BACHELOR THESIS

Determining the Required Spare Parts Inventory to Ensure Military Vehicle Availability

07-06-2023

B. J. Gunnink

Bachelor thesis Industrial Engineering and Management
Faculty of Behavioural, Management and Social sciences (BMS)

Determining the Required Spare Parts Inventory to Ensure Military Vehicle Availability

Author:

Bart Julian Gunnink

University of Twente

Drienerlolaan 5, 7522 NB Enschede

dr. M.C. van der Heijden (Matthieu)
ir. R.L.A. Harmelink (Rogier)

Verebus Engineering B.V.

Handelskade 49, 2288 BA Rijswijk

P. Fakkert (Patrick)

Preface

Dear reader,

The following is my bachelor thesis on “Determining the Required Spare Parts Inventory to Ensure Military Vehicle Availability” for the bachelor Industrial Engineering and Management at the University of Twente. This thesis has been performed at Verebus Engineering to gain insight into the selection of spare parts required to ensure a satisfactory level of vehicle availability for the newly introduced Iveco Manticore at the Dutch Ministry of Defence. I would like to thank Verebus and Patrick Fakkert for their support and the opportunity to carry out my thesis at Verebus, it has been a very educational and enjoyable experience.

Finally I would like to thank my supervisors from the University of Twente, Matthieu van der Heijden and Rogier Harmelink for their feedback and guidance throughout the process.

Bart Gunnink

June 2023

Management summary

The Dutch Ministry of Defence (MoD) has recently acquired 1185 Iveco Manticore vehicles, also known as the Medium Tactical Vehicle, the first of which are to be delivered during the second quarter of 2023. In order to guarantee the availability of the Manticores, Verebus Engineering has the task of setting requirements that ensure an availability of 350 days a year. Verebus sets these requirements by means of Integrated Logistics Support, a process that helps integrate and communicate information from several parties across the lifespan of a project.

The process of guaranteeing vehicle availability is subject to several factors. First of all, the novelty of the vehicle makes that users and mechanics are yet to gain experience with the vehicle. Therefore opinions on which measures to take to ensure availability vary. This is further complicated by the fact that there are multiple vehicle variations that each require a different selection of spare components. The final factor at play is the experiences the MoD has with leaving the creation and provision of spare parts packages for vehicles to the manufacturer, which previously resulted in significant overstocking of components. This leads to the main research question: "Which spare part composition should be maintained by Verebus to ensure the required availability of 350 days a year?"

Effectively, the MoD and Verebus are looking to establish a safety inventory for spare components that meets the availability requirements while minimising cost. The demand for spare components consists of two parts, one preventive, one corrective. A safety inventory intends to cover for uncertainty in the demand and supply of these components, with the objective to maximize availability for a cost that is as low as possible. As demand and supply for preventive maintenance is predictable, the focus will lie on managing uncertainty for corrective maintenance, which can be modelled as a Poisson process. Subsequently, the reordering policy can be modelled as a (s-1, s) process that calculates the expected backorders based on the current stock level of an item and the average pipeline, which is the product of the average annual demand and the repair time of a component. By comparing the backorder reduction achieved by the addition of one unit of stock of said component to its cost, the cheapest option to minimise the number of backorders can be found.

This single echelon model can then be extended into a two-echelon model that also includes a depot, which allows for cost savings by pooling inventory. To achieve this, the average pipeline to each workshop needs to be adjusted to reflect the average order and shipping time of two days between the depot and the workshops, where the pipeline for any item to the depot itself is now the product of the demand for said component at all workshops and the average repair or reorder time. Consequently, the total system availability can be found by taking the weighted average of the vehicle availability at each workshop. In turn, vehicle availability is based on the product of all component availabilities, which are dependent on the number of backorders for each component. Both models were created keeping in mind future changes in the number of items considered, as well as potential changes in the properties of the items such as demand, and lead time.

After some small adjustments for optimisation and to account for some requirements set by the MoD, the single echelon and two-echelon models can then be set to produce a result for the desired 350 days of system availability, keeping in mind the two days required to perform other tasks such as transport, diagnostics, and repairs. After performing calculations for both the single echelon and two-echelon models to the desired level of availability and comparing their performance, the two-echelon model comes forward as the best option for the MoD. The two-echelon models requires a spare parts inventory that is around 20% less expensive than the single echelon system.

As the manufacturer has not yet made any recommendations on a spare parts composition for the Manticore, we have established a rough baseline for inventory cost performance based on the Bushmaster and Mercedes G-Class vehicles. This baseline is a ratio comparing the cost of the spare parts inventory to the acquisition cost of the fleet of vehicles, this ratio is approximately 1:12.5. It should

be noted that the comparison to these vehicles is limited, due to the technical and financial differences between the vehicles. Calculations were performed for two scenarios. The first scenario represents the expected situation where preventive maintenance is easily plannable and therefore does not require safety inventory. The second scenario looks into what the results would be in case preventive maintenance is subject to random Poisson-distributed demand. The recommended spare parts distribution per location can be found in Appendices C1 and C2 for the single echelon model, and Appendices D5 and D6 for the two-echelon model.

Single echelon	**Indexed investment (millions)**	**Ratio**	**Availability**
Scenario 1	1.155	1 : 14.4	96.45%
Scenario 2	1.429	1 : 11.6	96.45%

Table I: Two-echelon spare part to fleet acquisition cost ratio

Two-echelon (adjusted)	**Indexed investment (millions)**	**Ratio**	**Availability**
Scenario 1	0.920	1:18.1	96.44%
Scenario 2	1.175	1:14.2	96.44%

Table II: Two-echelon spare part to fleet acquisition cost ratio

For the availability standards set by the MoD both models outperformed the baseline in the first scenario, as can be seen in Tables *I* and *II*. In the second scenario, only the two-echelon manages to outperform the baseline. A downside of the two-echelon model is that vehicle availability per workshop varies to a larger degree. Where the single-echelon model optimises for a vehicle availability that meets the requirements for every workshop individually, the two-echelon model approaches the fleet as a whole, meaning that the vehicle availability per workshop ranges from 95% to 98%. If this does not pose an issue, then the two-echelon model that only accounts for corrective maintenance, as found in Appendix D5, is the best option for the MoD.

Both models and scenarios showed diminishing returns on investment after approaching an availability of approximately 95%. It could therefore be a consideration for the MoD to slightly lower the desired vehicle availability to save costs. Furthermore, there is a selection of expensive items such as the complete transmission, the front axle, and armoured doors, windshields, and windows that take up a large share of the total spare part investment required. Purchasing more of these items during the current production phase as investment spares could help reduce costs in the future.

Table of contents

Acronyms

BO	Backorders
DI	Due in
DVOW	Defensiebrede Vervanging Operationele Wielvoertuigen
EBO	Expected backorders
ERP	Enterprise Resource Planning
FMECA	Failure Mode, Effects, and Criticality Analysis
ILM	Intermediate Level Maintenanc
ILS	Integrated Logistics Support
LORA	Level of Repair Analysis
LRU	Line Replaceable Unit
LSA	Logistics Support Analysis
METRIC	Multi-Echelon Technique for Recoverable Item Control
MoD	Ministry of Defence
MTBF	Mean Time Between Failures
OH	On-hand
SRU	Shop Replaceable Unit
OLM	Organic Level Maintenance

CHAPTER 1: INTRODUCTION

1.1 Background

As part of the defence-wide effort of replacing operational wheeled vehicles, or in Dutch, Defensiebrede Vervanging Operationele Wielvoertuigen (DVOW), the Dutch Ministry of Defence (MoD) has recently procured 1185 Iveco Manticore vehicles (Figure 1). The first Manticores are to be delivered during the second quarter of 2023. Verebus Engineering has the task of overseeing this process and setting requirements to ensure an availability of 350 days a year. The Manticore is a result of narrow cooperation between the MoD and Iveco and concerns not just a completely new type of vehicle, but also includes a new type of maintenance agreement, a performance-based contract, in which Iveco performs maintenance for almost half of the vehicles. As a result of this new way of operating, and the inexperience of mechanics with the new vehicle, there is currently no consensus at The MoD on what an ideal spare part composition would look like. The 15 days of allowed unavailability needs to account for problem diagnostics, the transportation of the vehicle to a workshop, and the preparations for repairs. Combined, this amounts to approximately one day. If all these conditions are met, the mechanics are able to return the vehicle to the state of mission capable within one day.

Figure 1: Iveco Manticore/Medium Tactical Vehicle (MTV)

The Manticore, also known as the Medium Tactical Vehicle (MTV) serves as a replacement for the established 'Tactical Armoured Vehicle with 12kN load capacity (12kN)' vehicle class. For the vehicles that will be maintained by Defence, four main variations can be identified: soft top, hard top, pick up, and casualty transport. For each variation, there are several sub variations, which usually is a matter of designated use case or compatibility with external components. In order to curb the scope of the assignment, the four main variations will be assessed. Due to the differences between the variations, the inventory composition will need to account for some variation-specific components. The Manticores will be maintained in six different state-owned-workshops, each workshop maintaining a different combination of vehicle variations as can be seen in Figure 2. Further impressions of each vehicle variation can be found in Appendix A1.

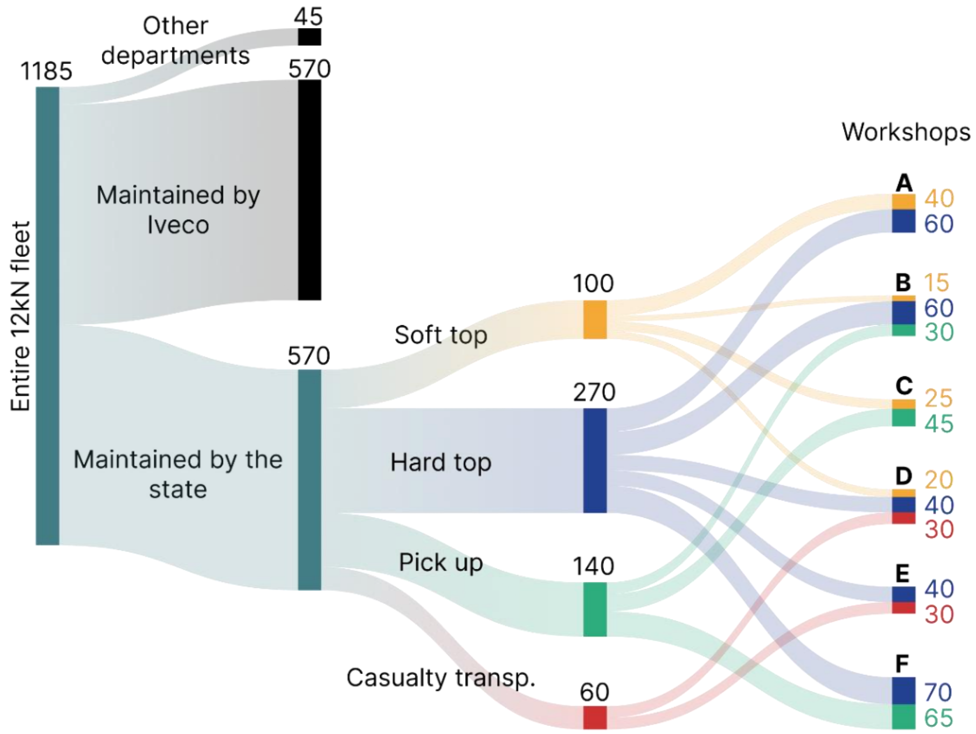


Figure 2: Vehicle variation distribution

Maintenance of the Manticore has been split into several levels of complexity. In the workshops, inventory needs to be kept for the lowest two levels, namely organic level maintenance (OLM), and intermediate level maintenance (ILM). OLM consists of activities that can be executed by a single user with no specific skills, with a limited amount of time, tools, and spare parts, with the support of the necessary documentation. Usually this is done both right before and right after use. OLM does not strictly have to be performed in a workshop, but the required spare parts for it to be performed will have to be kept at the location at which the vehicle is assigned. ILM is comprised of preventive, corrective, or reparative maintenance, and requires training and special tools. In short, the MoD refers to preventive maintenance as plannable due to normal component wear, which means a component has to be replaced after a certain expected lifetime. Corrective maintenance refers to unforeseen damage that has occurred as a result of training, exercise, or potential irresponsible use. Reparative maintenance refers to damage from combat situations. The distinction between reparative and corrective is mostly of a legal nature rather than a practical one.

As OLM and ILM are generally concerned with relatively top-level maintenance, the list of components required at the six workshops can be limited to a fair extent. In the maintenance agreement between the parties concerned, spare parts are defined as "all necessary resources (use and consumables), for executing ILM and OLM. This with reference, but not limited, to operating materials/fluids (excluding fuel), tires, wheels, filters, seals, batteries, exhausts, and components." Furthermore, there is one central distribution location that can supply any of the workshops within 48 hours if necessary. Shipments between workshops are disregarded for sake of model simplicity.

Findings are based on internal documents provided by Verebus, such as (vehicle) delivery agreements (between the MoD and Iveco), maintenance agreements, technical vehicle specifications, component specifications and maintenance guides. As per the confidentiality agreement with Verebus, in case some data are not suitable for publication they will be replaced by a representative value instead, which will be determined in agreement with Verebus. This is also applicable when some required data are not available due to for instance intellectual property rights or military confidentiality.

1.2 Scope

The required spare part composition is not just determined by the number of vehicles, but also by the conditions to which they are subjected. Peace keeping missions in different parts of the world could lead to considerable changes in the required spare parts composition when a subset of the vehicles would be deployed. Not only would the composition for the remainder of the vehicles at the workshops have to be adjusted, but a different spare part composition taking into account location, climate, and available resources for the concerning location would have to be provided for. Therefore, the spare part composition will be calculated only for the situation that all vehicles are in maintenance at their designated workshops, hence only in training situation in the Netherlands.

As many of the components of the Manticore require highly specialized tools and equipment to replace or repair, these tools are generally seen as part of any spare part package. Despite these tools having their own wear patterns these will be disregarded due to data availability. Instead, these tools will be assumed to be available at the designated workshops. Similarly, qualified engineers need to be present for different levels of repairs, assessing which mechanics need to be present at which location at which time is outside of the scope of the assignment and will therefore not be taken into account.

Furthermore, delivery of the Manticores will happen gradually over the following years, therefore, not all vehicles will be available right from the first deliveries during the second quarter of 2023. The to be determined spare part composition will be applicable for the situation when all vehicles have been delivered, so the ramp-up period will be disregarded.

1.3 Research approach

The Managerial Problem-Solving Method, or MPSM in short (Heerkens et al., 2021), offers a concise framework for tackling management issues. Heerkens identifies the following seven steps:

1. Defining the problem
2. Formulating the approach
3. Analysing the problem
4. Formulating (alternative) solutions
5. Choosing a solution
6. Implementing the solution
7. Evaluating the solution

Specifically, the first five steps of the MPSM are relevant for the problem at hand. As implementation of the inventory composition is a process that will happen after the timespan of this research assignment, this step will mainly consist of giving recommendations for implementation. Similarly, actual evaluation will have to be performed after the Manticore has been in service for a reasonable amount of time. Therefore the recommendation on the composition of spare parts will be evaluated based on some theoretical scenarios.

1.4 Problem identification

Applying the first step of the MPSM, we will start by defining the problem. Replacing the previous vehicles from the 12kN class comes with an array of logistical and managerial challenges. Part of the problem comes from the lack of experience with the situation at hand. The first part of the issue is a result of the fact that the implementation of a new technology within any organisation is normally paired with a period in which, in this case the users and mechanics, need time to get accustomed to the technology. This poses an issue, as the users as well as the engineers and mechanics have their own preferences as to what their ideal spare part composition should look like based on their previous experiences and insights, so it is difficult to pinpoint which composition is ideal. Additionally, there are varying viewpoints whether purchasing and inventory keeping should happen straight from each workshop, or inventory should be pooled at the depot.

Furthermore, use of the performance-based contract, where Iveco takes care of maintenance of half of the vehicles, has caused some unforeseen issues and disagreements between the MoD and Iveco as to where certain responsibilities lie. Within the MoD itself, the performance-based contract has caused another issue, in that transferring part of the responsibility of the maintenance of the vehicles to the manufacturer, has created a degree of nonchalance and a lack of feeling of responsibility for the project itself. In past experiences with different vehicles, this has led to significant overstocking of components and unnecessarily high costs, which Verebus evidently wants to prevent. Therefore, a core objective of finding a spare parts composition is to help Verebus and the MoD evaluate the manufacturer's recommendations. For the sake of simplicity, only the vehicles in maintenance by the State are evaluated, and the performance-based contract is disregarded, leaving costs and responsibilities to the MoD. Components are purchased from Iveco, and failed components are repaired by Iveco. Rule of thumb used by the MoD for repairs is that they are performed at 60% of the cost price of the component.

