen in Table 23.

<table>
<thead>
<tr>
<th>Number of Items</th>
<th>Computation Time</th>
<th>Number of Iterations Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>22.61 seconds</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>68.71 seconds</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>123.11 seconds</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>270.91 seconds</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>449.99 seconds</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 23 Impact of Number of Items on Computation Time

### NUMBER OF LOCATIONS / MAXIMUM BASE-STOCK LEVEL

Changing the number of locations impacts the model in a much more significant way. Whereas changing the number of items did not require changing the state transition matrix Q, changing the number of locations does or the maximum base-stock level does. The number of states in the model is computed using the following formula: \( N = \prod_{j=1}^{J} (S_j^I + 1) \). In its current form with 3 locations and a maximum base-stock level of 4, this means there are a 125 states (=5*5*5). Raising the maximum base-stock level by just one means that the number of states changes to 216 (=6*6*6). Alternatively adding one location to the model changes the number of states exponentially to 625 (=5*5*5*5).

Of these two scaling possibilities the one that impacts the model the least is raising the maximum base-stock level, since this does not require adding any new formulas to the Matlab code. When the number of locations is increased, not only does this mean a much longer computation time, it also means that new code has to be written to describe the transition behavior between the new location and the existing ones.
7 CONCLUSIONS AND RECOMMENDATIONS

Throughout this report the aim was to find answer to the research questions as they were posed in section 3.3. In this chapter the definite answers will be given to each of these questions, followed by the conclusions that can be drawn and recommendations that can be made.

7.1 CONCLUSIONS

1. **What is the structure and performance of the current inventory policy of Strukton Rail Netherlands?**

   As seen in chapter 2, in the current situation of Strukton Rail NL there is little to no coordination when it comes to the inventory levels of maintenance spare parts at the different warehouse locations. Due to this lack of coordination it is possible that unnecessarily high levels of inventory are being kept. In this current situation every warehouse holds inventory according to the local demand it faces. This means that for each of the five items considered in this research, at least one item should be kept in stock when the maximum average waiting time is shorter than one day. This is due to the fact that the fastest supply lead time is one day for items that fall under the service level agreement with RailPro, other items have longer and varying supply lead times. As seen in Table 21 and Figure 17 of section 6.2. This means a cost of €14,281.11 with average waiting times of 0.61, 0.26 and 0.92 hours for locations 1, 2 and 3 respectively. These numbers do not change unless the maximum average waiting time is raised above 1 day for each location, at which point only inventory is kept for items 2, 3 and 4 which each have an emergency supply lead time of 3.5 days. The costs in this case are €8,030.42 with a waiting times being 14.94, 16.98 and 17.58 hours for respectively locations 1, 2 and 3.

2. **Which key performance indicators have to be considered in the situation of Strukton Rail Netherlands?**

   In spare parts inventory management the most important trade-off to make is often between the desired service level and the costs that come along with this desired level. Typically the higher the desired service level, the higher the costs. In the case of Strukton Rail NL this is no different. A trade-off has to be made between the service level in terms of the time it takes for an item to be available for maintenance activities and the costs that are associated with this. Since the performance of Strukton Rail NL is judged by its customer based on the time it takes to restore functionality of the railway track, it makes sense to choose a service level measure that incorporates the element of time. In this research a choice has been made for a service level measure in terms of the time it takes on average for an item to be available for maintenance activities at a certain warehouse location. The costs that are included in this research are those of inventory holding, transshipment costs from one location to another and the costs for emergency shipments in case all locations are out of stock for an item.

3. **What is the most appropriate scientific model that can be used to analyze the situation of Strukton Rail Netherlands?**

   Based on the situation of Strukton Rail NL and the literature review done prior to this research, three main criteria have been formulated which were used to select an appropriate model. These criteria were

   1. Single-Echelon structure, since the Netherlands is a reasonably small country and suppliers of Strukton Rail are based within the Netherlands it would not make sense to setup an inventory system with more than one echelon. For example in a two-echelon structure a main warehouse would be created, which would often be redundant next to the warehouses of the suppliers.
II. A time based measure of service level performance. Since Strukton Rail’s performance is measured in the time it takes to restore functionality. It makes the most sense to select a model of which the performance is linked to time as well.

III. A multi-item approach would be preferred, since the maintenance activities of Strukton Rail require a large of number of different items which all impact the same service performance measure and since research has shown that using a multi-item approach can greatly reduce inventory holding costs compared to a single-item approach.

The models described in the papers by Wong et al. (2005) and Reijnen et al. (2009) were both suitable candidates. But since Wong et al. (2005) uses a multi-item approach, as opposed to the single-item approach of Reijnen et al. (2009), the choice was made to use the model from Wong et al. (2005).

4. **What is the performance level of the optimized current inventory policy?**

The performance level of the current inventory policy can be improved upon using a slightly adapted version of the Matlab model that was created based on the model by Wong et al. (2005). The model works virtually the same as the original, with the only difference being the fact that lateral transshipments are not allowed. So the greedy algorithm still decides which items should be stored at what location, but without considering the option of satisfying the demand of one location with the stock of another location. Compared to the current situation (scenario 1) this results in average times that are closer to the maximum average waiting times but with typically lower total system costs, as can be seen in Table 21 and Figure 17 of section 6.2. The total system costs for the optimized current situation where a maximum average waiting time of 6 hours is used are € 12,915.52.