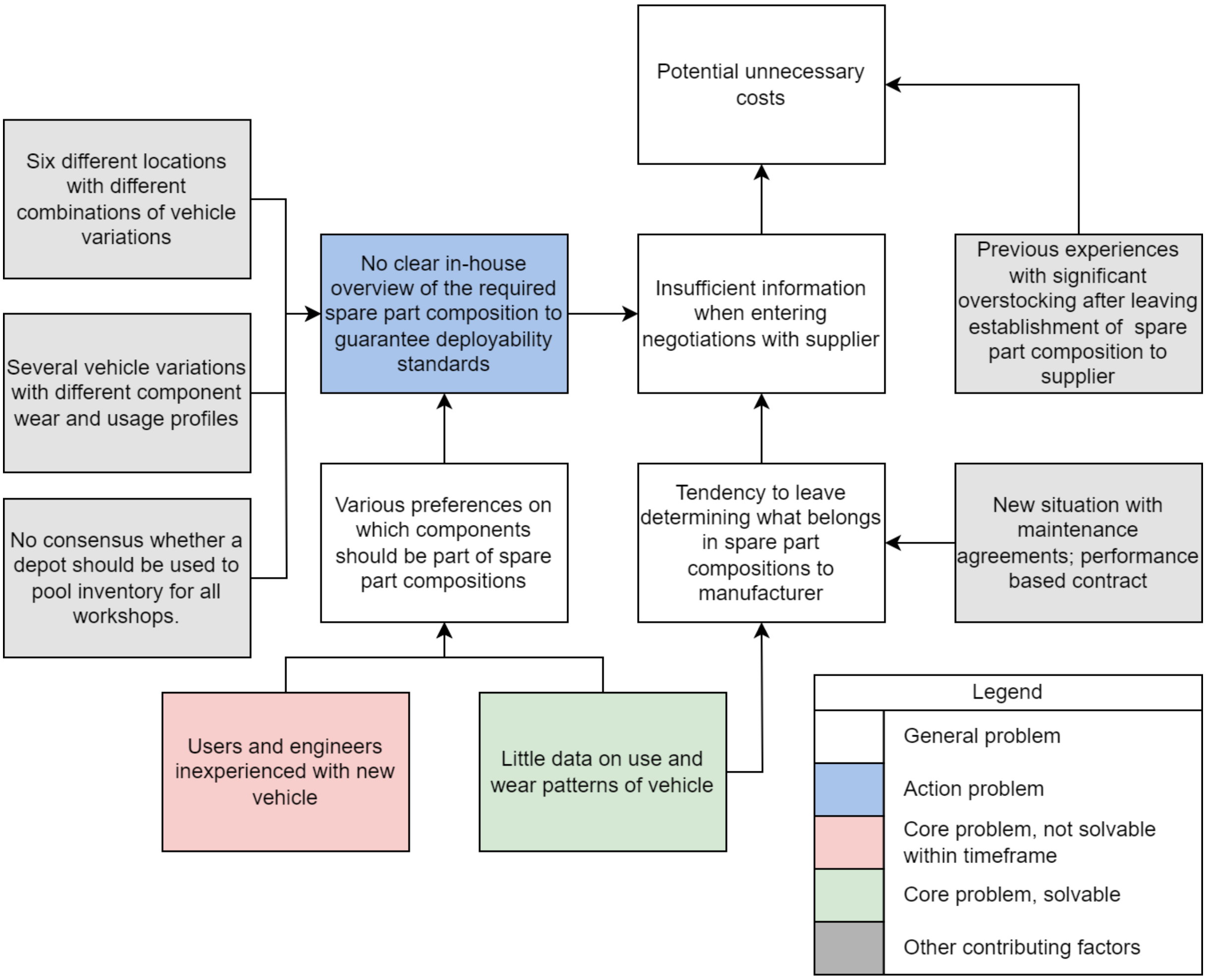


Figure 3: Problem cluster

The difference between norm and reality is slightly difficult to establish. In its simplest form – there currently is no spare part composition, and Verebus and the MoD would like there to be one. As of writing, the manufacturer has not yet shared a recommended spare parts composition, so we are not able to compare our findings to this either. It is difficult to compare relative monetary gains compared to a previous spare part stocking strategy, as this study concerns entirely different vehicles, and therefore the situations are not completely comparable. Nevertheless, we do want to offer a frame of reference of the existing situation. For this, we have selected two vehicles, these being the Bushmaster (Figure 4), due to the similarities with the Manticore in its deployment methods, and the Mercedes G-Class (Figure 5) as it has a comparable fleet size and has the same types of vehicle variations. The extent to which comparisons can be made will be limited as the confidential nature of the documents and data does not allow for extensive perusal, nor are they suitable for publication.

Figure 4: Bushmaster (Ministry of Defence - NL)

Figure 5: Mercedes-Benz 290GD (Ministry of Defence - NL)

1.5 Research goal

The core problem of the situation at hand is that there is no data on the use and wear patterns of the Iveco Manticore. This is simply a result of the fact that the vehicle is still in production. However, Verebus and the MoD do require some sort of spare part composition information for negotiations with Iveco. Therefore, the research goal is to find a composition of the required spare parts in each of the six workshops that ensures an availability of 350 days a year for each of the various variations of the Iveco Manticore, taking into account the various viewpoints from several stakeholders.

1.6 Research questions

The main research question that will be tackled is: *"Which spare part composition should be maintained by Verebus to ensure the required availability of 350 days a year?"* In order to answer the main research question, several sub-questions need to be answered first. These sub-questions will be answered in the remaining chapters. These chapters will cover the following topics:

Chapter 2: Context analysis

The problem owner has encountered issues regarding inventory management for other vehicles, experiencing significant overstocking and incurring unnecessary expenses. This chapter aims to identify the current strategy employed by the MoD and to assess where potential points of improvement lie. Therefore, the main research question is:

Research question 1: "What is the current vehicle spare part keeping strategy used by the MoD?"

In order to answer this research question the following activities will need to be carried out:

Approach	Data type	Activities
Interviews	Qualitative	• Assess various viewpoints of representatives of the user (gebruiker), maintainer (instandhouder), and standard-setter (normsteller) departments to evaluate preferences and requirements and current spare part management strategy. • Identify potential points of improvement. • Discuss with ILS manager Defensie to identify current and past inventory management practices employed by the MoD.
Data review	Qualitative	• Review data provided by Verebus to identify agreements on vehicle maintenance, identify potential root causes for previous experiences with overstocking.

Table 1: Activities for problem assessment

Chapter 3: Literature review
After identifying the strengths, weaknesses, and potential points of improvements of the current strategy employed by the MoD, this chapter will focus on finding an inventory modelling approach that takes into account the situation at hand and helps eliminate current weaknesses.

Research question 2. "Which inventory modelling approach can best be used to determine the required spare part composition for the Iveco Manticore?"

In order to answer this research question the following activities will need to be carried out:

Approach	**Data type**	**Activities**
Literature review	Qualitative	• Research which inventory modelling theories currently exist and compare findings. • Combine findings from literature review into suitable research approach. • Compare points of improvement of previous situation to available literature, identify potential solutions.

Table 2: Research types for systematic literature review

Chapter 4: Application of literature
Where the third chapter served to explore what literature currently exists to tackle the problem, this chapter aims to bundle the insights from the literature review and apply them to the Manticore.

Research question 3. "How can the selected approach be applied to the spare part composition required for the Iveco Manticore?"

In order to answer this research question the following activities will need to be carried out:

Approach	**Data type**	**Activities**
Model application	Qualitative	• Fitting the selected approach to the available data.
Validation	Qualitative	• Discuss suitability of model with Verebus.

Table 3: Activities for model definition

Chapter 5: Numerical analysis
In the fifth chapter the previously determined approach will be used to produce results. Together with the project supervisor from Verebus intermediate results will be validated in order to assess whether the produced results are realistic.

Research question 4. "Based on the previously determined approach, which spare part composition best meets the requirements set by Verebus?"

In order to answer this research question the following activities will need to be carried out:

Approach	**Data type**	**Activities**
Process data	Quantitative	• Prepare data for processing in model.
Application of data	Quantitative	• Apply data to model and find results.
Validate results	Qualitative	• Discuss initial results with ILS Manager, assess whether results seem likely or further adjustment is needed.
Analyse results	Quantitative	• Draw conclusions based on results.

Table 4: Activities for problem analysis

1.7 Deliverables
A prototype tool (spreadsheet, dashboard) that helps Verebus determine the required spare part inventory in each of the six workshops for the various variations of the Iveco Manticore.

CHAPTER 2: CONTEXT ANALYSIS

The aim of this chapter is to contextualise the problems discussed in the first chapter. Section 2.1 and 2.2 aim to offer insight into the theoretical approach from the MoD and Verebus to tackle the challenges around the Manticore. In turn, Section 2.3 and 2.4 will look into the expected usage of the vehicles, and the accompanying wear profiles. Section 2.5 looks into the uncertainty regarding component demand and supply. After sections one through five have given an illustration of the general situation, Section 2.6 will allow for some nuances specific to the military nature of this research assignment. Section 2.7 then provides a performance baseline for the Manticore, by analysing the performance of similar vehicles. Section 2.8 will provide an overview of the main conclusions from this chapter.

2.1 Project lifecycle

To paint a clear picture of the tasks Verebus has during the design process of the Manticore and on which levels it is involved, it is helpful to explore some definitions. Formally, Verebus is involved with 'Integrated Logistics Support'. According to the NATO Logistics Handbook (2012), integrated logistic support, or ILS, "is the deliberate integration of systems/equipment logistics support considerations into the system's life cycle management during the outset of the programme/project. ILS prescribes that all elements of logistic support be planned, acquired, tested, and provided in a timely and cost-effective manner." Similarly, Shukla et al. (2014) describe ILS as "an integrated and iterative process for developing material and support strategy, guiding the system engineering process to quantify and lower life cycle cost."

Hence, ILS processes are relevant during the entire life cycle of a project. The project lifecycle is generally subdivided by a "Logistics Support Analysis" (LSA)-framework. "LSA is a subset of ILS that provides the framework for monitoring and controlling the systematic development and execution of the ILS program." (Shukla et al., 2014). ASD/AIA (2010) identifies five phases of a project lifecycle. Consecutively, the "conception and risk reduction", "design and development", "production and introduction", "in-service" and finally the "waste disposal" phase. While Verebus is part of setting initial conventions for all phases, the project will be handed over to the MoD internally once the Manticores are fully in service.

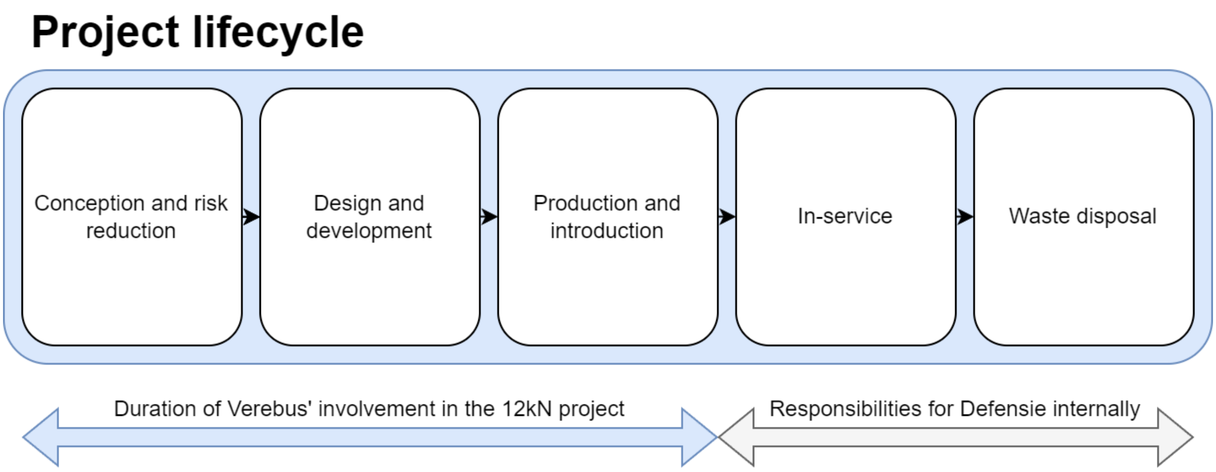


Figure 6: Project lifecycle

There is a wide selection of tasks during these phases upon which ILS touches, for instance, software support and personnel training needs, Failure Mode, Effects, and Criticality Analysis (FMECA), and Level of Repair Analysis (LORA) among many more. This research assignment focuses mainly on the design and development phase, but in reality, boundaries between the phases are not as clear, as there is a high level of feedback and communication between the phases. For example, the expectations set, and assumptions made during the design and development phase on, e.g., component failure rates, sets the precedent for the initial number of required spare components. Subsequently, this could lead to potential over- and understocking. If performed correctly, data from the in-service phase will return that actual component failure rates could be higher or lower than expected, upon which required stocking levels can once again be adjusted to meet some desired level of availability.

Another factor that is normally at play during the initial procurement of inventory, is that component prices change over time. The MoD uses price indices from the Dutch 'Centraal Bureau voor de Statistiek' (CBS) to account for price changes for different resources. Furthermore, components are often cheaper to procure during the first production run, as the manufacturer can make use of the advantages of economies of scale. This is especially relevant for the MoD, as many components are produced specifically for use in their vehicles, and for that reason not commercially available, again resulting in smaller production batches. Therefore, later orders for spare components often turn out to be significantly more expensive than the initial order as setup costs and times are high for the relatively low volume of required components. As we do not have accurate information on potential future price changes with regards to batch size, we disregard this for now.

In terms of the assignment at hand, this means that setting standards during the design and development phase has consequences for the in-service and waste disposal phases. The MoD has indicated that they want to ensure a high level of vehicle availability, meaning taking into account the in-service phase, while reducing waste. In this case, waste can be seen both in terms of expenditure, as well as preventing the purchase of items that are likely never to be used, or of which its shelf life will expire before the item is required.

Currently, the Iveco 12kN project is in the 'production and introduction' stage, as the vehicle is currently in production, and to be introduced later this year. In order to make an assessment of the required infrastructure to support the vehicle, a large number of analyses are performed. For instance, the FMECA analysis, as described by Jones (2006) "is an in-depth analysis of the total equipment that identifies all the ways in which it can fail." This means FMECA is highly detailed and offers insight into which components are expected to be a returning point of failure.

These points of failure can happen at multiple indenture levels. The indenture level specifies the 'tier' in which a component, or one of its subcomponents can be found, as exemplified in Figure 7. In turn, this allows for structuring and establishing line replaceable units (LRU), scheduling mechanics with varying levels of expertise for different tasks and enables the MoD and Verebus to start planning for preventive maintenance. Puig & Basten (2015) remark the following about line replaceable units: "Defective capital assets may be quickly restored to their operational condition by replacing the item that has failed. The item that is replaced is called the Line Replaceable Unit (LRU) […] when a replacement action is required in the field, service engineers can either replace the failed item itself or replace a parent assembly that holds the failed item." In the case of system failure, a mechanic at any of the workshops needs to be able to remove and replace any of the ILM-level components using LRUs. Generally, repairs that require high-level mechanics will be for components at a lower indenture level.

After the failed LRU has been replaced at a state-owned workshop, it is sent to Iveco for diagnosis of the issue, after which the failed subcomponent is replaced by a Shop Replaceable Unit (SRU). Driessen et al. (2020) describe this process as follows: "A failed LRU is replaced by a ready-for-use one from a single stock point […] The failed LRU is returned to a repair shop, where it is inspected to identify which Shop Replaceable Units (SRUs) caused the failure and is repaired by replacing the failed SRUs. After repair the LRU is ready-for-use again."

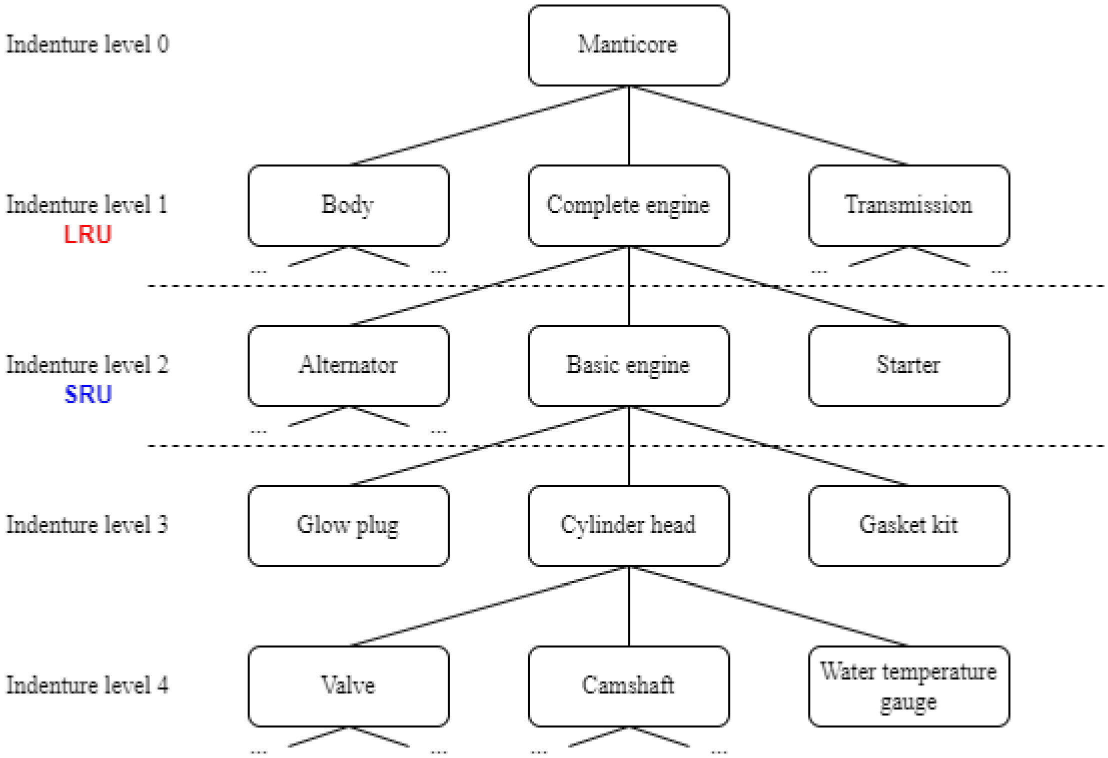


Figure 7: Tree diagram component indenture level Manticore

This is normally where a Level of Repair Analysis is performed. According to Basten et al. (2009) "Given a product design and a repair network, a level of repair analysis (LORA) determines for each component in the product (1) whether it should be discarded or repaired upon failure and (2) at which echelon in the repair network to do this." Due to the time available for this research assignment, the threshold used for this research assignment will be the one employed by the MoD, meaning that non-consumable components above €750 will be repaired.

In reality, this €750 mark will probably only reflect the threshold during the introduction of the Manticore. Once the vehicle has been in-service for a while, and more data is available on the lifespan and failure rates of components, it will likely be reconsidered. For instance, components close to the threshold that are often replaced and relatively expensive are likely subjects as it could result in cost savings. Nevertheless, as the Manticore is currently in the introduction phase, and no data on the components' lifespan is available yet, we assume that anything below the €750 mark will be discarded and replaced by a new item.

2.2 Technical specifications

In order to enable cooperation and interoperability among NATO members, several software and inventory keeping systems are set in place to allow involved parties to share data and information during the entire lifecycle of a vehicle. This ensures the specifications of the vehicle are up to date with renewed insights into previously unforeseen characteristics and issues. For this, a set of standards developed by the AeroSpace and Defence Industries Association of Europe (ASD) and Aerospace Industries Association (AIA) are used. A selection of these standards that apply to the Manticore project can be found in Table 5 below.

Sx000i	"The ASD/AIA SX000i is a joint transatlantic specification development, where both American and European aerospace manufacturers and customers participate, so as to establish a global integrated product support specification that is the overarching document for the AIA/ASD S-Series of IPS Specifications." (ASD/AIA, 2021-1)
S1000D	"S1000D is an international specification for the procurement and production of technical publications. It is an XML specification for preparing, managing, and using equipment maintenance and operations information." (ASD Europe, 2021)
S2000M	"The specification S2000M defines the processes, procedures and provides the information for data exchange to be used for material management throughout the lifecycle of a Product." (ASD/AIA, 2021-2)
S3000L	"The ASD/AIA S3000L is a joint transatlantic specification development, where European and American industrial, aerospace and defence manufacturers and customers participate. The goal is to establish a global specification describing the LSA process, which is one of the most important processes to realize the requirements of Integrated Logistic Support (ILS)." (ASD/AIA, 2021-3)
S4000P	"The ASD S4000P is a joint European specification development, where both manufacturers and customers participate, so as to establish a methodology for the development of scheduled maintenance plans and in-service maintenance optimization (ISMO)." (ASD/AIA, 2023)
S5000F	"The AIA/ASD S5000F is a joint transatlantic specification development, where both American and European aerospace manufacturers and customers participate, so as to establish a global specification describing the In-Service Data Feedback, which is critical to improve in-service support and the associated products." (ASD/AIA, 2021-4)

Table 5: Sx000i variations and descriptions

While all specifications are relevant for standardising the procurement process for the Manticore, the S2000M specification in particular is of use for the assignment at hand, as it will allow for insight into tests performed by Iveco. Casadiego Miranda et al. (2021) describe S2000M as "a standard for the management of materials management processes. Topics such as procurement, spare parts lists and material sourcing are covered here." Similarly, Shukla et al. (2014) states that "*S2000M* [is an] international publication for material management. This is a standard for spares and provisioning. S2000M defines the process and provides the mechanism for communicating and exchanging provisioning data between contractors, partners, and government agencies. This information is a key component of the required ILS data set."