5. **What is the performance level of the inventory policy in which the use of lateral transshipments is allowed between the regional warehouses?**

Using the Matlab model that was created based on the model described by Wong et al. (2005) is used to calculate the performance level of the situation in which lateral transshipments can be used to pool inventory. This has been done for several different maximum average waiting times, as can be seen in Table 21 and Figure 17 of section 6.2. The total system costs for the situation in which lateral transshipments are possible and where a maximum average waiting time of 6 hours is used are € 4,786.52.

6. **How do the performance levels of the inventory policies with and without lateral transshipments compare to each other?**

As seen in section 6.2.1 the performance levels between the three situations differ quite significantly. The most important conclusion here is that utilizing lateral transshipments can result in decreases of total system costs of roughly 50%, provided the maximum average waiting times are relatively low compared to the supply lead times of items. Another important finding is that even without lateral transshipments the inventory levels can be optimized, resulting in cost reductions ranging from 5-40% depending on the maximum average waiting time that is desired. It is also interesting to note that for the situation with lateral transshipments, small increases in the maximum average waiting time can mean large decreases in cost as can be seen in Figure 17.

Based on the answers given to the research questions in the previous paragraph some conclusions can be drawn. First off, the most important conclusion that can be drawn is that using lateral transshipments can prove beneficial for Strukton Rail Netherlands given the data that was available for this research.

Another important conclusion is that cost savings can be achieved simply by optimizing the inventory levels per location individually. Even though the cost reductions here are significantly lower than when lateral
transshipments are utilized, depending on the maximum average waiting times the cost savings can be as great as 40% compared to the current situation.

7.2 RECOMMENDATIONS

Based on the outcome of this research project as presented in chapter 6 and the answers given to the research questions, the most important recommendation is that Strukton Rail NL should seriously consider utilizing the concept of inventory pooling by allowing lateral transshipments to take place between the regional warehouses. However, in order to do so more reliable data is required about the items for each of the locations. Information such as demand figures, supply lead times are currently not accurate enough to make a reliable calculation of the possible cost savings. The results in this document, however, are based on the available data and show that significant cost savings are possible: using lateral transshipments can reduce costs by up to 50% compared to the current situation in which there is no coordination between the regional warehouses when it comes to base-stock levels.

The next steps that Strukton Rail Netherlands has to take if it wishes to pursue the idea of inventory pooling through lateral transshipments are as follows: creating a company wide database with accurate data on item usage per location, supply lead times per item per location, a system to monitor the current inventory levels at each warehouse at any given point in time. This will allow the regional warehouses to communicate directly about the demands they are facing for the items and quickly establish whether lateral transshipments might be a solution for satisfying an immediate demand.

When more accurate data, especially regarding the failure rates of items, is gathered and stored in a database, this can be used to perform analyses to determine if the failures occur according to a Poisson process. This would help with the validation of the mathematical model that has been presented in this master thesis.

Additionally, Strukton Rail has to be mindful of a clear communication with the procurement department so that they are aware that an item has been moved from one location to another. The procurement department can then communicate with the regional warehouses about whether or not replenishments are required and if so at which location(s). When more accurate the data on item demand and replenishment rates, the more accurate the mathematical model can determine the optimal base-stock level.

The most important recommendation for the literature is possibly researching the link between theoretical measurements for service levels and the practical service level measurements used in the railway industry. For instance, how can the availability of spare parts be translated to a workable measurement of the railway availability and which factors play a role in this? A possible measurement is using the average waiting time per location, as it has been used in this document, and expanding it with the time it takes to execute the other required activities before functionality is restored. This way an “expected time to restore functionality” could be computed.
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APPENDIX 1 – EVALUATION PROCEDURE

This appendix describes the functions related to the evaluation procedure that were implemented in Matlab in greater detail. The focus hereby lies on the functionality and challenges that arose. Each function is introduced in the same following format: the output between square brackets, the name of the function and finally the input required for this function between round brackets.

\[w,d,e\] = calcWDE\([m,u,y,S,TL,TE]\)

This function calculates per item: the waiting times \((w)\) per item per location, the waiting time per lateral transshipment request \((d)\) per item per location and the possibility of all locations having an inventory level of 0 \((e)\). In order to do this it uses the demand matrix \((m)\), the replenishment rate matrix \((u)\), the item number \((y)\), the base-stock level matrix \((S)\), the lateral transshipment duration matrix \((TL)\) and the emergency shipment duration matrix \((TE)\).

This function starts by creating the generator matrix \(Q\) per item. This matrix consists of all possible state transitions that can occur based on the number of locations and maximum base-stock level per location. In order to determine the state transitions, first the possible states must be defined.

The states are created in the form of a vector, the state vector \([1\ 0\ 0]\) for instance means that location 1 has a single item and location 2 and 3 have zero items, \([1\ 2\ 0]\) means location 1 has a single item, location 2 has two items and location 3 has zero items, and so on. Since this research is limited to 3 locations, 5 items and a maximum base-stock level of 4 per location (see section 5.1 for the explanation for this) the states in the generator matrix for a single item range from \([0\ 0\ 0]\) to \([4\ 4\ 4]\) this means that there are 125 \(=5*5*5\) possible states. Each state needs to have a transition rate to any other state, this means that the generator matrix \(Q\) has the size of 125x125.

To be able to allocate the states (which are in the form of a vector) to the generator matrix the state vectors should be transformed into a single unique number. This is done using the following system: the inventory level of the first location is multiplied by 1, the level of the second multiplied by 5, the level of the third location is multiplied by 25 and these three numbers are then added up. This is row and column in which that particular state is placed in the generator matrix. For example, state \([2\ 1\ 4]\) is placed in the row/column 107 \(=2*1+1*5+4*25\). The function created for this purpose is called funVTR.

The same system applies for transforming a row number to a state vector. For example, row number 86 is first divided by 25 and rounded down to the next integer number \(86/25= 3.44\), which is 3. This means the inventory level of the third location is 3. The remaining 11 \(=86-3*25\) is then divided by 5, which is 2.2 \(=11/5\). This is again rounded down, to 2, which is the inventory level of location two. The remaining is 1 \(=11-2*5\) is the inventory level of location one. This means the corresponding state vector to row/column number 86 is \([1\ 2\ 3]\). The function created for this purpose is called funRTV. The exception to this system is the state \([0\ 0\ 0]\) which has row number 125.

The transitions in the generator matrix can be split up into two categories. Those that lower the inventory level (demand) and those that increase the inventory level (replenishments). Each transition can only increase or decrease the inventory level by 1 at a time.

The transitions that increase the inventory level are calculated separately for each of the three locations. For each of the row/column numbers \((i)\) the corresponding vector \((a)\) is calculated. Then for one location the inventory level is raised by 1 creating a new vector \((b)\) and the new corresponding row/column number \((j)\) is calculated. The combination of the original row/column number \((i)\) and the new row/column number \((j)\) forms the location in the generator matrix \((i,j)\) where the transition rate should be placed. This replenishment
transition rate is calculated based on the inventory level that served as input for the function \((S)\) and the inventory level of the original vector \((a)\). The inventory level for that location in matrix \(S\) is reduced by the inventory level of that location in the vector \((a)\). The inventory level for that location in the original vector \((a)\) is deducted from the corresponding inventory level in the matrix \(S\), the remaining number is multiplied by the item’s replenishment rate found in the matrix \(u\). This is the transition rate from state \(i\) to state \(j\) and is added to the transition rate matrix \(Q\) at location \((i,j)\). The following code shows how this works when the inventory level for location one is raised. The same code exists for location 2 and 3 where \([1 0 0]\) is replaced by \([0 1 0]\) and \([0 0 1]\) respectively.

```matlab
for i=1:size
    a = funRTV(i);
    b = a + [1 0 0];
    if b(1)>S(y,1)
        j = funVTR(b);
        Q(i,j) = Q(i,j) + (S(y,1)-a(1))*u(y);
    end
end
```

The calculation of the transition rates that belong to lowering the inventory of one location are a little less straightforward because here the lateral transshipments are involved. If a location has some inventory, but one or both of the others has no inventory, then the demand rates of those two locations are added to the demand rate of the location which does have a positive inventory level. This is again done per location for each of the 125 states. The original vector is calculated and the inventory level is reduced by one and then the new state number is calculated. Then depending on the inventory levels of the other two locations the demand rates are added. For each location there are four possible scenarios, Table 24 gives an example for location one. This table works as follows, “+” means a positive inventory level for the item that is considered, “0” means there is no inventory for that particular item, “?” means that the inventory level could be either “+”or “0” since it does not matter because in this case the inventory level for location 1 is “0” as well which means that no inventory lowering transition can occur at this location.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 24 Possible inventory level scenarios for location 1

In the first four scenarios there is a lowering transition possible from location one. However, if the inventory level is at zero already (scenario 5) then no lowering transition can take place at that location. Each of these five scenarios correspond with the “elseif” functions in the following code. A similar code exists for location 2 and 3.

```matlab
for i=1:size
    a = funRTV(i);
    b = a - [1 0 0];
    if min(S(y,:))<0
        basestocklevelfault
    elseif a(1)>0 && a(2)==0 && a(3)==0;
        j = funVTR(b);
        Q(i,j) = Q(i,j) + (m(y,1)+m(y,2)+m(y,3));
    elseif a(1)>0 && a(2)>0 && a(3)>0;
```
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j) + m(y,1); \]
\[ \text{elseif } a(1) > 0 \land a(2) <= 0 \land a(3) > 0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j) + m(y,1) + m(y,2); \]
\[ \text{elseif } a(1) > 0 \land a(2) > 0 \land a(3) == 0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j) + m(y,1); \]
\[ \text{end} \]
\[ \text{end} \]

In a generator matrix the transition from state \( i \) to state \( i \) is equal to minus the sum of the rest of all transitions in row \( i \).

This process results in a complete transition rate matrix \( Q \) for each item. Using this matrix \( Q \) the long run probabilities of being in each of the states can be calculated. With these steady state probabilities the fraction of demand of one location that is satisfied by another location, through lateral transshipments, can be calculated. For instance, \( A[1,2] \) represents the fraction of demand faced at location 1 that is satisfied by inventory from location 2. These fractions are calculated for each of the three locations. The fraction of demand that is satisfied by emergency shipments is equal to the probability of being in state 125 [0 0 0]. Using the lateral transshipment fractions and the emergency shipment fractions, the fraction of demand that is satisfied by local demand can be calculated. For example: \( B_2 = 1 - A[2,1] - A[2,3] \cdot \pi(125) \), where \( B_2 \) is the fraction of demand faced at location 2 and satisfied by inventory from location 2, \( A[2,1] \) fraction of demand at location 2 satisfied by location 1, \( A[2,3] \) the demand at location 2 satisfied by location 3 and \( \pi(125) \) is the probability of being in state 125 and thus the probability of emergency shipments.