Ideally, a complete S2000M dataset would give insight into much of the information required for many of the activities that lie within the ILS range of responsibilities. Item properties are described in extremely high detail with up to 140 different identifiers, including, for instance: part numbers (for the MoD, NATO, and manufacturer), measurements (height, width, length, volume, both of the part itself as well as its packaging if applicable), weight, indenture level, mean time to repair, lead time, cost, mean time between failures (MTBF), and the level of mechanic required to replace/repair. The database allows for different parties involved along the lifespan of the vehicle to keep consistent records and share adjustments, to ensure efforts are well coordinated. In turn, this data is then used in the MoD's Enterprise Resource Planning (ERP) systems to coordinate internal resources and efforts along ILS processes.

2.3 Deployment areas and expected usage

The MoD has identified four deployment areas for training scenarios. These deployment areas give a general indication of yearly expected kilometres travelled for each respective deployment area, the average vehicle speed per deployment area, and help establish common forms of damage that will require corrective maintenance. These values can be found in Table 6. Figures 8, 9, 10 and 11 give a visual impression of the deployment areas.

Deployment area	Avg. distance covered (km/year)	Avg. Speed (km/h)	Expected yearly hours
Good pavement / asphalt	8000	60	135
Poor asphalt / good brick paving	2500	30	85
Poor paving brick / compacted rubble	1500	20	75
Off-road	1000	10	100
Running idle	-	-	100

Table 6: Expected yearly deployment.

Figure 8: Good pavement / asphalt

Figure 9: Poor asphalt / good brick paving

Figure 10: Poor brick paving / compacted rubble

Figure 11: Off-road

2.4 Preventive and corrective maintenance

Taking into account the default deployment scenario from Section 2.3, we shed some light on the average component failure and replacement rates. For this, we will divide the demand into the aforementioned preventive and corrective categories. The demand rates discussed in this section are applicable to the usage profile as discussed in Section 2.3.

Preventive maintenance can best be described as a combination of replacements due to a component reaching its expected lifespan or being replaced due to scheduled maintenance. While it may seem that for these are largely overlapping at first, the distinction lies in the difference between the mechanical failure of a component on the one hand, and wear as a result of use on the other. The data provided by the manufacturer such as the FMECA only takes into account isolated mechanical failures in laboratory circumstances, often resulting in mean time between failures of millions of hours, which would imply that a component would rarely ever have to be replaced. Scheduled maintenance on the other hand, is based on the expected lifespan in real world circumstances, and the average component wear that goes along with it. Scheduled maintenance is essentially a measure to replace the component on a regular basis to prevent it from actually failing, potentially damaging other components in the process.

Lastly, preventive maintenance does not just consist of regularly replacing components but vary from simple functional and visual checks of doors, hatches, and seals, to replacing oil or bearings. As long as this maintenance is performed correctly and regularly, some components, such as the engine, do not have a preventive demand rate, as they are not designed to be replaced regularly like an oil filter, nor are their isolated mechanical failure rates high enough to reasonably account for. As a result, the MTBFs provided by the manufacturer will not be particularly relevant in practice, as many components will be replaced through scheduled maintenance well before the end of their theoretical lifespan. Therefore, we will model the preventive demand as a result of scheduled maintenance. The figures for scheduled maintenance are based on the maintenance calendar provided by Verebus. For instance, the oil filter is replaced yearly, resulting in an annual preventive demand rate of 1 filter per vehicle.

Apart from the preventive, or plannable, maintenance, other aspects of spare component provision that need to be taken into consideration are corrective and reparative maintenance. In this case, reparative maintenance is straightforward; due to the assumed circumstances of vehicle use, this being 'in-training' only, no reparative maintenance, referring to maintenance that needs to be performed due to combat damage, will have to take place. Corrective maintenance is maintenance due to damage as a result of unforeseen circumstances such as training or transport incidents, component wear, irresponsible use, or sometimes unknown reasons.

While the concept of corrective maintenance is fairly straightforward, the difficulty lies in accurately predicting it. A good indicator would normally be a distribution based on historical data from other vehicles such as the Bushmaster or the Mercedes-Benz 290GD, but due to data confidentiality these were not available. Furthermore, the accuracy of the comparison would be limited, as the Manticore has a substantially different design resulting in damage to different components. Instead, corrective maintenance values are based on insights from the ILS manager at the MoD, providing a rough estimate. In the end, the figures for corrective maintenance will have to be treated as such. The tool provided to Verebus will offer room to adjust expected demand rates based on renewed insights at a later point in time.

Unfortunately, as of writing the S2000M dataset for the Manticore is incomplete, as important information such as component failure rates, price, multiplicity, as well as shipping and repair times is only available to a limited extent, which is not enough to draw any usable conclusions from. Therefore, the MoD has provided a reference list of components (Appendix A2). Essentially, the list is a concise overview of commonly stocked spare parts based on experiences from other vehicles. Strictly speaking, not all components on the reference list are first indenture, but we will treat them as such, as the MoD considers it to be a decent overview of relatively top-level items. With that, failures of items such as a glow plug, which would normally be considered third indenture, will not be considered as an engine failure, but as a separate, independent failure. Another consequence of using the reference list is that this means we cannot distinguish between the different vehicle variations, as the list is a representation of a generic vehicle similar to the Manticore. Therefore, variation-specific items are not accounted for as of now.

For data confidentiality, item cost has been indexed, the cost of the alternator being the reference point:

$$\left(\frac{item\ cost}{cost\ alternator} * 100\right).$$

Item name	Multiplicity	Average annual demand (corrective)	Average annual demand (preventive)	Indexed cost	Repair time (years)	Resupply time (years)
Oil Filter	1	0.125	1	1.35	-	0.0833
Engine	1	0.125		1681.28	0.5	-
Glow plugs	6	0.225	0.1	4.54	-	0.0833
Oil pan	1	0.125		302.41	-	0.0833
Spring rear	2	0.1667	0.333	6.69	0.5	-

Table 7: Item characteristics for selected components

We have randomly selected several components for means of demonstration in Table 7. The demand figures represent the average annual demand for single component, meaning the multiplicity of said component in each vehicle needs to be taken into account to find the average annual demand for a vehicle. As becomes evident from this selection of components, there are a few component types that need to be identified, which require diverging inventory keeping approaches. For instance, the oil filter is a component that cannot be repaired after it fails, so it will have to be replaced instead. Other components are repairable in theory, but considering the labour required and its accompanying cost, this is not financially feasible for the MoD to do so, therefore these components are discarded and reordered. Next to that, there are components that will be sent back to the manufacturer for repairs in case of failure, as repairing said component is cheaper than wholly replacing it.

The practical implication is that there is a set of items that will be repaired, for which the repair time applies, and a set of items that will be discarded after their respective lifecycle, for which the resupply time applies. For components to be considered viable for repairs, they need to exceed the threshold value of €750 set by the MoD (Section 2.1). We assume that all components that meet this threshold are actually repaired and disregard the fatal failure rate of components. While it is a possibility to add some percentage of fatal failures, there is no available data on this point, and therefore it would not help increase the accuracy of the model.

2.5 Demand, lead times, and uncertainty

Minner (2000) identifies two sources of uncertainty: “Uncertainty can result either from demand or from supply processes. In a single echelon system, these sources are external customers and suppliers whereas in a multi-echelon system, the corresponding sources are succeeding stockpoints which induce internal requirements on the demand side and preceding stockpoints on the supply side.” Therefore, the potential points of uncertainty stemming from preventive and corrective maintenance, as well as repairs and resupplies, need to be assessed. Due to the data confidentiality regarding historical spare parts use and supply, we cannot establish a numerical baseline.

Starting with the demand for spare parts for the Manticore, which consists of the aforementioned preventive and corrective maintenance. Preventive maintenance is predictable, as it is performed in a predetermined time interval. Therefore, the main source of demand uncertainty is due to inconsistency of damage during training and exercise, resulting in a demand stemming from corrective maintenance. For the supply side of things, there are two sources of uncertainty. First of all, failed components are sent to Iveco for repairs, and some delays may occur during shipping. As repairs are performed at Iveco locations within the Netherlands, shipping delays will likely be fairly minor. At the same time, there are some doubts at the MoD about the manufacturer’s capacity to repair components within a consistent timeframe, especially during times of significant demand for repairs, but this remains to be seen.

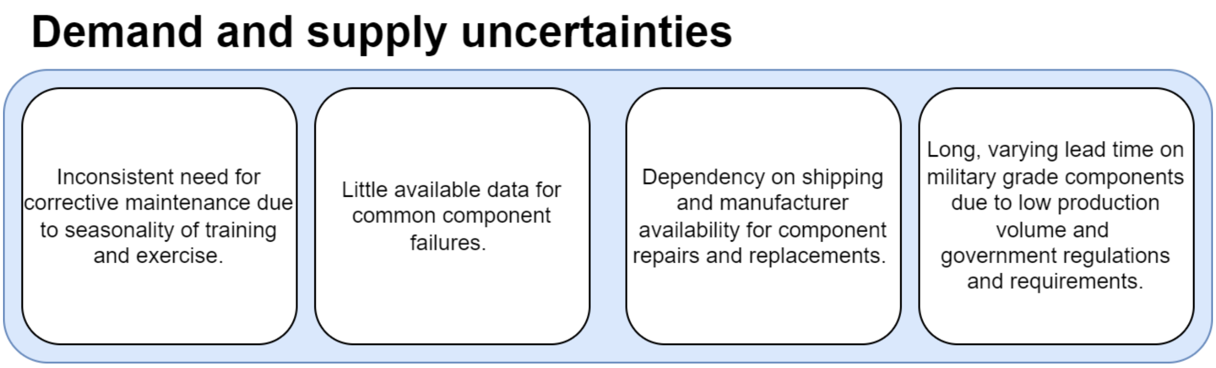


Figure 12: Demand and supply uncertainties

The second source of uncertainty for replacement parts lies in the limited volume of specific military components, resulting in long setup times for production. Furthermore, the manufacturer likely keeps little stock of these components, as they are not all commonly stocked for commercially available vehicles. Finally, due to the military nature of some of the components, they are subject to more strict government regulations and requirements, potentially resulting in more and longer delays. Nevertheless, this will likely not pose a problem for the MoD, as many of the components that are used for preventive maintenance are items that are commonly used in other vehicles, ensuring a reliable level of supply. With the assumption that no fatal component failures occur (Section 2.4), the reordering time and uncertainty for items that have a specific military designation can be disregarded.

2.6 Inventory keeping philosophy

As the Manticore project is still in the production and introduction stage, the first sets of spare parts are yet to be determined and acquired. Jones (2006) describes this as provisioning: "Provisioning is the process of identifying and obtaining the initial stock of spare parts required to support fielded equipment. […] Provisioning is one of the few ILS disciplines that uses input data from virtually all other disciplines. Therefore, it represents one of the final outputs of the integrated logistics support effort." During this provisioning stage, decisions need to be made on the level of vehicle availability the MoD wants to support and weigh it against the budget that would be required to do so.

Much of the existing literature surrounding spare parts inventory keeping considers a combination of both preventive and corrective maintenance, effectively outlining the demand and its uncertainties for certain spare components. Taking lead times into account, this then allows for deliberations to be made between availability and cost. For many companies, balancing between these two factors is the main driver for establishing an efficient inventory keeping system. As opposed to civil society, the MoD does not have to make this balancing decision to the same extent, allowing for decision making that is less restricted by financial limitations. A good example of this is the purchase of "investment spares". Investment spares are procured as an extra layer of insurance for especially expensive components, which, in normal circumstances, are often not economically viable to stock. Jones (2006) affirms this: "Investment spares are items that are normally extremely expensive; they are procured at the same time as the equipment they are to support in order to get a lower price by having them built concurrently with the prime equipment. The concept behind this process is to invest money up front to avoid a major expense at a later date. […] a spares model may not recommend that any of a specific item be procured as spares, but a few are procured as insurance just in case one is required."

The most concrete application of these non-standard inventory keeping practices is reflected in the decision to keep at least one unit of stock for every item at every workshop. As will become apparent in Chapter 5, this can lead to sub-optimal solutions, especially when a large part of the stock is kept in the depot. Expensive, low-volume items will require significant investments to stock at locations where they might not be required to reach a certain level of availability.

2.7 Current performance

There are a few things that first need to be taken into account in order to establish a performance baseline regarding spare parts keeping and overstocking. As previously mentioned, we have selected the Bushmaster and Mercedes G-Class vehicles as frame of reference for the Manticore. Reason for selection of these vehicles are the similar usage profiles and expected deployment areas, as well as the somewhat comparable vehicle characteristics. Nevertheless, we do want to nuance this by emphasizing that the similarities between vehicles are limited, and therefore any comparison these vehicles present, should be treated as such. Due to the confidentiality of data, many of the key performance indicators (KPI) that the MoD uses were not available for reference. Therefore, an extensive exposition of the current performance regarding vehicle availability and spare part inventories cannot be offered.

The main indicator for vehicle availability is defined as 'Material readiness' (G_R). We cannot directly share these values with the reader, but they are evidently available to Verebus and the MoD for comparison. The material readiness is defined as the average percentage of vehicles that were deemed mission capable (MC) as part of the entire fleet, which includes vehicles which were deemed not mission capable (NMC), measured over a year, thus:

$$G_r = \frac{MC}{MC + NMC}$$

Another factor that we can use is the value of the spare parts inventory. Due to the confidential nature of the figures, no concrete numbers can be shared with the reader. However, the ratio between the value of the spare parts inventory and the value of the total fleet of vehicles is roughly 1:10. The spare parts list from Appendix A2, as discussed in Section 2.4, is a general reflection of spare parts that are usually kept for comparable vehicles, based on experience with other vehicles. Therefore, we assume this ratio to be applicable for this selection of spare components as well. As the MoD used to keep SRUs for other vehicles as well but is not planning to do so for the Manticore, we adjust for the fact that LRUs account for roughly 80% of spare part expenditures resulting in a ratio of 1:12.5.

2.8 Summary

- The MoD uses an integrated logistics support structure, buttressed by the Sx000i integrated product support specification for their vehicle maintenance and as input for their ERP systems. The S2000M dataset, part of the Sx000i specification, is not yet fully available for the Manticore and can therefore not be used.
- The indenture level defines the 'tier' in which a component, or one of its subcomponents can be found inside the vehicle. Component failure can happen at multiple indenture levels.
- The MoD aims to only keep LRUs in stock, meaning failed SRUs need to be repaired or replaced at the manufacturer.
- The decision between either repairing or replacing a failed LRU is made on basis of the cost of the component, with any components priced below €750 being discarded immediately after failure.
- The demand for components can be split into corrective and preventive maintenance. Preventive demand is straightforward as it is deterministic, but the stochastic nature of corrective demand will require further enquiry.
- The MoD desires to keep at least one unit of stock of every item at every workshop.
- 'Material readiness' represents the average percentage of available vehicles in the fleet.
- The 'spare part inventory to acquisition value ratio', can be used as a benchmark for the current inventory costs, this ratio is roughly 1:12.5 for comparable vehicles.

CHAPTER 3: LITERATURE REVIEW

In the previous chapters, we have described the situation as a two-echelon system with four levels of indenture. As there only is data available for a list of components that roughly approximates a set of first-indenture items, and the MoD is not planning on keeping any lower indenture level items, we will only consider a first indenture system. Lateral transhipments are disregarded. Furthermore, the MoD has set the requirement of 350 days of availability per year. Section 3.1 explores ways to model the demand stemming from corrective and preventive maintenance, after which it discusses the implications of the demand on the repair and reorder distributions for repairable and consumable parts. Section 3.2 and 3.3 tackle single- and two-echelon systems respectively, and an availability metric comparable to the G_R discussed in Section 2.7 is established. Finally, Section 3.4 will provide an overview of the main conclusions from this chapter.

3.1 Demand and repair time modelling

The premise of this research assignment is that the MoD and Verebus are looking for the spare parts inventory required to maintain 350 days of vehicle availability. In order to guarantee this, a safety inventory needs to be established. Chopra (2019) defines safety inventory as: "inventory held in case demand exceeds expectation; it is held to counter uncertainty." This is corroborated by Silver et al. (2017), who state that keeping safety inventory is not necessary if there is no uncertainty: "Safety stock is the amount of inventory kept on hand, on the average, to allow for the uncertainty of demand and the uncertainty of supply in the short run. Safety stocks are not needed when the future rate of demand and the length of time it takes to get complete delivery of an order are known with certainty." Therefore, the inventory the MoD and Verebus are looking to create is to account for the uncertainty in the spare component demand and supply.

As we have found that the majority of uncertainty stems from random failures, we will shift our attention towards corrective maintenance. According to Sherbrooke (2004), a common method to model demand as a result of random failures is the Poisson distribution. "The Poisson […] is the common choice for modeling random demand, as contrasted with wear-out phenomena." This is buttressed by Gayer (2010): "Poisson distribution […] allows knowing repeatability for a particular phenomenon without knowing its causes, assuming that they are independent, and establishing the probability that an accidental event, which causes its occurrence, exists or not."

Similarly, Louit et al. (2011) state the following about the use of the Poisson distribution to model random component failures: "Many models discussed in the literature assume that demand for spares follows a Poisson process, where the failure (or replacement) rate for a population of m components in operation follows a Poisson distribution with mean mλ, where λ is the failure (or replacement) rate of an individual component. This assumption is less restrictive than it initially seems, as the number of identical units in operation is often relatively large. When this occurs, the superposed demand process for all the units converges rapidly to a Poisson process, independently of the underlying time to failure distribution […]. Because of this, the use of the Poisson distribution in spare parts inventory modeling has found wide application." Considering the fact that we do not have specific data regarding the underlying distribution of the failures of components, we assume that they follow a Poisson distribution.