Now that all the fractions have been calculated, they can be used to compute the average waiting time per location for the given item. The same goes for the average time it takes for a lateral transshipment to arrive.
\([W, Z] = \text{calcWZ}(S)\)

Using the previous function the waiting times \((W)\), lateral transshipment times \((D)\), the emergency shipment probabilities \((E)\) for all items can be calculated for a given base-stock level \((S)\). Which can then be formulated in three matrices which described \(W\), \(D\) and \(E\) for all combinations of items and locations. Using the following code, where \(y\) is the item number. The other input parameters are explained in the section on the previous function.

\[
\text{for } y=1:5 \\
[W(y,:),D(y,:),E(y,:)] = \text{calcWDE}(m,u,y,S,TL,TE); \\
\text{end}
\]

Using these matrices the costs for each of the item and locations combinations can be calculated. Using the following lines of code, in which \(j\) is the location, \(CH\) is the holding costs per item, \(CT\) is the transshipment cost per time unit for an item and \(CE\) is the emergency shipment cost of an item.

\[
\text{for } y=1:5 \\
\text{for } j=1:3 \\
[Z(y,j)] = CH(y)*S(y,j)+CT(y)*m(y,j)*D(y,j)+CE(y)*m(y,j)*E(y); \\
\text{end} \\
\text{end} \\
\]

\([WJ] = \text{calcWJ}(S)\)

A simple function that calculates the average waiting times per location for a given inventory level allocation \((S)\). The demand matrix \((m)\) is summed up per column \((Mj)\) (location) so that per item it is known how much it contributes to the total demand per location by the following fraction: \((m(y,j))/M(j)\). The waiting times that have been calculated in the previous function and stored in matrix \(W(y,j)\) are then multiplied by the aforementioned fraction which forms the matrix \(wyj\) of weighted waiting times. These are then added up to compute the weighted average waiting time per location.

\[
\text{for } y=1:5 \\
\text{for } j=1:3 \\
[W,~] = \text{calcWZ}(S); \\
[wyj(y,j)] = (m(y,j)/Mj(j))*W(y,j); \\
\text{end} \\
\text{end} \\
WJ = \text{sum}(wyj,1); \\
\]

This function will be used after every iteration in the greedy algorithm to determine whether the goal of the maximum average waiting time has been reached.
This appendix describes the functions related to the optimization procedure that were implemented in Matlab in greater detail. The focus hereby lies on the functionality and challenges that arose. Each function is introduced in the same following format: the output between square brackets, the name of the function and finally the input required for this function between round brackets.

\[ \text{[S,WJ\_end,Total\_costs]} = \text{Greedy(WJ\_max)} \]

In addition to the (near) optimal base-stock level allocation, the greedy algorithm also computes the corresponding average waiting times per location and the total system costs.

First the base-stock level are set to zero for all items and locations and the average waiting time is calculated.

\[
S = \text{zeros}(5,3) \\
WJ = \text{calcWJ}(S)
\]

Next the change in waiting time and costs need to be calculated for adding one item of inventory for every combination of item and location.

\[
\text{[deltaWyj]} = \text{calc\_deltaWyj}(S,WJ\_max); \\
\text{[deltaZyj]} = \text{calc\_deltaZyj}(S);
\]

\[ \text{[deltaWyj]} = \text{calc\_deltaWyj}(S,WJ\_max) \]

This function, which uses the current base-stock level allocation \( S \) and the maximum average waiting time per location \( W\_\text{max} \) in order to compute the reduction in waiting time for each of the three locations when one item is added.

\[
wj = \text{calcWJ}(S); \\
\text{for } y=1:5 \\
\text{for } j=1:3 \\
\text{if } S(y,j) \geq 4 \\
\text{wjy} = \text{calcWJ}(S); \\
\text{else} \\
\text{wjy} = \text{calcWJ}(S+fune\_yj(y,j)); \\
\text{end} \\
\text{[deltaWyj}(y,j)] = \text{max}(0,(wj(j)-W\_\text{max}(j)))-\text{max}(0,(wjy(j)-W\_\text{max}(j))); \\
\text{end} \\
\text{end}
\]

This functions starts by computing the waiting times per location for the given base-stock level \( S \). Then for each combination of item \( (y) \) and location \( (j) \) first it is checked if the base stock level is not already greater or equal to 4, since then it cannot be raised anymore. If it is, then \( wjy \) receives the same value as \( wj \) which means that there is no reduction in waiting time. If the base-stock level is not yet at that level, then \( wjy \) receives the value of \( S+fune\_yj(y,j) \) where \( fune\_yj(y,j) \) represents adding one item \( (y) \) at a location \( (j) \).

Then the matrix \( \text{deltaWyj} \) is calculated by computing the reduction in average waiting time per location for each combination of \( y \) and \( j \).

Since adding an item to any of the three locations impacts the waiting time of the other two locations through lateral transshipments, a large number of calculations have to be made in order to create the total \( \text{deltaWyj} \) matrix. However, since adding one item does not impact the waiting time of other items, subsequent iterations of the greedy algorithm only have to compute the row of the \( \text{deltaWyj} \) matrix which corresponds to the item that has been added last. This way the total computation time can be greatly reduced.
This function computes the change in total system cost when an item is added to a certain location. First the total system costs of the current base-stock level allocation is calculated ($Z_0$). Then for each combination of item ($y$) and location ($j$) it is checked if the inventory level is not already greater than or equal to 4. If it is, then the system cost does not change. If the inventory level is below 4 still, then the total system costs ($Z_1$) are calculated for $S$ where an additional item ($y$) is added at location $j$. The matrix deltaZyj is formed by subtracting the original total system costs ($Z_0$) from the new system costs for each of the items and locations.

\[
\begin{align*}
[\sim, Z] &= \text{calcWZ}(S); \\
Z_0 &= \text{sum}(Z(:)); \\
Zyj &= \text{zeros}(5,3); \\
\text{for } y=1:5 \\
\quad &\text{for } j=1:3 \\
\quad &\quad \text{if } S(y,j) \geq 4 \\
\quad &\quad \quad [\sim, Z_1] = \text{calcWZ}(S); \\
\quad &\quad \quad Zyj(y,j) = \text{sum}(Z_1(:)); \\
\quad &\quad \text{else} \\
\quad &\quad \quad [\sim, Z_1] = \text{calcWZ}(S+fune_yj(y,j)); \\
\quad &\quad \quad Zyj(y,j) = \text{sum}(Z_1(:)); \\
\quad &\quad \text{end} \\
\quad &\quad [\text{deltaZyj}(y,j)] = Zyj(y,j) - Z_0; \\
\text{end} \\
\text{end}
\end{align*}
\]

Greedy algorithm continued

The remainder of the greedy algorithm is structured as follows. For as long as the average waiting time for a location is higher than the maximum average waiting time for that location the algorithm starts a new iteration. This begins by calculating the ratio $\text{ryj}_\text{adj}$ using the deltaWyj and deltaZyj matrices. For each combination of item ($y$) and location ($j$) the deltaWyj is divided by the corresponding deltaZyj, which results in a ratio $\text{ryj}$. To ensure that base stock levels that are already at 4 are not raised any further the $\text{ryj}$ ratio of the item/location combinations that have an inventory level of 4 already are set to -1. The remaining matrix is called $\text{ryj}_\text{adj}$ and from this matrix the highest value is selected. The inventory level for the item at the location that belong to this value is then increased by 1. For the last added item the rows of the deltaWyj and deltaZyj matrix are recalculated. The outcome replaces the old row in the two matrices that were calculated prior to starting the greedy algorithm and finally the average waiting times per location are calculated again and compared to the maximum average waiting times. If they are all below their maximum value, the algorithm stops and computes the total system costs. If they are still above, another iteration is started.

\[
\begin{align*}
\text{for } j=1:3 \\
\quad \text{while } WJ(j) > WJmax(j) \\
\quad \quad [\text{ryj}_\text{adj}] = \text{calc_r_adj}(S,\text{deltaWyj},\text{deltaZyj}); \\
\quad \quad \text{ryj}_\text{max} = \text{max}(\text{ryj}_\text{adj}(::)); \\
\quad \quad [y_, j_] = \text{find}(\text{ryj}_\text{adj}==\text{max}(\text{ryj}_\text{adj}(::)),1); \\
\quad \quad S = S+fune_yj(y_,j_); \\
\quad \quad \text{deltaWy} = \text{calc_deltaWy}(y_,S,WJmax); \\
\quad \quad \text{deltaWyj}(y_,:) = \text{deltaWy}; \\
\quad \quad \text{deltaZy} = \text{calc_deltaZy}(y_,S); \\
\quad \quad \text{deltaZyj}(y_,:) = \text{deltaZy}; \\
\quad \quad WJ = \text{calcWJ}(S) \\
\quad \text{end} \\
\text{end}
\end{align*}
\]
APPENDIX 3 – MATLAB CODE

function [w,d,e] = calcWDE(m,u,y,S,TL,TE)

%Creating the generator matrix Q and calculating the steady state
%probabilities in a situation with two locations and a maximum inventory
%level of 2 per location.
%In which:
%S is base-stock level
%m is demand rate matrix
%u is replenishment rate matrix
%y is item number

%Create empty matrix Q of size x size
size = 125;
Q = zeros(size);

%tic
%start with row "i" and increase first location of the corresponding start
%vector "a" with 1, if this is greater than 4 (the max inventory level per
%location)
%then do nothing %else find row/column number "j" that belongs to new
%vector "b".
%If a(1,1) was 0 then add 2*u to Q(i,j) or if a(1,1) was 1 then add u to
%Q(i,j).
for i=1:size
    a = funRTV(i);
    b = a + [1 0 0];
    if b(1)>S(y,1)
        j = funVTR(b);
        Q(i,j) = Q(i,j) + (S(y,1)-a(1))*u(y);
    end
end

for i=1:size
    a = funRTV(i);
    b = a + [0 1 0];
    if b(2)>S(y,2)
        j = funVTR(b);
        Q(i,j) = Q(i,j) + (S(y,2)-a(2))*u(y);
    end
end

for i=1:size
    a = funRTV(i);
    b = a + [0 0 1];
    if b(3)>S(y,3)
        j = funVTR(b);
        Q(i,j) = Q(i,j) + (S(y,3)-a(3))*u(y);
    end
end