Assuming this Poisson distribution for the demand of components, we can apply Palm's theorem: "If demand for an item is a Poisson process with annual mean m, and the repair time for each failed unit is independently and identically distributed according to any distribution with mean T years, then the steady-state probability distribution for the number of units in repair has a Poisson distribution with mean mT." (Sherbrooke, 2004). The use of Palm's theorem in multi-echelon systems is buttressed by the repairable inventory theory review, performed by Guide et al. (1997). In their review Guide et al show that METRIC theory, which makes use of Palm's theorem (Section 3.3), and many variations and additions to METRIC are commonplace in repairable inventory planning: "… [METRIC] represents a fundamental development in repairable inventory theory […] so many later models are METRIC-based.”. Palm’s theorem allows us to calculate the pipeline (μ), meaning the average number of items in repair, simply by multiplying the average yearly demand for an item by its average repair time, without having to measure the distribution of repair times. Therefore, Palm’s theorem helps us tackle the issues of resupply and reordering uncertainty. Similarly, as our demand for consumable items also follows a Poisson distribution, we assume the same for items that are reordered instead of repaired.

3.2 Single echelon

As discussed in Section 1.3, there are diverging viewpoints on whether inventory should be pooled at a depot, or if all inventory should be kept at the workshops. The case in which inventory is kept only at the workshops, results in six single echelon systems, amounting to six single-site inventory systems with different combinations of vehicle variations. Each of the sites needs to directly order from the supplier to ensure its own supply of components to meet its respective demand and keep inventory on location.

For this, we will make use of Sherbrooke’s (2004) single-site inventory system, specifically the ‘repairable item inventory policy’, or (s-1, s). Sherbrooke: “these repairable items tend to be high-cost, and low demand at a workshop […] Because of this one-for-one repair, the reorder point (or the asset position at which we send an item to repair) is s - 1.” Hence resulting in the (s-1, s) notation. It should be noted that not all items from our component list meet the ‘high-cost, low demand’ description, and that there are other inventory models available to better meet the properties of these items. Nevertheless, with the limited time available for this assignment we have decided to opt for Sherbrooke’s (s-1, s) model because it is a commonly used inventory modelling approach for spare parts. Furthermore, it allows us to produce a result without having to make assumptions on areas such as holding cost and order cost, for which the data is not available. As data availability has already proved an obstacle, introducing more assumptions into the model would further impair the validity of the results.

Assuming that vehicle use and wear patterns are identical across each workshop, the demand for each component on every site is dependent on the number of vehicles of each variation that are stationed at said workshop. The mean demand for each component, m, is given by: $E[X] = \sum_{x=1}^{\infty} xPr\{X = x\}$. As we are using a Poisson distribution, the variance is equal to the expectation. The goal of the (s-1, s) policy is to optimise the number of items in stock to minimise the cost while simultaneously accounting for availability. Sherbrooke defines the stock level, s, as:

$$s = OH + DI - BO \qquad (eq. 1)$$

where:
OH = number of items on hand
DI = number of items due in (from repair and resupply)
BO = number of backorders

Combining the Poisson-distribution demand with the given demand figures from Section 2.4, allows us to calculate the expected number of backorders for a given stock level and a fixed amount of time. Note that when s equals 0, EBO(s) = E[X]:

$$EBO(s) = \sum_{x=s+1}^{\infty} (x - s)\, Pr(X = x) \qquad (eq. 2)$$

To simplify the computation of this formula, it can be rewritten as:

$$EBO(s) = \mu \sum_{x=s}^{\infty} Pr(X = x\,) - s \sum_{x=s+1}^{\infty} Pr(X = x) \qquad (eq. 3)$$

Now that we have a value for the number of expected backorders of an item given a certain stock level, we need to evaluate which item grants the largest relative decrease the total number of system backorders, offset against its purchasing cost. For this, we will apply marginal analysis. Sherbrooke describes this as "the marginal decrease in expected backorders divided by the item cost." This can be done by finding the delta value for each item, given its stock level at that point:

$$\Delta = \frac{EBO(s-1) - EBO(s)}{c} \quad for\ s > 0 \qquad (eq. 4)$$

The equation for the delta value can also be simplified into the following for a single site, single indenture system:

$$\Delta = \frac{\sum_{x=s+1}^{\infty} Pr(X = x)}{c} \qquad (eq. 5)$$

The delta value allows us to select the item that yields the greatest backorder reduction for the cost. Subsequently, the stock level for that item is incremented by one, resulting in a reduced EBO and with that, its delta value. Once again, we will then evaluate the delta value for all items, incrementing the stock level of the item with the highest delta value, until the desired level of expected system availability has been achieved.

For the mathematical proof of the optimality marginal analysis, we would like to refer the reader to Sherbrooke (2004). In short, it relates to the convexity of the curve when plotting the number of expected backorders against the total cost. Sherbrooke describes this as follows: "Since the expected backorder function is convex, the marginal analysis values {EBO(s - 1) - EBO(s)}/c, […], are non-increasing. […] Suppose that the backorder functions were not convex. The marginal analysis procedure of looking at the next improvement in backorders per dollar for each item could not guarantee an optimal solution." Therefore, the convexity ensures that each added item is a slightly inferior deal compared to the previous item when considering its backorder reduction and cost.

For the availability of each component γ, A_γ, we subtract the expected number of backorders from the total number of systems with said component and divide this by the total number of vehicles that contain this component in the workshop. Since the same part is sometimes present multiple times per vehicle, we have to be mindful of the fact that this does affect the demand and total failure rate for said component. As a single failure already leads to any vehicle being non-mission capable, the number of backorders needs to be compared to the number of vehicles in which the component is present, as opposed to the total number of said component being present in the vehicles at any workshop.

$$A\gamma = \frac{No.\ systems\ with\ component - EBO(s)}{No.\ systems\ with\ component} \qquad (eq. 6)$$

As many of the repairable inventory models have their origins in aircraft fleet management, we will use similar availability assumptions here. Guide et al. (1997) state the following about the impact of component failure on system availability: "Components on aircraft fail and lack of any component or part will render an aircraft unavailable for a mission.". Although some nuances could be made about the consequences between a fatal error in an aircraft compared to a vehicle, failure of most first-indenture items on a mission would result in it not being deployable.

Therefore, we consider the failure of one LRU to result in a vehicle being non-mission capable, enabling us to compare this to the metric of material readiness, G_R, from Section 2.8 employed by the MoD. Subsequently, we can then calculate the total system availability, at a workshop A_W, by taking the product of all component availabilities.

$$A_w = \prod_{\gamma=1}^{n} A\gamma \qquad (eq. 7)$$

Finally, we can repeat this procedure for each workshop, and find the total vehicle availability across all workshops, A_T, as the weighted average of the vehicle availabilities at each workshop.

$$A_T = \frac{\sum_{w=1}^{i} A_w * N_w}{\sum_{w=1}^{i} N_w} \qquad (eq. 8)$$

$where, N_w = no. vehicles\ at\ workshop\ w$

3.3 Two-echelon

Now that the base terminology for the situation with six individual single echelon systems has been established, we can expand the model by adding a depot, where items can be pooled to reduce the total amount of required inventory. For this, we will first discuss the Multi-Echelon Technique for Recoverable Item Control (METRIC), as proposed by Sherbrooke (2004).

Sherbrooke defines the following variables for a single item in the METRIC system:

- $m_j = average\ annual\ demand\ at\ base\ j$
- $T_j = average\ repair\ time\ (in\ years)\ at\ base\ j$
- $\mu_j = average\ pipeline\ at\ base\ j$
- $r_j = probability\ of\ repair\ at\ base\ j$
- $O_j = average\ order\ and\ ship\ time\ from\ depot\ to\ base\ j$
- $where\ j = 0\ refers\ to\ the\ depot, and\ j = 1..6\ to\ bases\ A\ through\ F$

Using these parameters, the average demand on the depot can be calculated as the sum of the demand at each workshop, subtracted by the share of items that can be repaired at said workshop. Note that in our situation, no items will be repaired at the workshops, effectively removing this last parameter.

$$m_0 = \sum_{j=1}^{n} m_j\,(1 - r_j) \qquad (eq. 9)$$

Subsequently, the average pipeline at the depot μ_0 can be found by multiplying the demand at the depot by the average repair or reorder time.

$$\mu_0 = m_0 T_0 \qquad (eq. 10)$$

In turn, this means the expected number of workshop resupply requests can be expressed by:

$$EBO(S_0|m_0T_0) \qquad (eq. 11)$$

Using these values, the average pipeline for each item at workshop j can be calculated.

$$\mu_j = m_j\ \left(r_jT_j + (1 - r_j)\big(O_j + EBO(S_0|m_0T_0)/m_0\big)\right) \qquad (eq. 12)$$

Then, the placement of each LRU needs to be assessed individually, for every potential total number of units of said component in stock. Again, this can be done by applying marginal analysis. As each LRU is assessed individually, item cost does not have to be accounted for. This means that the location (either the depot, or one of the workshops) that achieves the biggest EBO reduction compared to the previous stock level for said LRU is selected. The optimal value for each stock level can then be found by analysing the diagonal line between the cumulative stock at all workshops and the corresponding depot stock level and selecting the lowest value. This is illustrated in Table 8, where each value represents the EBO for the given combination of workshop and depot stock.

Depot Stock Level	Total Stock at Bases, Optimally Allocated								
	0	1	2	3	4	5	6	7	8
0	3.5087	3.0044	2.5002	1.9959	1.4916	0.9873	0.8309	0.6745	0.5181
1	2.6043	2.1983	1.7923	1.3863	0.9803	0.5743	0.4777	0.3811	
2	1.9240	1.6046	1.2852	0.9658	0.6464	0.3269	0.2694		
3	1.5072	1.2469	0.9867	0.7264	0.4662	0.2060			
4	1.2965	1.0681	0.8397	0.6113	0.3829				
5	1.2070	0.9925	0.7780	0.5636					
6	1.1743	0.9650	0.7557						
7	1.1639	0.9562							
8	1.1610								

Table 8: EBO at all possible stocking combinations for each stock level (Sherbrooke, 2004).

In turn, this then yields a combination of optimal stock placements, considering a given desired number of units in stock. Unfortunately, this does not always yield a convex curve, which is required for the solution to be optimal, as discussed in Section 3.2. In order to solve this, Sherbrooke suggests to simply disregard the solutions that are non-convex. "… when we reach a non-convex point the slope will be flatter than if we look at the next convex point. Thus, the backorder reduction per dollar for that item will be understated. By dropping the interior points, the marginal analysis will jump to the next convex point at the correct time (buying at least two more units of stock of the item because of the eliminated interior point or points)". This procedure can then be repeated for all LRUs, after which marginal analysis can be performed once again, to find the 'best-value' item at each workshop, for each stock potential stock level, subsequently allowing iteration until the desired availability has been reached.

While this approach produces mathematically optimal solutions, it is does have a major downside in that it is computationally quite complex and inefficient. For instance, a single item with a mean demand of 500 per year would require over $\sum_{n=0}^{500}(n+1)$ calculations just to find the "stock optimisation" Table (see Table 8), after which the non-convex point would still have to be removed. Therefore, we can simplify this approach and drastically decrease the number of required computations by applying marginal analysis across all LRUs. Cohen et al. (2017) describe this as follows: "The standard solution algorithm for solving ME models is a greedy heuristic based on a marginal analysis that evaluates the benefit of stocking one more item at the bases or at the depot." Similarly, Patriarca et al. (2016) demonstrate marginal analysis in a multi-echelon system without lateral transhipments: "… an iteration consists in finding the best value in terms of A_{TOT} [system availability] and C_{TOT} [system stock costs] considering all the possible allocations of a new item at a specific site." Analogously with the single echelon model, the model again optimises for the best backorder reduction to item price ratio.

Therefore, similarly to before, the problem can be approached by adding a single item to any workshop or the depot. The main difference being that adding an item to the depot will require recalculation of the pipeline to each workshop. Then, the procedure for finding the delta value for a level of base stock i is as follows:

1. Calculate the depot pipeline.
2. Calculate the pipeline to each workshop for $S_0 = i$.
3. Calculate the EBO at each workshop using the pipeline from step 2
4. Calculate the EBO at the depot by enumerating the EBOs found in step 3.
5. Calculate the EBO at each workshop for workshop stock + 1, $S_0 = i$
6. Calculate the delta value for every workshop.
7. Calculate the pipeline to each workshop for $S_0 = i + 1$
8. Calculate the EBO at each workshop using the pipeline from step 7.

9. Calculate the EBO at the depot by enumerating the EBOs found in step 8.
10. Calculate the delta value for the EBO values from steps 4 and 9.
11. Increment the stock level for the item and location with the highest delta value.

The downside of this approach is that it is an iterative process. Once a certain piece of stock has been assigned to a workshop, it will not be reconsidered for subsequent solutions. For instance, if the solution at seven pieces of stock is $S_0 = 1, S_A = 1, S_B = 1, S_C = 1, S_D = 1, S_E = 1, S_F = 1$, the solution for eight units is based on the existing situation for seven pieces. This means that a potential solution of $S_0 = 3, S_A = 0, S_B = 1, S_C = 1, S_D = 1, S_E = 1, S_F = 1$, will not be considered, due to the fact that our solution at seven items has already placed one piece of stock in location A.

The average vehicle availability per workshop can once again be found by calculating the weighted average of the vehicle availability per workshop, similarly to Section 3.1. Finally, the process can be repeated until a satisfactory level of expected vehicle availability has been reached.

3.4 Summary

- Due the deterministic nature of preventive maintenance, safety inventory for preventive maintenance is not required.
- The demand for corrective maintenance is the result of random failures, which can be modelled using the Poisson distribution, even when the cause for failure is unknown.
- Assuming the Poisson distribution allows for the use Palm's theorem, which helps estimate the average number of items in repair or resupply, called the pipeline.
- Using Sherbrooke's (s-1, s) policy we can optimise for the number of items in stock while minimizing the cost by reducing the number of backorders.
- The number of expected backorders can be calculated by assessing it for the current number of items in stock and the demand rate for any item.
- The delta criterion can be calculated through marginal analysis, by taking the fraction of the backorder reduction for adding one item of stock of a LRU, and the cost of said item. The highest delta yields the best backorder reduction to cost ratio.
- The two-echelon system builds upon the single echelon system by adding a depot to allow for inventory pooling.
- The delta criterion for the depot can be found by using the difference of the sum of the expected backorders at depot levels i and $i + 1$.

CHAPTER 4: APPLICATION OF LITERATURE

Now that the existing factors and circumstances have been assessed and potential solutions have been identified, the aim of this chapter is to apply the identified approaches to the situation at Verebus and the MoD. Similar to the previous chapter, the complexity of the model will gradually be increased along each section. In Section 4.1, the single echelon model will be used to establish a baseline performance of the situation in its most elementary form. Then, in 4.2, a depot is added, allowing for resources to be pooled more effectively. Finally, Section 4.3 will provide an overview of the main conclusions of this chapter.

4.1 Single echelon

As remarked in the previous section, in this model each workshop can be approached separately. The assumption being that every workshop will be supplied directly by the manufacturer for the demand at said workshop. Therefore, each of these sites can be assessed separately, yielding six single echelon systems with a set number of vehicles, as per Table 9.

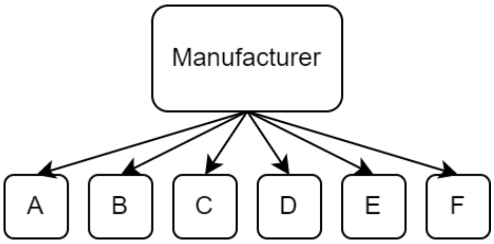


Figure 13: Single echelon system.

Therefore, we will first have to define the demand for components at each workshop. The full list of components, consisting of 51 items, and their demand rates can be found in Appendix A2. Excel will be used to model the situation and perform calculations.

Vehicle Variations	# stationed at workshop A	# stationed at workshop B	# stationed at workshop C	# stationed at workshop D	# stationed at workshop E	# stationed at workshop F
Soft-top	40	15	25	20	0	0
Hard-top	60	60	0	40	40	70
Pick-up	0	30	45	0	0	65
Casualty transport	0	0	0	30	30	0

Table 9: Distribution of vehicle types present per workshop.

Before elaborating on the implementation of the theory presented in chapter 3, we will first consider the underlying assumptions. The (s-1, s), single echelon model is a model for repairable inventory, but as we have seen in Section 2.4, it can apply to low demand consumable items as well. Furthermore, as illustrated in Figure 13, no lateral transhipments, will take place. Finally, demand for components is assumed to be Poisson-distributed.

Item	Multiplicity	Average annual demand (corrective)	Repair time (years)	Reorder time
Oil filter	1	0.125	-	0.08333
Engine	1	0.125	0.5	-
Glow plugs	6	0.225	-	0.08333
Spring rear	2	0.125	0.5	-
Oil pan	1	0.1667	-	0.08333

Table 10: Component characteristics for selection of components, demand per part

As the calculations and modelling process for each workshop are identical, the following example will make use of the vehicles stationed at workshop A. For each item the pipeline can be calculated by multiplying the repair or resupply time by the corrective demand at each workshop. The total demand for a component can be found by taking the product of the demand of a LRU (Table 10) and the number of vehicles in which it is present at that workshop. Due to the fact that the reference list does not make a difference in the components for each vehicle variation, we can currently not take this into account. Nevertheless we would like to include this step, as it is relevant once a full component list for the different vehicle variations of the Manticore is available. The pipeline μ (Table 11) can then be found by taking the product of the total demand across all vehicles at the workshop, and the average lead time.

Item	Multiplicity	# vehicles present	Total demand (corrective)	Repair/Lead time (years)	Pipeline (μ)
Oil filter	1	100	12.5	0.08333	1.041666667
Engine	1	100	12.5	0.5	6.25
Glow plugs	6	100	135	0.08333	11.25
Spring rear	2	100	33.33333333	0.5	16.66666667
Oil pan	1	100	12.5	0.08333	1.041666667

Table 11: Pipeline calculation

Subsequently, the estimated backorders can be found by equation 1, In turn, this can then be computed in Excel by the following expression:

$$\mu\big(1 - Poisson.dist(s-1, \mu, TRUE)\big) - s\big(1 - Poisson.dist(s, \mu, TRUE)\big) \qquad (eq. 13)$$

Similarly, the delta value can be found by:

$$\big(1 - Poisson.dist(s, \mu, TRUE)\big)/cost \qquad (eq. 14)$$

Starting from a stock level of 0, the EBO for each item can be used to find the delta (equation 4) for the first 'best value' stock to increment to by applying the aforementioned marginal analysis (Section 3.2).

Item	Indexed Cost	EBO(0)	EBO(1)	Δ
Oil filter	1.35	1.0417	0.3945	0.4779077
Complete engine	1681.28	6.2500	5.2519	0.0005936
Glow plugs	4.54	11.2500	10.2500	0.2202244
Spring rear	302.41	16.6667	15.6667	0.0033068
Oil pan	6.69	1.0417	0.3945	0.0967660

Table 12: Delta value calculation

As becomes clear from Table 12, the delta value for the Oil filter is the highest, hence its stock level will be incremented by one. For each component, we can find the availability for its current stock level by applying equation 6. Subsequently, the total system availability can be found by computing the product of all component availabilities. Then the iteration process can be repeated until a desired level of system availability is achieved, meaning 96.44% in this case (350 days + 2 days for other activities per section 1.1). This process can be repeated for all components at all workshops, implementation of this process can be found in appendix B1. Finding the total vehicle availability at all workshops can then be computed by averaging the estimated availabilities at each workshop, weighted for the number of vehicles per workshop.