%Lower location 1 of start vector "a" by 1 and calculate transition
%rates.
for i=1:size
    a = funRTV(i);
    b = a - [1 0 0];
    if min(S(y,:))<0
        basestocklevelfault
    elseif a(1)>0 && a(2)==0 && a(3)==0;
end
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+(m(y,1)+m(y,2)+m(y,3)); \]
\[ \text{elseif} \ a(1)>0 \ \& \ a(2)>0 \ \& \ a(3)>0; \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,1); \]
\[ \text{elseif} \ a(1)>0 \ \& \ a(2)==0 \ \& \ a(3)>0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,1)+m(y,2); \]
\[ \text{elseif} \ a(1)>0 \ \& \ a(2)>0 \ \& \ a(3)==0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,1); \]
\[ \text{end} \]
\[ \text{end} \]
%Lower location 2 of start vector "a" by 1 and calculate transition %rates.
\[ \text{for } i=1:\text{size} \]
\[ a = \text{funRTV}(i); \]
\[ b = a - [0 1 0]; \]
\[ \text{if } \min(S(y,:))<0 \]
\[ \text{basestocklevelfault} \]
\[ \text{elseif} \ a(2)>0 \ \& \ a(1)==0 \ \& \ a(3)==0; \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+(m(y,1)+m(y,2)+m(y,3)); \]
\[ \text{elseif} \ a(2)>0 \ \& \ a(1)>0 \ \& \ a(3)>0; \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,2); \]
\[ \text{elseif} \ a(2)>0 \ \& \ a(1)==0 \ \& \ a(2)>0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,2); \]
\[ \text{elseif} \ a(2)>0 \ \& \ a(1)>0 \ \& \ a(3)==0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,1)+m(y,2); \]
\[ \text{end} \]
\[ \text{end} \]
%Lower location 3 of start vector "a" by 1 and calculate transition %rates.
\[ \text{for } i=1:\text{size} \]
\[ a = \text{funRTV}(i); \]
\[ b = a - [0 0 1]; \]
\[ \text{if } \min(S(y,:))<0 \]
\[ \text{basestocklevelfault} \]
\[ \text{elseif} \ a(3)>0 \ \& \ a(1)==0 \ \& \ a(2)==0; \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+(m(y,1)+m(y,2)+m(y,3)); \]
\[ \text{elseif} \ a(3)>0 \ \& \ a(1)>0 \ \& \ a(2)>0; \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,3); \]
\[ \text{elseif} \ a(3)>0 \ \& \ a(1)==0 \ \& \ a(2)>0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,3); \]
\[ \text{elseif} \ a(3)>0 \ \& \ a(1)>0 \ \& \ a(2)==0 \]
\[ j = \text{funVTR}(b); \]
\[ Q(i,j) = Q(i,j)+m(y,3); \]
\[ \text{end} \]
\[ \text{end} \]
%fill in the diagonal for all rows which is -1*sum of the row
\[ \text{for } i=1:\text{size} \]
\[ Q(i,i)=-\text{sum}(Q(i,:)); \]
\[ \text{end} \]
%Showing the completed generator matrix Q
Q;
%xlswrite('Qmatrix.xlsx',Q,1);

%Transposing matrix Q
QT = Q';

%Replacing all numbers in the last(9th) row with ones
QT(size,:)= [1,];

%Defining column vector B with all zeros except for a one in the last row
B = zeros(size,1);
B(size,:)= [1,];

%solving the linear system of equations QT*pi = B which result in the
%steady state probabilities
pi = inv(QT)*B; %#ok<MINV>

%check steady state probabilities add up to 1
Sum_pi = sum(pi);

%Total_Calculation_time = toc

%calculating A12 (= fraction of demands location 1 satisfies by lateral
%transshipment from location 2
X12 = zeros(125,1);
for x=1:125
    d = funRTV(x);
    if d(1)==0 && d(2)>0
        X12(funVTR(d),1) = X12(funVTR(d),1)+ 1;
    else
        end
end

a12 = zeros(125,1);
for i=1:125
    a12(i) = a12(i)+(pi(i)*X12(i));
end
A12 = sum(a12);

%calculating A13 (= fraction of demands location 1 satisfies by lateral
%transshipment from location 3
X13 = zeros(125,1);
for x=1:125
    d = funRTV(x);
    if d(1)==0 && d(2)==0 && d(3)>0
        X13(funVTR(d),1) = X13(funVTR(d),1)+ 1;
    else
        end
end

a13 = zeros(125,1);
for i=1:125
    a13(i) = a13(i)+(pi(i)*X13(i));
end
A13 = sum(a13);

%Calculating fraction of demand satisfied by local stock at location 1
B1 = 1-A12-A13-pi(125);

%calculating A21 (= fraction of demands location 2 satisfies by lateral
%transshipment from location 1
X21 = zeros(125,1);
for x=1:125
    d = funRTV(x);
    if d(2)==0 && d(1)>0
        X21(funVTR(d),1) = X21(funVTR(d),1)+ 1;
    else
        end
end

a21 = zeros(125,1);
for i=1:125
    a21(i) = a21(i)+(pi(i)*X21(i));
end

A21 = sum(a21);

%calculating A23 (= fraction of demands location 2 satisfies by lateral
%transshipment from location 3
X23 = zeros(125,1);
for x=1:125
    d = funRTV(x);
    if d(3)==0 && d(2)==0 && d(1)>0
        X23(funVTR(d),1) = X23(funVTR(d),1)+ 1;
    else
        end
end

a23 = zeros(125,1);
for i=1:125
    a23(i) = a23(i)+(pi(i)*X23(i));
end

A23 = sum(a23);

%Calculating fraction of demand satisfied by local stock at location 2
B2 = 1-A21-A23-pi(125);

%calculating A31 (= fraction of demands location 3 satisfies by lateral
%transshipment from location 1
X31 = zeros(125,1);
for x=1:125
    d = funRTV(x);
    if d(3)==0 && d(2)==0 && d(1)>0
        X31(funVTR(d),1) = X31(funVTR(d),1)+ 1;
    else
        end
end

a31 = zeros(125,1);
for i=1:125
    a31(i) = a31(i)+(pi(i)*X31(i));
end

A31 = sum(a31);

%calculating A32 (= fraction of demands location 3 satisfies by lateral
%transshipment from location 2
X32 = zeros(125,1);
for x=1:125
    d = funRTV(x);
    if d(3)==0 && d(2)>0
        X32(funVTR(d),1) = X32(funVTR(d),1) + 1;
    else
    end
end

a32 = zeros(125,1);
for i=1:125
    a32(i) = a32(i)+(pi(i)*X32(i));
end

A32 = sum(a32);

%Calculating fraction of demand satisfied by local stock at location 3
B3 = 1-A31-A32-pi(125);

%Probability demand is satisfied by emergency supplies
e = pi(125);

for y=1:3
    d = zeros (1,3);
    d(1,1) = d(1,1)+ A12*TL(1,2) + A13*TL(1,3);
    d(1,2) = d(1,2)+ A21*TL(2,1) + A23*TL(2,3);
    d(1,3) = d(1,3)+ A31*TL(3,1) + A32*TL(3,2);
    d;

    w = zeros(1,3);
    w(1,1)= w(1,1)+ (B1*0 + A12*TL(1,2) + A13*TL(1,3) + e*TE(y));
    w(1,2)= w(1,2)+ (B2*0 + A21*TL(2,1) + A23*TL(2,3) + e*TE(y));
    w(1,3)= w(1,3)+ (B3*0 + A31*TL(3,1) + A32*TL(3,2) + e*TE(y));
    w;
end

function [x] = funVTR(y)
%UNTITLED6 Summary of this function goes here
% Detailed explanation goes here
if y == [0 0 0];
    x = 125;
elseif max(y)>4;
    x = basestocklevelfault;
elseif min(y)<0;
    x = basestocklevelfault;
else
    x = y(1,1)*1+y(1,2)*5+y(1,3)*25;
end
end
function x = funRTV(y)
if y == 125;
    x = [0 0 0];
elseif y > 125
    x = basestocklevelfault;
else
    x = [0 0 0];
    x(1,3)=x(1,3)+floor(y/25);
    x(1,2)=x(1,2)+floor((y-x(1,3)*25)/5);
    x(1,1)=x(1,1)+(y-x(1,3)*25-x(1,2)*5);
end
end

function [W,Z] = calcWZ(S)
%format long
m = [0.006 0.006 0.02;
     0.001 0.001 0.003;
     0.003 0.001 0.002;
     0.002 0.001 0.005;
     0.003 0.001 0.004];

u = [1 0.142857 0.142857 0.142857 1];

TL = [0 0.065 0.076;
      0.065 0 0.074;
      0.076 0.074 0];

TE = [1 3.5 3.5 3.5 1];

CH = [1521.6 1005.8 781 753.6 695.8];
CT = [4160 4160 4160 4160 4160];
CE = [11412 7543.5 5857.5 5652 5218.5];

for y=1:5
    [W(y,:),D(y,:),E(y,:)] = calcWDE(m,u,y,S,TL,TE);
end

W;
D;
E;

Z = zeros(5,3);
for y=1:5
    for j=1:3
        [Z(y,j)] = CH(y)*S(y,j)+CT(y)*m(y,j)*D(y,j)+CE(y)*m(y,j)*E(y);
    end
end
Z;
end
function [WJ] = calcWJ(S)
format long

m = [0.006 0.006 0.02;
     0.001 0.001 0.003;
     0.003 0.001 0.002;
     0.002 0.001 0.005;
     0.003 0.001 0.004];

[Mj] = sum(m,1);

wyj = zeros(5,3);
for y=1:5
    for j=1:3
        [W,~] = calcWZ(S);
        [wyj(y,j)] = (m(y,j)/Mj(j))*W(y,j);
    end
end

WJ = sum(wyj,1);
end

function [ e ] = fune_yj(y,j)
%Matrix e with all zeros except for a 1 on (y,j)

e = zeros(5,3);
e1 = ones(5,3);

[e(y,j)] = e(y,j)+1*e1(y,j);
end

function [deltaWyj] = calc_deltaWyj(S,WJmax)
format long

deltaWyj = zeros(5,3);
wj = calcWJ(S);
for y=1:5
    for j=1:3
        if S(y,j) >= 4
            wjy = calcWJ(S);
        else
            wjy = calcWJ(S+fune_yj(y,j));
        end
        [deltaWyj(y,j)] = max(0,(wj(j)-WJmax(j)))-max(0,(wjy(j)-WJmax(j)));
    end
end
end
function [deltaWy] = calc_deltaWy(y,S,WJmax)
    format long
    wj = calcWJ(S);
    deltaWy = zeros(1,3);
    for j=1:3
        if S(y,j) >= 4
            wjy = calcWJ(S);
        else
            wjy = calcWJ(S+fune_yj(y,j));
        end
        deltaWy(y,j) = max(0,(wj(j)-WJmax(j)))-max(0,(wjy(j)-WJmax(j)));
    end
    deltaWy = deltaWy(y,:);
end

function [deltaZyj] = calc_deltaZyj(S)
    deltaZyj = zeros(5,3);
    format bank
    [~,Z] = calcWZ(S);
    Z_0 = sum(Z(:));
    Zyj = zeros(5,3);
    for y=1:5
        for j=1:3
            if S(y,j)>=4
                [~,Z_1] = calcWZ(S);
                [Zyj(y,j)] = sum(Z_1(:));
            else
                [~,Z_1] = calcWZ(S+fune_yj(y,j));
                [Zyj(y,j)] = sum(Z_1(:));
            end
            [deltaZyj(y,j)] = Zyj(y,j)-Z_0;
        end
    end
end