4.2 Two-echelon

Now that a base model for supplying inventory to each workshop has been established, it can be expanded by adding a depot. This allows the manufacturer to supply to the depot, where the depot internally redistributes components to the workshops. Again, we assume the that the level of item criticality is equal across all items. Redistribution time from the depot to a workshop is assumed to be two days.

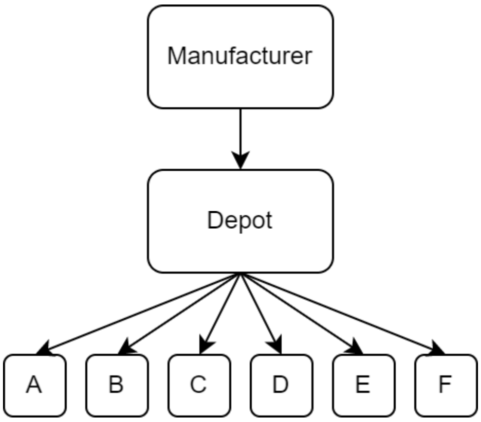


Figure 14: Two-echelon system.

Again, the same definition of demand is used, referring to the Poisson-distributed demand for components as a result of corrective maintenance. The total demand at each workshop can then be found by taking the product of the multiplicity of the item, its demand, and the number of vehicles in which it is present at that workshop. Then, the demand at the depot is the sum of the demand at the workshops.

Using the same distribution of vehicles per workshop as in the single echelon system (Table 9), the demand for components at the depot, m_0, can be found using equation 9: $m_0 = \sum_{j=1}^{n} m_j\left(1 - r_j\right)$. As repairs will be performed at the manufacturer $r_j = 0$. Then the second term $\left(1 - r_j\right) = 1$, and can therefore be omitted. What remains is simply the sum of the demand figures at each workshop $m_0 = \sum_{j=1}^{n} m_j$. Similar to before, the same sample of items (Table 10) will be used for illustrative purposes. Then the average demand per workshop can be found as per Table 13.

Item	**Average annual demand m_j for LRU at workshop**						
	A	**B**	**C**	**D**	**E**	**F**	**DEPOT**
Oil filter	12.5	13.125	8.75	11.25	8.75	16.875	71.25
Engine	5	5.25	3.5	4.5	3.5	6.75	28.5
Glow plugs	135	141.75	94.5	121.5	94.5	182.25	769.5
Spring rear	33.33333	35	23.33333	30	23.33333	45	190
Oil pan	12.5	13.125	8.75	11.25	8.75	16.875	71.25

Table 13: Average annual demand for selected items at each workshop

With this, the depot pipeline μ_0 for each item can be calculated for each LRU, using equation 10:

Item	m_0	T_0	μ_0
Oil filter	71.25	0.08333	5.9375
Engine	28.5	0.5	14.25
Glow plugs	769.5	0.08333	64.125
Spring rear	190	0.5	95
Oil pan	71.25	0.08333	5.9375

Table 14: Depot pipeline calculation

Subsequently, we can now apply equation 12 to calculate the average pipeline from the depot to each workshop: $\mu_j = m_j\ \left(r_j T_j + \left(1 - r_j\right)\left(O_j + EBO(S_0|m_0 T_0)/m_0\right)\right)$. Again, no component repairs at any of the workshops yields a simplified version of the equation:

$$\mu_j = m_j\left(O_j + EBO(S_0|m_0 T_0)/m_0\right). \qquad (eq. 15)$$

Using the aforementioned two days of order and shipping times O_j, allows us to find the pipelines for each item at every workshop, and follow the steps from section 3.3. A demonstration of the delta value calculation can be found in Appendix B3. Once the highest delta value is selected, one item is added to the inventory at the selected location. If an item is added to the depot, the pipeline for that item towards each workshop needs to be re-evaluated, yielding a new set of delta values. The procedure can then be repeated until the desired expected level of system availability has been achieved. The procedure to find the system availability is identical to the single echelon model.

4.3 Summary

- The single echelon system has no communication between workshops, resulting in six separate single echelon systems. The two-echelon system includes a depot, for which shipping to each of the workshop takes two days.
- The total demand for a component can be found by taking the product of the demand of a LRU and the number of vehicles in which it is present at that workshop. Subsequently, the pipeline μ can be found by taking the product of the total demand and the average lead time.
- The calculation of the EBO can expressed in Excel using the following formula: $\mu(1 - Poisson.dist(s-1, \mu, TRUE)) - s(1 - Poisson.dist(s, \mu, TRUE))$
- The calculation of the delta value can be expressed in Excel using the following formula: $(1 - Poisson.dist(s, \mu, TRUE))/cost$

CHAPTER 5: NUMERICAL ANALYSIS

The aim of this chapter is to compare and validate the results from the different models. Sections 5.1 and 5.2 will discuss the results for the single and two-echelon models. Section 5.3 will weigh the advantages and disadvantages of both models and their applicability for the Manticore, and 5.4 will focus on analysing for adjustments that could be made to ensure a good fit with the previously set requirements. 5.5 then compares the performance of the models to the performance established in Section 2.7. Finally, in Section 5.6 will provide an overview of the main conclusions from this chapter.

For both models, two scenarios will be considered, one in which preventive maintenance is plannable, and one in which preventive maintenance is based on the same Poisson-distributed demand as corrective maintenance.

5.1 Single echelon

Using the implementation of a single echelon, (s-1, s) system as proposed in Section 4.1, results can be generated for every single workshop. For sake of legibility, the same sample of items as before will be used for demonstration of the results. A full table of results can be found in Appendix C1 (scenario 1), the list of iterations for workshop A can be found in Appendix C6. The model is subject to the following assumptions:

- *Repair capacity is infinite, personnel and equipment are available at each workshop.*
- *No lateral transhipments are allowed.*
- *The fleet size is consistent across time, therefore the pipelines as well.*
- *A one-for-one ordering policy is assumed, no batch shipping.*
- *Item criticality is 1, and equal between all LRUs.*

Single echelon, scenario 1.

Component	A	B	C	D	E	F	Total
Oil Filter	6	6	5	6	5	7	35
Engine	8	8	6	7	6	10	45
Glow plugs	23	24	18	22	18	29	134
Spring rear	24	25	18	22	18	31	138
Oil pan	5	5	5	5	5	6	31

Table 15: Number of items to be placed at workshops A through F for a selection of items, single echelon model, scenario 1.

Workshop	A	B	C	D	E	F	Weighted average
Availability	96.44%	96.46%	96.44%	96.45%	96.44%	96.47%	96.45%

Table 16: Single echelon, scenario 1, availabilities for workshops A through F (after adjustments).

Running the model up to an availability of 352 days, meaning 350 days plus two days for shipping, preparations, diagnostics, and repairs (section 1.1) for the corrective demand first, returns the recommended stock distribution from appendix C1, a selection of which can be found in Table 15. For the total inventory composition, 3071 iterations, meaning 3071 individual items of safety stock, are required to reach a minimum availability of 96.44% across all workshops (averaging 96.48% across all workshops). The (indexed) investment required to do so is 1,156,434.05.

As for workshop A in particular, a total of 533 iterations are required to reach the desired level of system availability. The total (indexed) investment required to achieve this level of availability is 201,234.23. Low-cost, high demand items are prioritized, as can be seen in the full Table of all iterations (Appendix C6), especially those with a higher lead time. Nevertheless, due to the nature of the model, at some point the even the more expensive items will get stocked, as the probability of stockouts leading to non-deployable vehicles at that point outweighs the cost of stocking said item. To illustrate this, the total number of iterations has been divided into buckets (Figure 15) each bucket representing 10% of the total items stocked. For instance, for workshop A, 533 iterations are performed, so bucket one (denoted by

10%) represents iterations 1 through 53 and bucket two (denoted by 20%) iterations 54 through 106. Figure 15 buttresses the fact that lower cost items are prioritized, as the average unit cost for the first 50% of incrementations is quite low. Another interesting observation is that average unit price peaks around the 80% mark, and then decreases again. This can be explained by the fact that a stock level for expensive items is generally established around this bucket. As there is little to no stock for those items before this point, the EBO reduction per item is still significant. Once some level of stock has been established, it is unlikely that this expensive item will be selected again for quite some time, as it will become very costly to realise a reasonable EBO reduction, hence middle-priced items will be selected first.

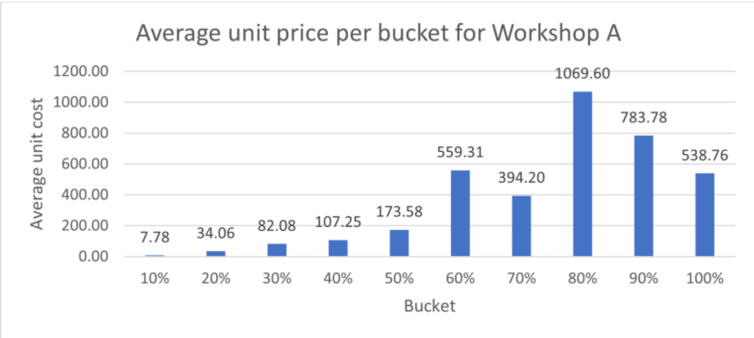


Figure 15: Average LRU price per bucket for workshop A, single-echelon, scenario 1

Offsetting the total investment against the vehicle availability (Figure 17) allows us to make some observations about the behaviour of our model. The blue line represents the total investment at selected levels of system availability, the orange line is the 96.44% system availability representative of 352 days of availability. Two things in particular stand out: the rapid rise of availability during the very first investments, as well as the diminishing returns on investment once availability hits roughly 95%. (Figure 16).

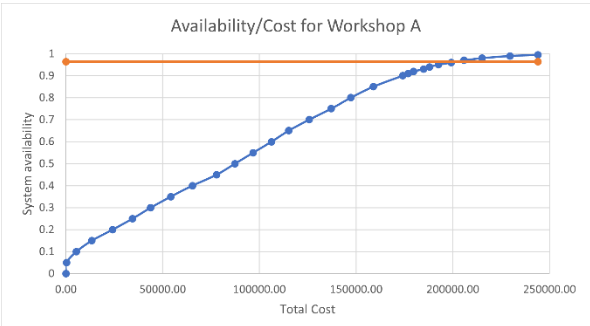


Figure 17: Availability/cost graph for workshop A, single echelon, scenario 1

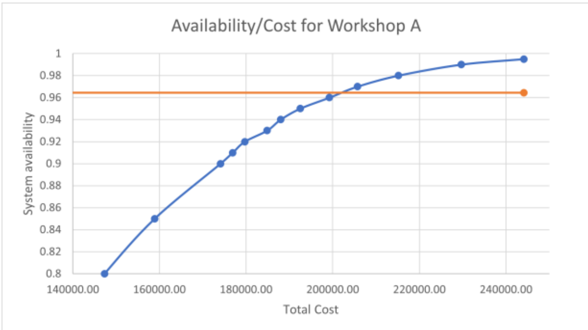


Figure 16: Availability/cost graph for workshop A, single echelon, scenario 1, magnified.

The first phenomenon can be explained by the acquisition of low-cost items, which, due to the assumed equality in item criticality, require relatively little investment for significant gains in the availabilities of those particular LRUs. Once some stock for these items has been established, availability quickly rises, and the stock steadily increases until it approaches 95%. At this point, a reasonable level of stock has been established for all items, so the backorder reduction is per item is diminishing. Availability for inexpensive items has already nearly approached 100%, so adding more safety inventory for those does not improve system availability. Therefore, in order to increase availability beyond the 95%-point, significant investments need to be made in more costly items, which already have some level of base stock. Hence, investments yield a lower EBO decrease than earlier points along the curve, and the expenses per EBO reduction are higher.

It should be noted that the graph in Figure 17 is not convex, as discussed in Section 3.1, but concave. This is because the (s-1, s) optimises for backorder reduction per euro spent. Therefore, our delta value should be ever decreasing, which can be confirmed by analysing the delta column from Appendix C6. If we plot an (increasing) availability against investment (as opposed to a decreasing number of backorders), we are left with a concave curve. Furthermore, there are parts in which the curve is not smooth. This is due to the way in which we calculate component availability; as long as the number of expected backorders outnumbers the number of vehicles in which the component can be found, availability is 0, so reducing the number of backorders on items with very high demand does not have an immediate effect on the availability of the vehicles. The other workshops exhibit the same behaviour, as can be seen in Appendix C3.

Finally, an interesting observation to make is that the last iteration, the 533rd, increases system availability to 96.47% to cross the threshold availability of 96.44% *(specifically: 96.4384%, as 352/365 days is not exactly 96.44%)* as can be seen in Table 17. The delta value for this item is indeed optimal, so it has the highest backorder decrease per euro spent for the inventory distribution being in the state of 533 iterations. However, the 532nd iteration already brings the system availability up to 96.26%, so the extra unit of stock added only needs to add 0.18% system availability to meet the availability threshold of 96.44%. Therefore, costs can be reduced by substituting this relatively expensive item by the cheapest item that would also surpass the availability threshold. For workshop A this means the front axle from iteration 533 can be replaced by a vehicle door, reducing expenditure by 81.04. Implementation in the model can be found in appendix B2.

#	PN	Delta	Avail.	Cost	SumBO
529	6	0.000026297	96.19%	76.62	3.8794
530	19	0.000025569	96.24%	325.67	3.8262
531	40	0.000025330	96.25%	91.59	3.8114
532	44	0.000024074	96.26%	24.93	3.8075
533	24	0.000023881	96.47%	1430.79	3.589

Table 17: Iterations 523 through 527 for workshop A, single echelon, scenario 1.

This means that for the final recommendation, for each workshop the last iteration will have to be considered and adjusted if necessary. Table 18 illustrates the adjusted recommendations based on this observation for each workshop. Adjusting for these items then yields a new total system availability of 96.4515%, reducing investments by 1324.01, for a new total of 1,155,110.04.

Work-shop	Iteration #	Attained availability	Previous item on last iteration	Replace last iteration by:	New availability	Cost savings
A	533	96.47%	Complete front axle	Vehicle door left or right front or rear	96.44%	81.04
B	552	96.46%	Vehicle door left or right front or rear	Already optimal	-	-
C	417	96.54%	Side window left or right front or rear	Engine flywheel	96.44%	580.96
D	490	96.45%	Complete transfer case	Already optimal	-	-
E	417	96.54%	Side window left or right front or rear	Engine flywheel	96.44%	580.96
F	662	96.48%	Complete front axle	Vehicle door left or right front or rear	96.47%	81.04

Table 18: Adjustments to recommended spare part composition.

Single echelon, scenario 2.

For the second scenario, we will not treat preventive and corrective maintenance separately, but rather as a single source of demand, which is subject to random events and therefore Poisson-distributed. The total demand will then simply be the sum of the demand for preventive and corrective maintenance.

Component	A	B	C	D	E	F	Total
Oil Filter	22	23	18	21	18	27	129
Engine	8	8	6	7	6	10	45
Glow plugs	31	32	24	28	24	38	177
Spring rear	62	65	46	57	46	81	357
Oil pan	5	5	5	5	5	6	31

Table 19: Excerpt of results for single echelon model, scenario 2.

Workshop	A	B	C	D	E	F	Weighted average
Availability	0.9645	0.9645	0.9644	0.9644	0.9644	0.9645	96.45%

Table 20: Single echelon, scenario 2, availabilities for workshops A through F (after adjustments).

Running the model for the scenario as described above, returns the recommended stock distribution from appendix C2, an excerpt which can be found in Table 19. After 5601 iterations, an average availability 96.53% across all workshops has been achieved, for which the total indexed investment is 1,433,255.48. Unsurprisingly, cheaper, high demand items are once again prioritized. As preventive maintenance only applies to a selection of items, such as the oil filter, the safety stock for these items is increased significantly. Items which are not replaced preventively are barely impacted, if at all, which is as expected considering the demand for these items did not increase either. Similar to scenario 1, we can again adjust based on the fact that the last iteration tends to overshoot the availability threshold. These adjustments can be found in appendix C5, and lower availability to 96.45%, saving 4040.62 for a total of 1,429,214.86.

For workshop A specifically, 974 iterations are required to reach the desired level of system availability, by investing a little under 249,366.32. Analysing the average unit price per bucket again, yields a similar distribution compared to scenario 1 (appendix C4). Again, the average unit price is relatively low for the first half of iterations, after which it peaks, and drops again. The peak occurs at a slightly later interval, which can be explained by the fact that most items required for preventive maintenance are relatively cheap, which means the delta criterion for these items is more favourable compared to the first scenario.

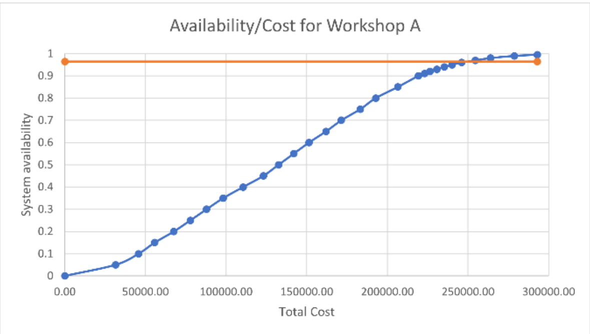


Figure 19: Availability/cost graph for workshop A, single echelon, scenario 2

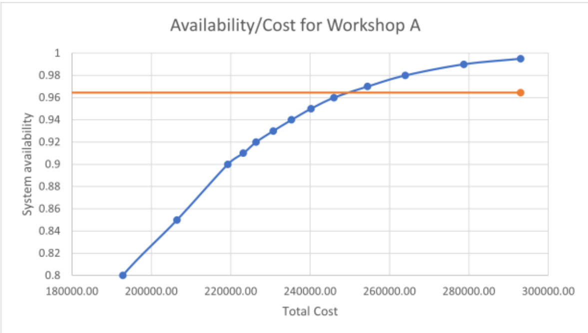


Figure 18: Availability/cost graph for workshop A, single echelon, scenario 2, magnified.

Figure 18 illustrates the achieved availability offset against the total investments. For the most part, the behaviour is similar to the first scenario, but where the first scenario had a quick increase of system availability for the first investments, the second scenario displays a ramp-up period. This is again due to the fact that for some items the EBO outnumbers the total number of vehicles with said component, which results in availability of 0 for those items. As the total system availability is the product of all component availabilities, this means that system availability will not start to increase until a reasonable level of safety stock for these components has been established. Due to the fact that average annual demand for preventive maintenance is quite high compared to corrective maintenance, this effect is more pronounced in the second scenario.

5.2 Two-echelon

For the two-echelon model, the same two scenarios, the first excluding preventive maintenance, the second including preventive maintenance will be considered. The same assumptions from the single echelon model apply, now adding the following assumption:

- *Shipping from the depot to the workshops is constant, two days.*

Two-echelon, scenario 1.

Repeating the marginal analysis for a two-echelon system method as proposed in Section 4.2, the number of components kept per workshop and in the depot can be found by iterating until the desired system availability has been achieved. After performing 2224 iterations and investing 912,434.77, achieving an availability of 96.51%, resulting in the figures from Table 21 (full results in Appendix D1). Again, the last iteration can be adjusted, replacing a front axle at the depot by a steering box at workshop B, which in turn yields an availability of 96.4404%, saving 1270.69 for a total investment of approximately 911,164.09.

Component	Depot	A	B	C	D	E	F	Total
Oil Filter	10	2	2	2	2	2	2	22
Engine	14	0	0	0	0	0	0	14
Glow plugs	68	5	5	4	5	4	6	97
Spring rear	97	2	2	1	2	1	2	107
Oil pan	10	2	2	1	2	1	2	20

Table 21: Excerpt of results for two-echelon model, scenario 1.

Workshop	A	B	C	D	E	F	Weighted average
Availability	96.39%	96.26%	95.55%	96.04%	95.55%	97.82%	96.44%

Table 22: Two echelon, scenario 1 availability in workshops A through F (after adjustments).

Plotting the availability against the investment (Appendix D3) yields a curve similar to scenario 1 in the single echelon system. Again, inexpensive, high demand items are prioritized first, leading to a relatively quick rise of availability during the first investments, and the same diminishing returns after approaching 95% availability. As can be seen from Table 21, the biggest difference between the single- and two-echelon systems is that, considering the relatively short order-and-ship time between the depot and workshops, little stock has to be kept at the workshops themselves.

As both the single echelon and the two-echelon models exhibit the diminishing returns after reaching approximately 95% (~347 days) vehicle availability, it should be noted that it is perhaps interesting for the MoD to consider dropping the desired availability to this level.

Two-echelon, scenario 2.

Component	Depot	A	B	C	D	E	F	Total
Oil Filter	58	5	5	4	5	4	6	87
Engine	14	0	0	0	0	0	0	14
Glow plugs	97	6	6	5	6	5	7	132
Spring rear	252	10	11	7	9	7	16	312
Oil pan	10	2	2	1	2	1	2	20

Table 23: Excerpt of results for two-echelon model, scenario 2.

Repeating the process for the second scenario yield the results from Table 23 (full results Appendix D2). After a total of 4494 iterations the desired of 96.44% can be approached to 96.46%, with a total investment of 1,167,202.86. Subsequently the last iteration can once again be adjusted to approach the desired availability more closely by replacing a co-driver seat for a rim at the depot, saving 283.95, bringing the new level of availability to 96.44% at 1,166,918.91. Plotting cost against availability again yields a similar pattern to the second scenario in the single-echelon model (Appendix D3), again showing the relatively slow ramp-up period due to some items remaining at a low availability for some amount of time, as described in Section 5.1.

Workshop	A	B	C	D	E	F	Weighted average
Availability	96.32%	96.29%	95.47%	95.91%	95.47%	98.00%	96.44%

Table 24: Two echelon, scenario 2 availability in workshops A through F (after adjustments).

The biggest divergence from the other from the runs so far can be found in the average unit price per bucket, each bucket containing 10% of total iterations (Figure 20). This can be related to two factors, the first being the significantly higher demand for relatively cheap items replaced during preventive maintenance, just like the second scenario in the single echelon model. The second factor that is most likely at play is the pooling effect from the depot. One item of stock of an expensive but relatively low demand item at the depot already yields a considerable backorder reduction across the entire system. Although the safety inventory is "shared" with other workshops, it allows for a significant reduction in the pipeline for each workshop, as the pipeline for a workshop in two-echelon system considers the order and ship time from the depot to each workshop, as opposed to the lead time from the manufacturer.

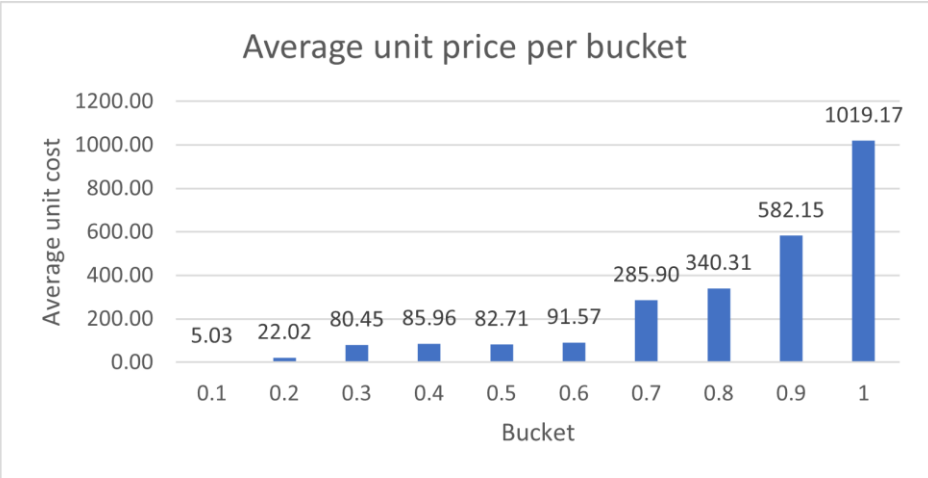


Figure 20: Average LRU price per bucket, two-echelon, scenario 2

5.3 Comparison of one- and two-echelon systems

Now that the results of each of the models and both scenarios have been determined, they can be compared to one another to find the most suitable model for the situation at the MoD. Summarized results can be found in Tables 25 and 26.

Single-echelon	Achieved availability after adjustments	Investment required to achieve availability. (millions)	Investment difference with *two-echelon* for the same scenario	Total no. items stocked
Scenario 1	96.45%	1.155	+ 26.77%	3071
Scenario 2	96.45%	1.429	+ 22.48%	5601

Table 25: Single echelon results

Two-echelon	Achieved availability after adjustments	Investment required to achieve availability. (millions)	Investment difference with *single echelon* for the same scenario	Total no. items stocked
Scenario 1	96.44%	0.911	-21.12%	2224
Scenario 2	96.44%	1.167	-18.35%	4494

Table 26: Two-echelon results

Evidently, the number of items that have to be stocked for the second scenario is considerably higher than the first scenario, however, as the investment required shows, they are mostly relatively cheap items. Therefore, despite the fact that we have previously expressed that safety inventory is unlikely to be necessary for preventive maintenance, as it is subject to little-to-no inventory, it could be added for a relatively limited increase in total investments.

Analysing Tables 25 and 26 returns that for both scenarios, the two-echelon model can approach the level of desired availability at an almost 20% lower cost. Furthermore, the number of items that have to be stocked is lower by a similar fraction. This reflects the pooling effect as discussed in Section 5.3. If we look at Tables 27 and 28, we can illustrate that the pooling effect generally lies somewhere between 15% to 30%. For this, item cost has been split into five ranges, where α represents the average item cost. Evidently, the selection criterion (Δ) is not just dependent on cost, but also on backorder reduction, which is dependent on the lead time for an item. This could in turn could explain the small skewness to the extremes, due to the cost preference for low-cost items, and the generally longer lead time for more expensive items.

Item cost range	**<0.25α**	**0.25α - 0.5α**	**0.5α - 2α**	**2α - 4α**	**>4 α**	**Total**
Single echelon *Scenario 1*	1159	650	333	490	439	3071
Two-echelon *Scenario 1*	758	457	249	408	352	2224
Pooling effect:	-34.60%	-29.69%	-25.23%	-16.73%	-19.82%	-27.58%

Table 27: Pooling effect scenario 1

Item cost range	**<0.25α**	**0.25α - 0.5α**	**0.5α - 2α**	**2α - 4α**	**>4 α**	**Total**
Single echelon *Scenario 2*	1852	2040	772	493	444	5601
Two-echelon *Scenario 2*	1259	1814	660	408	353	4494
Pooling effect:	-32.02%	-11.08%	-14.51%	-17.24%	-20.50%	-19.76%

Table 28: Pooling effect scenario 2

A last observation between the single and two echelon model is the difference between availabilities at the workshops. Where the single echelon model approaches each workshop separately, the two-echelon model approaches the fleet as a whole. Therefore, the vehicle availabilities between workshops themselves vary slightly between 95% and 98%, as opposed to the single echelon model which consistently achieves the 352-day benchmark of 96.44%.

5.4 Model adjustments

So far, our results have yet to incorporate the desire expressed by the MoD that every workshop stocks at least one unit of every LRU (Section 2.6). Analysing the results of the single echelon model for both scenarios shows (Appendix C1, C2) that this requirement is met for the single echelon model, and rerunning the model for a stock level of one for all items indeed yields the same results, therefore no adjustments have to be made to the model to meet this requirement.

The two-echelon model, however, has items such as the engine, which are only stocked in the depot (Appendix D1, D2). Therefore, the model can be run again by initialising the model with a stock level of 1 for all items at the workshops, yielding the results from Appendix D5 and D6. The first scenario, after 1924 iterations and adjusting by removing a steering box from the depot and adding a driver's seat to the same location, yields an availability of 96.4421% with a total investment of 919,629.98.

The second scenario requires 4195 iterations, and after adjusting by removing a front axle at the depot, and adding a vehicle door to workshop D, we are left with an availability of 96.4395% for an investment of 1,174,780.44.

	Two-echelon (standard)	**Two-echelon (adjusted)**	**Difference**
Scenario 1	911,164.09	919,629.98	8,465.89
Scenario 2	1,166,918.91	1,174,780.44	7,861.53

Table 29: Two-echelon models comparison for MoD-requirements adjustments

As can be seen by comparing Appendices D1 with D5, and D2 with D6, the recommended inventory composition is mostly different by changes of one or two components at most locations. Somewhat surprisingly, the difference in cost between the mathematical optimal model and the adjusted model is fairly minor (Table 29), meaning that the MoD can apply their requirement of setting a minimum stock level of one unit per LRU at all workshops at a minor fee.

5.5 Comparison to current performance

In Section 2.7, we briefly touched upon the performance of current systems in use at the MoD, referring to the Bushmaster and the Mercedes G-Class. Accounting for price differences in vehicle variations, the total fleet cost for the Manticore amounts to approximately 17 million. Again, this price is indexed to account for confidentiality. With a spare part to fleet procurement cost ratio of roughly 1:12.5, we can compare the expected costs of the safety inventory required for each scenario:

Single echelon	**Indexed investment (millions)**	**Ratio**	**Availability**	**Days of availability**
Scenario 1	1.155	1 : 14.4	96.45%	352*
Scenario 2	1.429	1 : 11.6	96.45%	352*

Table 30: Single echelon spare part to fleet cost ratio

Two-echelon (adjusted)	**Indexed investment (millions)**	**Ratio**	**Availability**	**Days of availability**
Scenario 1	0.920	1:18.1	96.44%	352*
Scenario 2	1.175	1:14.2	96.44%	352*

Table 31: Two-echelon spare part to fleet cost ratio

It should be noted that the comparison between the vehicles is crude at best. As previously discussed, there are significant differences between the physical composition the vehicles themselves, and there was little available data to offer a proper frame of reference. Furthermore, demand estimates for each of the components for the Manticore are based on estimates, and the outcome of the model is as good as the estimates would allow for. The ratios as per Tables 30 and 31 therefore aim to give a first impression of results but can perhaps best be used to assess performance between models, where the two-echelon system allows for significant cost reduction and would therefore be the best fit. However, this does depend on the fact whether provisions for a depot are already set up, otherwise one would have to consider the costs of running an additional location as well shipping costs between the depot and the workshop.

The impact of setting the availability threshold to a higher level has been visualized in Figure 21, full results can be found in Appendix E1, the accompanying distribution of availabilities per workshop can be found in Appendix E2. The single echelon model outperforms the baseline until an availability of approximately 361 days in the first scenario but fails to meet the target in at any availability of 350 days and up in the more pessimistic second scenario. Both of the two-echelon scenarios outperform the baseline, making this an option for consideration in case the MoD desires to achieve a higher level of vehicle availability.

*Excluding days required for transport, diagnostics, setup, repairs, and other tasks.

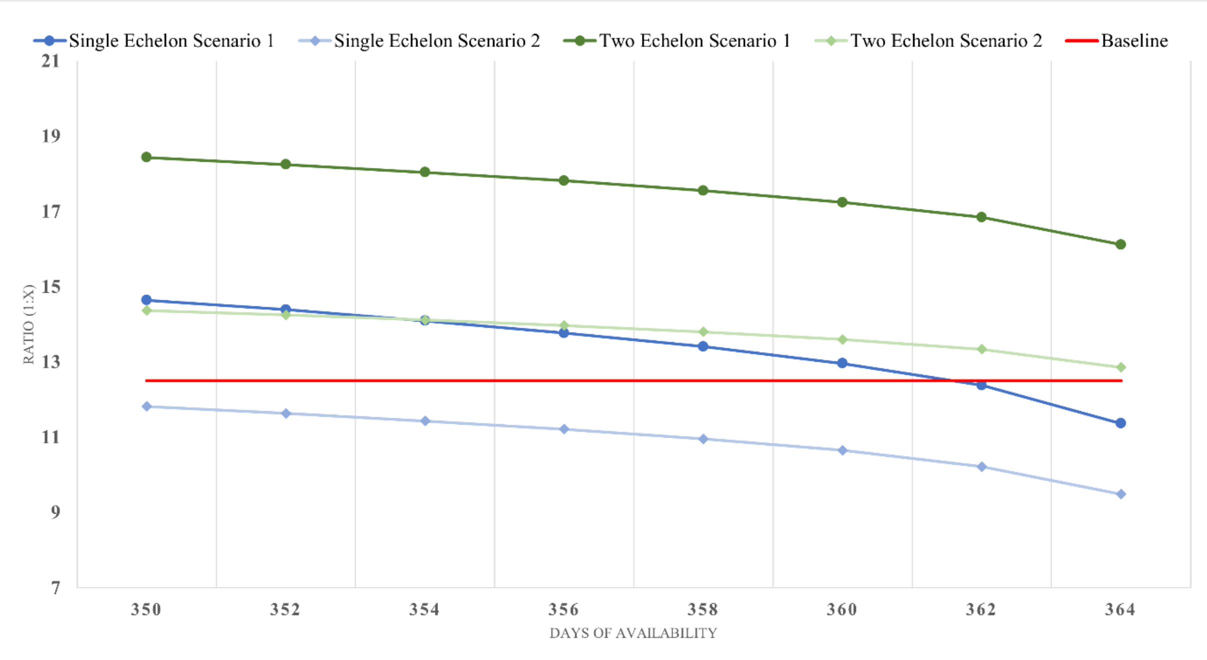


Figure 21: Spare parts inventory to acquisition cost ratio for selected availability levels

Figure 22 represents the spare parts inventory to acquisition cost ratio for 352 days of availability for the first scenario for both models at varying levels of demand, full results in Appendix E3. As previously found, both models appear to outperform the baseline at the expected demand rate and below. If we increase the demand by a multiplication factor, we can see that the single echelon model manages to outperform the baseline up until a demand that is 15% higher than expected, and the two-echelon model manages to do so up until a demand that is 40% higher than expected. This further underlines the advantages of the two-echelon model when considering the limitations and uncertainty of the available data.

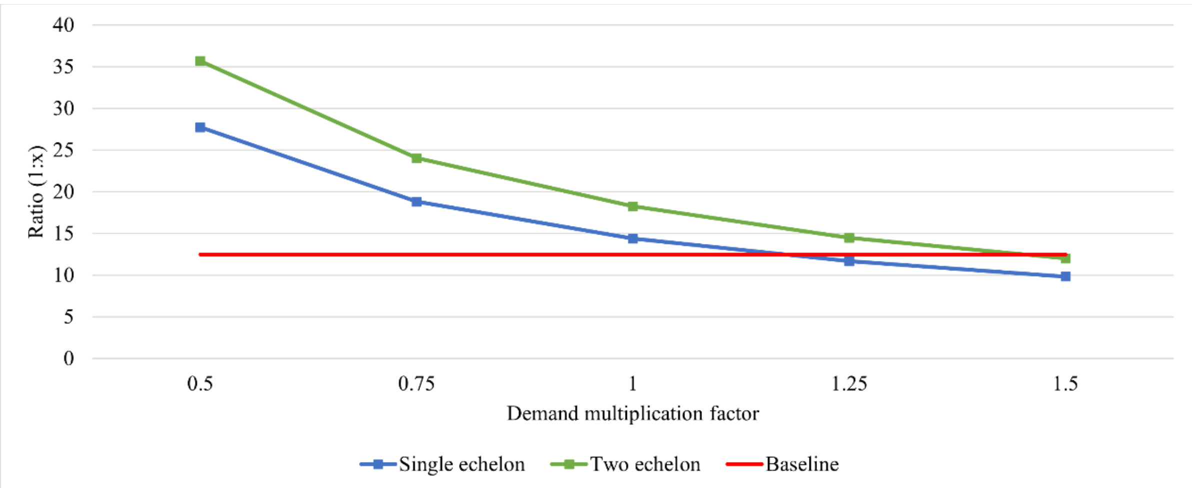


Figure 22: Spare parts inventory to acquisition cost ratio after adjusting demand (352 days, scenario 1)

In both models and scenarios a few items have come forward as particularly expensive (Appendices E4 & E5) such as the complete transmission, the front axle, and armoured doors, windshields, and windows which are a large share of the total investment required. Between the models, items such as the basic engine do require significantly more investment in the single echelon system, requires more stock per base, where the pooling effect at the depot makes that this is not necessary for the two-echelon model. When also considering for preventive maintenance, some high demand items such as front and rear springs come forward, as they are relatively costly considering their demand. Once more information is available about the cost savings through the purchase of investment spares (section 2.6), Verebus and the MoD should focus on these items, depending on their preferred inventory model.