function [deltaZy] = calc_deltaZy(y,S)
    deltaZy = zeros(1,3);
    %deltaZyj = zeros(5,3);
    format bank
    [~,Z] = calcWZ(S);
    Z_0 = sum(Z(:));
    Zy = zeros(5,3);
    for j=1:3
        if S(y,j)>=4
            [~,Z_1] = calcWZ(S);
            [Zy(y,j)] = sum(Z_1(:));
        else
            [~,Z_1] = calcWZ(S+fune_yj(y,j));
            [Zy(y,j)] = sum(Z_1(:));
        end
        [deltaZy(y,j)] = Zy(y,j)-Z_0;
    end
    [deltaZy] = deltaZy(y,:);
end
function [ryj_adj] = calc_r_adj(S,deltaWyj,deltaZyj)

function [ryj_adj] = calc_r_adj(S,deltaWyj,deltaZyj)
format long
ryj = zeros(5,3);
for j=1:3
    for y=1:5
        [ryj(y,j)] = deltaWyj(y,j)/deltaZyj(y,j);
    end
end

for j=1:3
    for y=1:5
        if ryj(y,j) < 0 && ryj(y,j)~= -99
            [ryj(y,j)] = ryj(y,j)+1000000;
        elseif ryj(y,j) == Inf
            [ryj(y,j)] = 1;
        else
            [ryj(y,j)] = ryj(y,j)+1000000;
        end
    end
end

for y=1:5
    for j=1:3
        if S(y,j) >= 4
            ryj(y,j) = -99;
        else
            [ryj(y,j)] = ryj(y,j)+1000000;
        end
    end
end
ryj_adj = ryj;
end

function [S,WJ_end,Total_costs] = Greedy(WJmax)

tic
%step 1
%Set initial solution S = 0 and calculate WJ(0) for all locations
S = zeros(5,3);
WJ = calcWJ(S);

%Step 2
%for all items and all locations calculate delta_Wyj and delta_Zyj and ryj
[deltaWyj] = calc_deltaWyj(S,WJmax);
[deltaZyj] = calc_deltaZyj(S);

for j=1:3
    while WJ(j) > WJmax(j)
        [ryj_adj] = calc_r_adj(S,deltaWyj,deltaZyj);
        ryj_max = max(ryj_adj(:));
        [y_,j_] = find(ryj_adj==max(ryj_adj(:)),1);
        S = S+fune_yj(y_,j_);
        deltaWy = calc_deltaWy(y_,S,WJmax);
        deltaWyj(y_,:) = deltaWy;
        deltaZy = calc_deltaZy(y_,S);
        deltaZyj(y_,:) = deltaZy;
        WJ = calcWJ(S);
    end
end
S;
format long
WJ_end = calcWJ(S);
[~,Z] = calcWZ(S);
Total_costs = sum(Z(:));
toc
end
Inventory pooling through lateral transshipments at a railway contractor

Investigating the potential benefits of using lateral transshipments to pool the maintenance spare part inventories of several regional warehouses. A case study at Strukton Rail Netherlands.

Introduction
The master thesis research project presented here describes the mathematical implementation of a spare part inventory pooling model that utilizes lateral transshipments (LT). The project has been conducted at Strukton Rail Netherlands (SRNL) with regard to their maintenance spare parts at different regional warehouses (RW) spread throughout the Netherlands.

This mathematical model is used to determine the performance of the inventory management system in three different scenarios:
1. the current situation,
2. the situation in which the inventory levels of the current situation are optimized,
3. the situation in which lateral transshipments are used to pool the inventory of three RW.

Figure 1 shows the structure of the supply chain, the red rectangle defines the scope of this research.

Figure 1: Supply Chain and scope

Research question
The aim of the research is finding an answer to the following research question:

“Would inventory pooling, by allowing lateral transshipments between the regional warehouses, improve the performance of the inventory control for failure spare parts, in terms of costs and service level, compared to the current situation of Strukton Rail Netherlands?”

Research methods
Mathematical model
A simplified representation of the implemented mathematical model by Wong et al. (2005) is presented in figure 2. Which shows the situation for 3 locations, each facing:
• Outgoing Demand (m)
• Incoming Replenishments (r)
• Incoming Emergency supplies (EM)
• Incoming and outgoing lateral transshipments (LT)

Each location has a certain base-stock level for each of the items it holds. If demand cannot be met locally, a LT is issued if possible. Otherwise an EM is required.

Figure 2: Mathematical model

Results
The results of inputting the data gathered from SRNL into the implemented mathematical show that inventory holding costs can be reduced by roughly 50% compared to the current situation when lateral transshipments are utilized. Another important result is that simply optimizing the current situation, without using lateral transshipments, can yield cost reductions of up to 40% depending on the maximum average waiting time. This is illustrated in figures 3 and 4.

Figure 3: Cost Reduction compared to current situation

Figure 4: Results, Total costs vs. Maximum Average Waiting Time

Conclusions & Recommendations

Conclusions:
1. Using lateral transshipments (scenario 3) can prove beneficial for Strukton Rail Netherlands given the data that was available for this research.
2. Alternatively, cost savings can be achieved simply by optimizing the inventory levels per location individually (scenario 2). Even though the cost reductions here are significantly lower than when using lateral transshipments.

Recommendations:
1. Strukton Rail NL should seriously consider utilizing the concept of inventory pooling by allowing lateral transshipments to take place between the regional warehouses.
2. Collect and make use of more reliable and extensive data regarding item demand, failure rate and supply lead times.
3. The recommendation for further research is related to investigating the translation from practical to theoretical performance measures specifically for the railway industry.

References