5.6 Summary

The research question prior to this chapter was: *"Based on the previously determined approach, which spare part composition best meets the requirements set by Verebus?"*

- The first scenario (no preventive maintenance) exhibited a fast rise in performance for the first investments, while the second scenario (including preventive maintenance) required a ramp-up period.
- Both the single echelon as well as the two-echelon showed increasing diminishing returns on investment after reaching an availability of approximately 95%.
- The last iteration after matching the desired availability can be adjusted to not select for the item that produces the greatest backorder reduction at the lowest cost, but instead for the cheapest item that will produce an availability increase great enough to increase the system availability of the second-to-last iteration to meet the set threshold.
- The single echelon system already accounts for the requirement set by the MoD that every workshop should contain at least one item of each LRU. The actual implication of this requirement for the two-echelon model is relatively minor, as total investments required to ensure the set vehicle availability across all workshops barely increase when comparing the mathematical optimum of the two-echelon system to the adjusted version.
- The two-echelon system that does not account for preventive maintenance produces the most cost-optimal result and produces a superior result when compared to the performance as established by the Bushmaster and Mercedes G-Class.
- In practice, the comparison is limited as the difference between the Manticore, and these other vehicles is not a one-to-one, and the data availability to model the demand for components and set a spare-part-to-fleet-acquisition-cost ratio was limited.
- Both of the two-echelon scenarios outperform the baseline for the tested levels of vehicle availability.

CHAPTER 6: VALIDITY AND LIMITATIONS

As discussed in chapter 2, data availability on many areas required to give a well-founded recommendation on a required spare parts composition for the Manticore has been limited. For confidentiality reasons, limited data was available regarding the demand for components, which meant that we had to rely on estimates from the ILS manager at the MoD, as well as presenting the outcome in case of other demand figures. Data for other factors, such as component price, as well as the actual components present in the Manticore and their multiplicity per vehicle were also not readily available. This has mostly been accounted for by using a reference list of spare components that are commonly used for vehicles similar to the Manticore. Nevertheless, the use of a dataset that would be a better reflection of the actual situation would be more desirable to come to an actual recommendation, especially as the reference list does not consider the fact that there are multiple vehicle variations, as well as the fact that some of the items on the list are not strictly first-indenture, even though they are treated as such. To counter this, the tool developed to calculate the recommended spare part composition is easily modifiable and can be adjusted to account for different insights at a later point in time.

In order to approach a reasonable estimated component demand, some interviews were conducted with the ILS manager at the MoD, while this is an expert opinion on the matter, a quantitative analysis of actual demand figures would have been preferable. Unfortunately, no other people were available during the course of the study, and therefore the views expressed could potentially be one-sided. For similar reasons as getting an impression of the actual demand of spare parts, the distribution of this demand could not be approximated either. Based on the literature review performed in chapter 3, a core assumption in our models is that the demand for spare components is Poisson distributed. The use of the Poisson-distribution for random failures of components is, as discussed in Section 3.1, a common method. Nevertheless, it is possible that the actual distribution of failures can be better approximated by a different distribution.

Generally speaking, the models used for this study are well-established for the management of repairable spare parts inventory. Nevertheless, several things should be noted. First of all, as discussed in Section 3.3, the two-echelon model produces results that closely approximate the mathematical optimum, but still is a simplification that does produce slightly sub-optimal results quite often. Furthermore, the (s-1, s) inventory policy assumes a situation in which failed components are immediately sent out for repairs, or the immediate ordering of a replacement. In practice, the viability of this strategy for cheaper, low-demand items is limited, as order costs alone of some of these items would be higher than the item itself, so normally shipping would occur in batches. Another assumption from the first scenario we established is that preventive maintenance is subject to no uncertainty, both on the demand as well as on the supply side, in practice, this might not entirely be the case, and therefore a separate model for the deterministic demand for preventive, accounting for uncertainty in the supply may be a better approximation. Lastly, the assumption that all items are first-indenture, even though the component list contains some items that are second- or third indenture, needs to be kept in mind as these items would normally cause failure for higher indenture items as well.

Finally, there is the case of the establishment of a performance benchmark to compare the outcomes of the models to. Unfortunately, again due to data confidentiality, there was little information that could be given to offer a better frame of reference. Therefore, not just the outcomes of the models are as accurate as the information that was available, but also the ratio to which this outcome was compared. Furthermore, the MoD evidently does not want to give any information on the share of vehicles that are not mission capable, so it could be possible that comparison of spare part inventory costs between the Manticore and the Bushmaster and G-Class does not reflect an equal level of availability, therefore warping the comparison.

CHAPTER 7: CONCLUSIONS

7.1 Conclusions

The main research question posed in this thesis was the following: *"Which spare part composition should be maintained by Verebus to ensure the required availability of 350 days a year?"* In order to answer this, four sub questions were discussed.

Research question 1: "What is the current vehicle spare part keeping strategy used by the MoD?"

The MoD uses an Integrated Logistics Support structure, supported by the Sx000i specification for their vehicle maintenance and as input for resource planning. In general, the MoD aims to only keep LRUs in stock, therefore failed LRUs will have to be sent to the manufacturer for repairs or replacing. Any items priced below €750 are not considered for repairs and are therefore replaced immediately in case of component failure. A hard requirement that the MoD has set is that at least one unit of stock of every item must be available at every workshop. Availability is expressed by the 'material readiness' KPI, which represents the average percentage of available vehicles across the entire fleet. Assessment of the current spare part keeping performance is difficult due to data availability, but we can use a ratio of spare parts inventory cost compared to the acquisition value of a fleet of vehicles as a rough estimate. This ratio is based on the Bushmaster and Mercedes G-Class vehicles and amounts to approximately 1:12.5.

Research question 2: "Which inventory modelling approach can best be used to determine the required spare part composition for the Iveco Manticore?"

The demand for components can be split into corrective and preventive maintenance. Due the deterministic nature of preventive maintenance, safety inventory for preventive maintenance is not required. Corrective maintenance can be modelled using the Poisson-distribution, as it is the result of random failures. With this, Palm's theorem can be applied to calculate the pipeline, which represents the average number of items in repair or resupply. Then, a (s-1, s) policy for repairable items can be applied to optimise for the minimization of the number of expected backorders until a desired level of availability has been achieved through the application of marginal analysis. This policy allows us to produce a result without having to make assumptions on areas such as holding cost and order cost, for which the data is not available. Furthermore, it can be extended into a two-echelon system that includes a depot, such that a comparison between a system with- and without a depot can be made.

Research question 3: "How can the selected approach be applied to the spare part composition required for the Iveco Manticore?"

The single echelon system has no communication between workshops, resulting in six separate single echelon systems. The two-echelon system includes a depot, for which shipping to each of the workshop takes two days. For both models, shipments between workshops are disregarded. The total demand for a component can be found by taking the product of the demand of a LRU and the number of vehicles in which it is present at that workshop. Because we are using a reference list of components, we cannot distinguish between the differences in required components for the different vehicle variations, but normally this distinction would have to be taken into account.

Research question 4: "Based on the previously determined approach, which spare part composition best meets the requirements set by Verebus?"

The two-echelon models requires a spare parts inventory that is around 20% less expensive than the single echelon system for an availability of 350 days, plus two days for other activities, resulting in 96.44%. Calculations were performed for two scenarios. The first scenario represents the expected situation where preventive maintenance is easily plannable and does therefore not require safety inventory. The second scenario looks into what the results would be in case preventive maintenance is subject to the same random demand as corrective maintenance.

Single echelon	Indexed investment (millions)	Ratio	Availability
Scenario 1	1.155	1 : 14.4	96.45%
Scenario 2	1.429	1 : 11.6	96.45%

Table 32: Single-echelon spare part to fleet acquisition cost ratio

Two-echelon (adjusted)	Indexed investment (millions)	Ratio	Availability
Scenario 1	0.920	1 : 18.1	96.44%
Scenario 2	1.175	1 : 14.2	96.44%

Table 33: Two-echelon spare part to fleet acquisition cost ratio

For the availability standards set by the MoD both models outperformed the baseline of 1:12.5 in the first scenario, as can be seen in Tables 32 and 33. In the second scenario, only the two-echelon manages to outperform the baseline. A downside of the two-echelon model is that vehicle availability per workshop varies to a larger degree. Where the single-echelon model optimises for a vehicle availability that meets the requirements for every workshop individually, the two-echelon model approaches the fleet as a whole, meaning that the vehicle availability per workshop ranges from 95% to 98%. Both models in both scenarios down a diminishing return on investment once availability has approached approximately 95%, after which significantly more investment is required to further increase availability.

7.2 Recommendations

The goal of this research assignment was to find a composition of spare parts that produces a safety inventory that meets the availability goals set by the Dutch Ministry of Defence. As we have discussed, it is unlikely that safety inventory for preventive maintenance is required. Therefore, a two-echelon model that covers corrective maintenance as found in Appendix D5 would be the most appropriate approach for Verebus and the Dutch Ministry of Defence, provided that the minor differences in projected availability between workshops does not pose an issue.

Furthermore, there is a selection of expensive items such as the complete transmission, the front axle, and armoured doors, windshields, and windows that take up a large share of the total spare part investment required. Therefore, it could be of interest for Verebus and the MoD to further look into the purchase investment spares for these items. Once more information is available on the difference in cost for these items at a later point in time, it is recommended that Verebus and the MoD evaluate potential savings by acquiring these items ahead of time.

Finally, there is the matter of the diminishing returns on investment once availability approaches 95%. Currently, the desired availability is set at 96.44%, which is fairly close to this level. In case other activities such as transport, diagnostics and repairs cannot be carried out within two days, it would require significant investments from the MoD to still meet the 350 days of availability. Therefore, it could be advisable to slightly relax this requirement, weighing the stakes of doing so.

7.3 Future research

Before making further improvements as suggested in this section it is first important to pinpoint that the accuracy of a model is dependent on its input. As described in chapter 6, a major source of underlying reasons that assumptions had to be made was due to the fact that data availability and reliability were limited. Therefore, the first enquiries could for instance be into creating a better understanding of the demand of spare components and the sources and distribution of this demand. This could be done by either analysing the historical performance of comparable vehicles through the analysis of e.g., inventory patterns of the spare parts for these vehicles, or by thoroughly tracking the Manticore during its introduction phase.

As briefly touched upon in chapter 6, the current model aims at optimising for the creation of a spare parts inventory of repairable components and uses a one-for-one replacement policy. In order to extend the model to better include the diversity of items, enquiry could be done into other inventory policies that apply batch shipping. Similarly, as of now, the model excludes lateral transhipments. In reality, lateral transhipments between bases will be possible, so extending the model to include this would provide further accuracy. Furthermore, the current model only accounts for a first-indenture spare parts inventory. Even though the MoD has decided to aim for a spare parts inventory that consists solely of first-indenture items, it could be worth assessing the potential advantages of keeping SRUs, especially considering the fact that the reference spare components list already contains several non-LRU items.

The current approach consists of a two-echelon model. As the MoD has expressed the desire to minimise obsolete inventory, an option could be to explore the advantages of a three-echelon model that includes the manufacturer. Allowing the manufacturer to gain insight into internal use figures could help reduce uncertainty, potentially decreasing costs and increasing availability. Currently, the MoD already has some vehicles in use that are maintained following a similar structure, but some difficulties lie in data confidentiality, as some of the data transferred from the vehicles are considered too critical to share. A further enquiry weighing the advantages and disadvantages of this system at the MoD could therefore help future decision making for similar use cases.

Another potential area is research can be done by assessing the criticality of different components. Our current assumption is that the failure of a single component means that the vehicle is no longer mission capable. In reality, it is likely that the Manticore will continue to be mission capable after the failure of one or more components. Therefore, further enquiry should be made into assessing the criticality of each component and take this into account during the establishment of an improved spare parts composition.

Finally, Verebus and the MoD have already expressed the interest in exploring the impact of different deployment scenarios on the required spare parts composition. The current recommendation is based on a training scenario within The Netherlands. The deployment of Manticores in different parts of the world would considerably change the required spare parts composition. Component wear will occur differently under different environmental conditions, shipping will likely take longer and be subject to more uncertainty, and repairs and replacements will have to be performed with limited resources. In line with this, it could also be potentially useful to look into the wear patterns across the vehicle variations, as it is likely that a pick-up, designed for transport will be used differently than a casualty transport vehicle.

REFERENCES

ASD/AIA (2021-1). *SX000i, International specification for Integrated Product Support (IPS), Issue 3.0.* https://www.sx000i.org/

ASD Europe (2021). *S1000D, International specification for the procurement and production of technical publications.* https://www.asd-europe.org/s1000d

ASD/AIA (2021-2). *S2000M, International specification for Material Management, Issue 7.0.* https://www.s2000m.org/about-s2000m/

ASD/AIA (2021-3). *S3000L, International procedure specification for Logistics Support Analysis LSA.* https://www.s3000l.org/

ASD/AIA (2021-4). *S5000F, International specification for in-service data feedback. Issue 3.0.* https://www.s5000f.org/downloads/

ASD/AIA (2023). *International specification for developing and continuously improving preventive maintenance. Issue 2.2.* https://www.s4000p.org/

Basten, R. J. I., Schutten, J. M. J., van der Heijden, M. C. (2009). *An efficient model formulation for level of repair analysis.* https://doi.org/10.1007/s10479-009-0516-5

Casadiego Miranda, L. P., Bastos Blandos, E. A., Paipa Sanabria, E., Ruiz Pianeta, M., Pinzón Ramírez, J. S., & Zuñiga Portillo, N. F. (2021). *Analysis of integrated logistics support (ILS) in the shipbuilding industry. Advantages and improvement opportunities for the naval industry.* COTECMAR case study. Ciencia Y tecnología De Buques, 14(28), 9–17. https://doi.org/10.25043/19098642.211

Chopra, S. (2019). *Supply Chain Management: Strategy, Planning, and Operation.* Pearson, 7th edition.

Cohen, I., Cohen, M. A., & Landau, E. (2017). *On sourcing and stocking policies in a two-echelon, multiple location, repairable parts supply chain.* Journal of the Operational Research Society, 68(6), 617–629. https://doi.org/10.1057/s41274-016-0108-0

Driessen, M. A., van Houtum, G. J., Zijm, W. H. M., Rustenburg, W. D. (2020). *Capacity assignment in repair shops with high material uncertainty.* https://doi.org/10.1016/j.ijpe.2019.09.005

Gayer, C. F. (2010). *Assessment Of Poisson Model For Airliners' Repairable Spare Parts Demand Forecasting.* JOURNAL OF THE BRAZILIAN AIR TRANSPORTATION RESEARCH SOCIETY • VOLUME 6 • ISSUE 1 • 2010

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

Heerkens, H., Van Winden, A., & Tjooitink, J. W. (2021). *Solving Managerial Problems Systematically*. Taylor & Francis.

Jones, J. V. (2006). *Integrated logistics support handbook*. Sole Logistics Press

Louit, D., Pascual, R., Banjevic, D., & Jardine, A. K. S. (2011). *Optimization models for critical spare parts inventories—a reliability approach.* Journal of the Operational Research Society, 62(6), 992–1004. doi:10.1057/jors.2010.49

Minner, S. (2000). *Strategic Safety Stock in Supply Chains.* Springer

Puig, J. P., & Basten, R. J. I. (2015). *Defining line replaceable units*. European Journal of Operational Research, 247(1), 310–320. https://doi.org/10.1016/j.ejor.2015.05.065

Patriarca, R., Costantino, F., & Di Gravio, G. (2016). *Inventory model for a multi-echelon system with unidirectional lateral transshipment.* Expert Systems With Applications, 65, 372–382. https://doi.org/10.1016/j.eswa.2016.09.001

Sherbrooke, C. C. (2004). *Optimal Inventory Modeling of Systems.* Kluwer.

Shukla, S. K., Kumar, S., Selvaraj, P., & Rao, V. S. (2014). *Integrated Logistics System for Indigenous Fighter Aircraft Development Program.* Procedia Engineering, 97, 2238–2247. doi:10.1016/j.proeng.2014.12.468

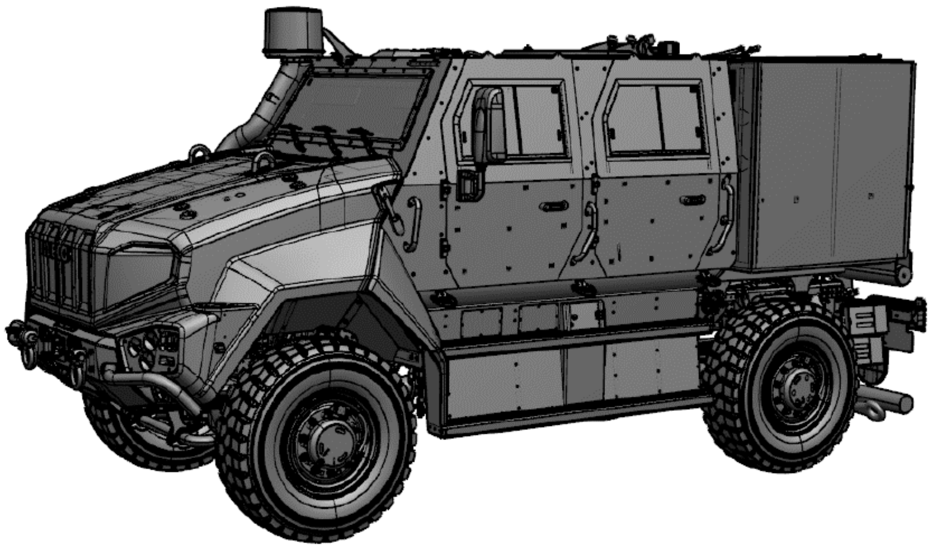
Silver, E. A., Group, T. &. F., Pyke, D. F., & Thomas, D. J. (2021). *Inventory and Production Management in Supply Chains*. CRC Press.

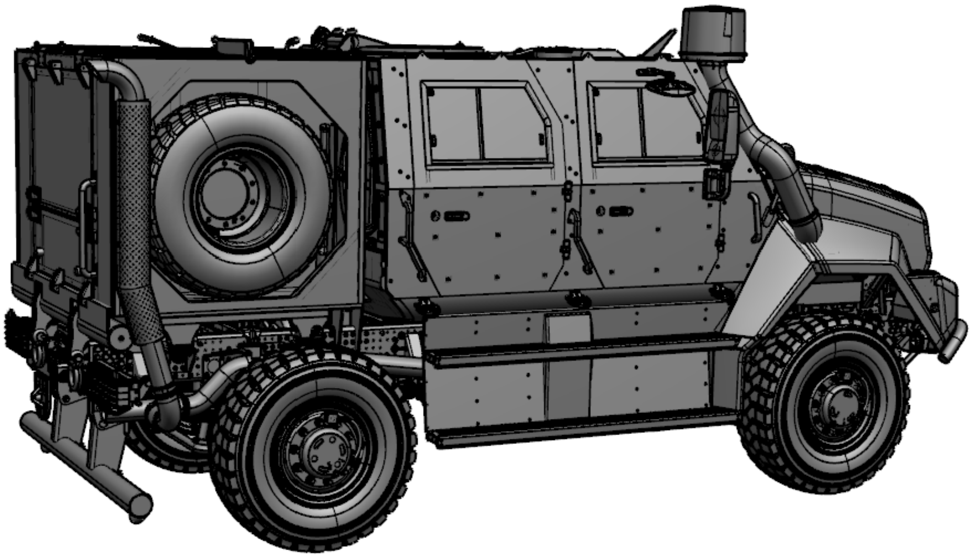
Appendices

Appendix A: Vehicle impressions and properties

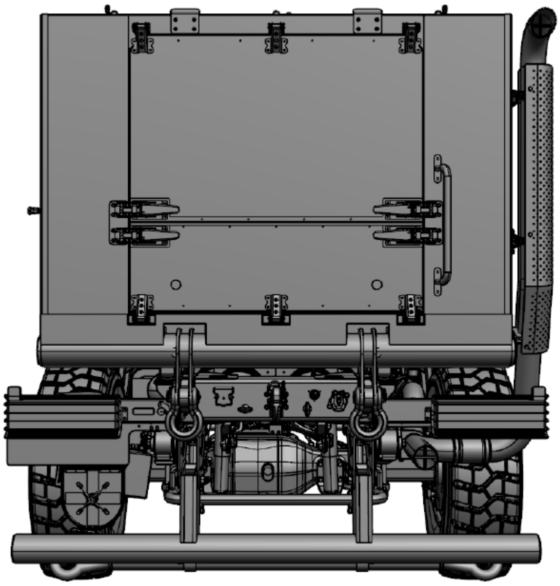
Appendix A1: Vehicle variation impressions

Soft Top	Hard Top	Casualty Transport	Pick-up
			

Left


Right


Front


Back


Appendix A2: Component list

PN	Item name	Multi-plicity	Demand (corr.)	Demand (prev.)	Demand (per vehicle)	Indexed Cost	Repair time (Years)	Resupply time (years)
1	Oil Filter	1	0.125	1	1.125	1.35		0.083333
2	Air Filter Element	1	0.125	1	1.125	4.81		0.083333
3	Fuel Filter	1	0.125	1	1.125	2.89		0.083333
4	Valve cover	2	0.125		0.25	26.07		0.083333
5	Engine	1	0.125		0.125	1681.28	0.5	
6	Turbo charger	1	0.225		0.225	76.62		0.25
7	Intercooler	1	0.125		0.125	3.68		0.083333
8	Set of injectors	6	0.225		1.35	35.06		0.083333
9	Glow plugs	6	0.225	0.1	1.95	4.54		0.083333
10	Fuel injection high pressure pump	1	0.125		0.125	85.44		0.25
11	Oil pan	1	0.125		0.125	6.69		0.083333
12	Coolant radiator	1	0.125		0.125	39.30		0.083333
13	Coolant pump	1	0.225		0.225	5.85		0.083333
14	Engine flywheel	1	0.125		0.125	60.01		0.25
15	Exhaust gas system	1	0.433333	0.2	0.6333333	16.62		0.083333
16	Complete transmission	1	0.3		0.3	657.46	0.5	
17	Complete transfer case	1	0.066667		0.0666667	1154.14	0.5	
18	Steering box	1	0.125		0.125	741.18	0.5	
19	Spring front	2	0.166667	0.3333333	1	325.67	0.5	
20	Shock absorber front	2	0.166667	0.3333333	1	8.68		0.083333
21	Spring rear	2	0.166667	0.3333333	1	302.41	0.5	
22	Shock absorber rear	2	0.166667	0.3333333	1	10.10		0.083333
23	Complete rear axle	1	0.1		0.1	926.01	0.5	
24	Complete front axle	1	0.166667		0.1666667	1430.79	0.5	
25	Wheel bearing front axle	2	0.125	0.1	0.45	6.15		0.083333
26	Wheel bearing rear axle	2	0.03125	0.1	0.2625	9.56		0.083333
27	Fuel tank	1	0.125		0.125	42.67		0.083333
28	Brake shoes / brake pad front axle	1	0.125	0.5	0.625	18.88		0.083333
29	Brake shoes / brake pad rear axle	1	0.03125	0.5	0.53125	21.74		0.083333
30	Brake drum / brake disk front axle	1	0.125	0.5	0.625	24.34		0.083333
31	Brake drum / brake disk rear axle	1	0.03125	0.5	0.53125	27.28		0.083333
32	Brake calliper	4	0.05	0.1	0.6	114.44	0.25	
33	Compressor	1	0.125	0.0666667	0.1916667	32.75		0.083333
34	Evaporator	1	0.125		0.125	24.60		0.083333
35	Pump	1	0.125		0.125	2.35		0.083333
36	Alternator	1	0.125	0.1	0.225	100.00	0.25	
37	Starter	1	0.125	0.1	0.225	35.98		0.083333
38	Power steering pump	1	0.125		0.125	32.26		0.083333
39	ECU for motor management	1	0.05		0.05	101.29	0.25	
40	Windshield	1	0.125		0.125	91.59	0.25	
41	Front bumper complete	1	0.125		0.125	75.26	0.25	
42	Rear bumper complete	1	0.03125		0.03125	8.02		0.083333
43	Headlamp complete	2	0.125		0.25	16.85		0.083333
44	Mirror left or right complete including house and glasses	2	0.25		0.5	24.93		0.083333
45	Windshield(s) (set of armoured glass)	1	0.125		0.125	1691.90	0.5	
46	Side window left or right front or rear	4	0.2		0.8	640.97	0.5	
47	Vehicle door left or right front or rear	4	0.2		0.8	1349.75	0.5	
48	Driver's seat	1	0.05		0.05	516.44	0.5	
49	Co-driver seat	1	0.05		0.05	410.60	0.5	
50	Tire	4	0.125	2	8.5	85.96		0.25
51	Rim	4	0.125		0.5	126.65	0.5	

Appendix B: Model implementation

Appendix B1: Stock iteration

```
Function FindMaxCell() As Range
    ' Declarations
    Dim maxCell As Range
    Dim cell As Range
    Set maxCell = Range("H4")

    'Checks if value is higher than previous maxCell, if true, then becomes new maxCell
    For Each cell In Range("H4:H8")
        If cell.Value > maxCell.Value Then
            Set maxCell = cell
        End If
    Next cell

    'Returns the highest value in the indicated range
    Set FindMaxCell = maxCell
End Function
```

```
Sub IncrementStock()

    'Declarations
    Dim maxCell As Range
    Set maxCell = FindMaxCell()

    ' Find the max cell and increment the value in the stock range
    maxCell.Offset(0, -4).Value = maxCell.Offset(0, -4).Value + 1

End Sub
```

Appendix B2: Threshold item replacement

```
Sub ThresholdReplacement()

Dim LowestCost As Double
Dim CheapestItem As Range
Dim CheckItem As Range
Dim i As Integer


For i = 21 To 1000

    'Check if item exceeds the minimum added availability
    If Range("J" & i).Value > Range("D11").Value Then

        'Set the first item in the range as the current cheapest option
        If CheapestItem Is Nothing Then
            Set CheapestItem = Range("D" & i)
            LowestCost = Range("D" & i).Value

        'Check if any other item is cheaper
        Else
            Set CheckItem = Range("D" & i)
            If CheckItem.Value < LowestCost Then
                Set CheapestItem = CheckItem
                LowestCost = CheckItem.Value
            End If
        End If
    End If
Next i

Range("E13").Value = LowestCost

End Sub
```

Appendix B3: Multi-echelon delta calculation

The pipeline values for each workshop have been calculated for depot stock level 0.

Item	Average pipeline μ_j for $S_0 = 0$					
	A	B	C	D	E	F
Oil filter	1.110	1.166	0.777	0.999	0.777	1.499
Engine	2.527	2.654	1.769	2.275	1.769	3.412
Glow plugs	11.990	12.589	8.393	10.791	8.393	16.186
Spring rear	16.849	17.692	11.795	15.164	11.795	22.747
Oil pan	1.110	1.166	0.777	0.999	0.777	1.499

Average pipeline μ_j for $S_0 = 0$ for selected items at Workshops A through F

In turn, this allows us to find the EBO(0) and EBO(1) at the depot and the workshops.

Item	Expected backorders $EBO_j(0)$						
	DEPOT	A	B	C	D	E	F
Oil filter	5.9375	1.110	1.166	0.777	0.999	0.777	1.499
Engine	14.25	2.527	2.654	1.769	2.275	1.769	3.412
Glow plugs	64.125	11.990	12.589	8.393	10.791	8.393	16.186
Spring rear	95	16.849	17.692	11.795	15.164	11.795	22.747
Oil pan	5.9375	1.110	1.166	0.777	0.999	0.777	1.499

Expected backorders $EBO_j(0)$ for $S_0 = 0$ at Workshops A through F, and $S_0 = 0$ at the depot

Item	Expected backorders $EBO_j(1)$						
	DEPOT	A	B	C	D	E	F
Oil filter	4.9401	0.4397	0.4774	0.2368	0.3673	0.2368	0.7221
Engine	13.2500	1.6073	1.7242	0.9397	1.3775	0.9397	2.4450
Glow plugs	63.1250	10.9897	11.5892	7.3930	9.7908	7.3930	15.1861
Spring rear	94.0000	15.8493	16.6918	10.7945	14.1644	10.7945	21.7466
Oil pan	4.9401	0.4397	0.4774	0.2368	0.3673	0.2368	0.7221

Expected backorders $EBO_j(1)$ for $S_0 = 0$ at Workshops A through F, and $S_0 = 1$ at the depot

As the stock levels at the workshops are still 0 at this point, the average pipeline is equal to the expected backorders. Plugging the expected backorders into equation 2 then yields the delta value and allows us to select the 'best value' item for reducing the number of backorders, between the entire selection of items among all workshops and the depot.

Item	Delta value for item at workshop						
	DEPOT	A	B	C	D	E	F
Oil filter	0.7366	0.4952	0.5083	0.3990	0.4666	0.3990	0.5735
Engine	0.0006	0.0005	0.0006	0.0005	0.0005	0.0005	0.0006
Glow plugs	0.2202	0.2202	0.2202	0.2202	0.2202	0.2202	0.2202
Spring rear	0.0033	0.0033	0.0033	0.0033	0.0033	0.0033	0.0033
Oil pan	0.1491	0.1003	0.1029	0.0808	0.0945	0.0808	0.1161

Delta value for selected items at each location for $S_{0, A, B, C, D, E, F} = 0$

Appendix C: Single echelon results

Appendix C1: Single echelon inventory composition (scenario 1)

Component	A	B*	C	D	E*	F	Total
Oil Filter	6	6	5	6	5	7	35
Air Filter Element	5	6	5	5	5	6	32
Fuel Filter	6	6	5	5	5	7	34
Valve cover	7	7	6	6	6	8	40
Complete Engine excluded the mounted alternator and starter	8	8	6	7	6	10	45
Turbo charger	12	12	9	11	9	14	67
Intercooler	6	6	5	5	5	7	34
Set of injectors	21	21	16	19	16	26	119
Glow plugs	23	24	18	22	18	29	134
Fuel injection high pressure pump	8	8	6	7	6	9	44
Oil pan	5	5	5	5	5	6	31
Coolant radiator	4	4	4	4	4	5	25
Coolant pump	7	8	6	7	6	9	43
Engine flywheel	8	8	6 (+1)	7	6 (+1)	10	45 (+2)
Exhaust gas system complete excluding exhaust manifold	10	10	8	9	8	12	57
Complete transmission	20	21	15	18	15	26	115
Complete transfer case	5	5	4	5	4	6	29
Steering box	9	10	7	9	7	12	54
Spring front	24	25	18	22	18	30	137
Shock absorber front	9	9	7	8	7	11	51
Spring rear	24	25	18	22	18	31	138
Shock absorber rear	9	9	7	8	7	11	51
Complete rear axle	7	8	6	7	6	9	43
Complete front axle	11 (-1)	11	8	10	8	14 (-1)	62 (-2)
Wheel bearing front axle	8	8	6	7	6	9	44
Wheel bearing rear axle	4	4	3	3	3	4	21
Fuel tank	4	4	4	4	4	5	25
Brake shoes / brake pad front axle	5	5	4	4	4	6	28
Brake shoes / brake pad rear axle	2	2	2	2	2	3	13
Brake drum / brake disk front axle	5	5	4	4	4	5	27
Brake drum / brake disk rear axle	2	2	2	2	2	3	13
Brake calliper	10	11	8	9	8	13	59
Compressor	4	5	4	4	4	5	26
Evaporator	5	5	4	4	4	5	27
Pump	6	6	5	6	5	7	35
Alternator	7	8	6	7	6	9	43
Starter	4	4	4	4	4	5	25
Power steering pump	4	5	4	4	4	5	26
ECU for motor management	4	4	3	4	3	5	23
Windshield	8	8	6	7	6	9	44
Front bumper complete	8	8	6	7	6	9	44
Rear bumper complete	3	3	2	3	2	3	16
Headlamp complete	7	7	6	7	6	8	41
Mirror left or right complete including house and glasses	11	11	8	10	8	13	61
Windshield(s) (set of armoured glass)	8	8	6	7	6	10	45
Side window left or right front or rear	48	51	36 (-1)	44	36 (-1)	63	278 (-2)
Vehicle door left or right front or rear	45 (+1)	47	33	41	33	59 (+1)	258 (+2)
Driver's seat	5	5	4	5	4	6	29
Co-driver seat	5	5	4	5	4	6	29
Tire	21	22	16	19	16	26	120
Rim	36	37	27	33	27	46	206

*Already optimal, no last iteration adjustments

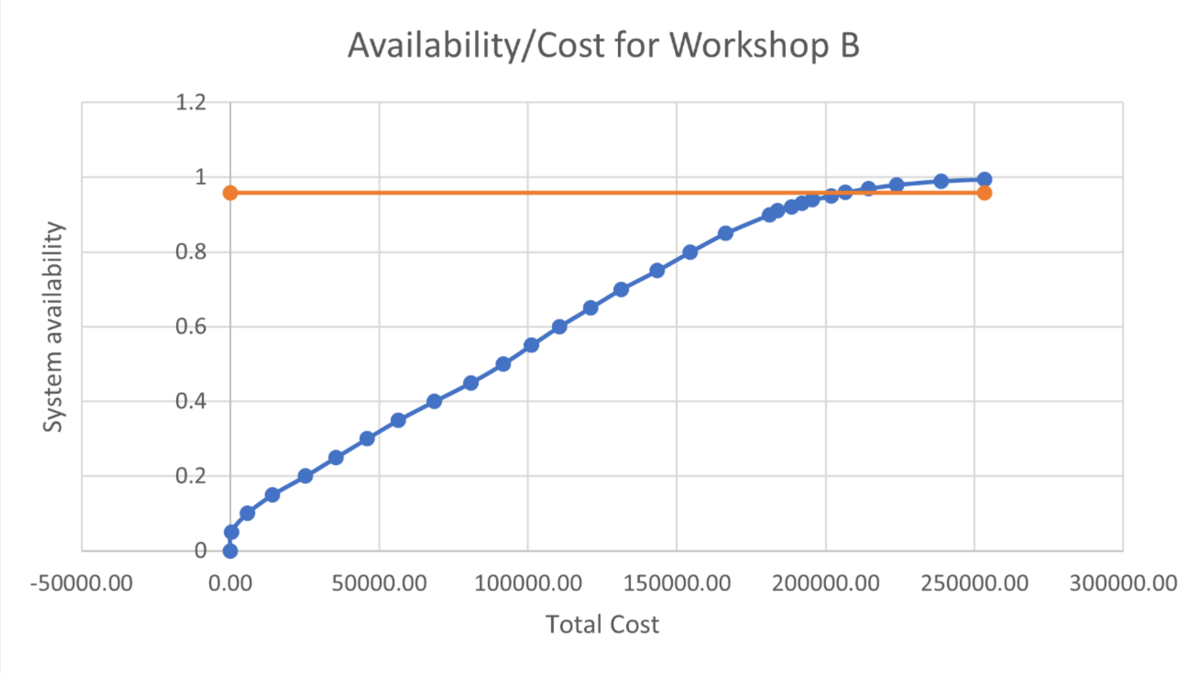
Appendix C2: Single echelon inventory composition (scenario 2)

Component	A	B*	C	D	E	F*	Total
Oil Filter	22	23	18	21	18	27	129
Air Filter Element	21	21	16	19	16	25	118
Fuel Filter	21	22	17	20	17	26	123
Valve cover	7	7	6	6	6	8	40
Complete Engine excluded the mounted alternator and starter	8	8	6	7	6	10	45
Turbo charger	12	12	9	11	9	14	67
Intercooler	6	6	5	5	5	7	34
Set of injectors	21	22	16	19	16	26	120
Glow plugs	31	32	24	28	24	38	177
Fuel injection high pressure pump	8	8	6	7	6	9	44
Oil pan	5	5	5	5	5	6	31
Coolant radiator	4	4	4	4	4	5	25
Coolant pump	7	8	6	7	6	9	43
Engine flywheel	8	8	7	8	7	10	48
Exhaust gas system complete excluding exhaust manifold	13	13	10	12	10	16	74
Complete transmission	20 (+1)	21	15	19	15	26	116 (+1)
Complete transfer case	5	5	4	5	4	6	29
Steering box	9	10	7	9	7	12	54
Spring front	62	65	46	57	46	81	357
Shock absorber front	18	19	15	17	15	22	106
Spring rear	62	65	46	57	46	81	357
Shock absorber rear	18	19	14	17	14	22	104
Complete rear axle	8 (-1)	8	6	7	6	9	44 (-1)
Complete front axle	11	11	8	10	8	14	62
Wheel bearing front axle	11	11	9	10	9	13	63
Wheel bearing rear axle	8	8	6	7	6	9	44
Fuel tank	4	4	4	4	4	5	25
Brake shoes / brake pad front axle	13	13	10	12	10	15	73
Brake shoes / brake pad rear axle	11	11	9	10	9	13	63
Brake drum / brake disk front axle	12	13	10	12	10	15	72
Brake drum / brake disk rear axle	11	11	9	10	9	13	63
Brake calliper	24	25	18	22	18	30	137
Compressor	6	6	5	5	5	7	34
Evaporator	5	5	4	4	4	5	27
Pump	6	6	5	6	5	7	35
Alternator	11	12	9	11	9	14	66
Starter	6	6	5	6	5	7	35
Power steering pump	4	5	4	4	4	5	26
ECU for motor management	4	4	4	4	4	5	25
Windshield	8	8	6	7	6	9	44
Front bumper complete	8	8	6 (+1)	7	6 (+1)	9	44 (+2)
Rear bumper complete	3	3	2	3	2	3	16
Headlamp complete	7	7	6	7	6	8	41
Mirror left or right complete including house and glasses	11	11	9	10	9	13	63
Windshield(s) (set of armoured glass)	8	8	6	7	6	10	45
Side window left or right front or rear	49	51	36	44	36	63	279
Vehicle door left or right front or rear	45	48	34 (-1)	42 (-1)	34 (-1)	60	263 (-3)
Driver's seat	5	5	4	5	4	6	29
Co-driver seat	5	5	4	5	4	6	29
Tire	246	257	178	223	178	325	1407
Rim	36	37	27	33 (+1)	27	46	206 (+1)

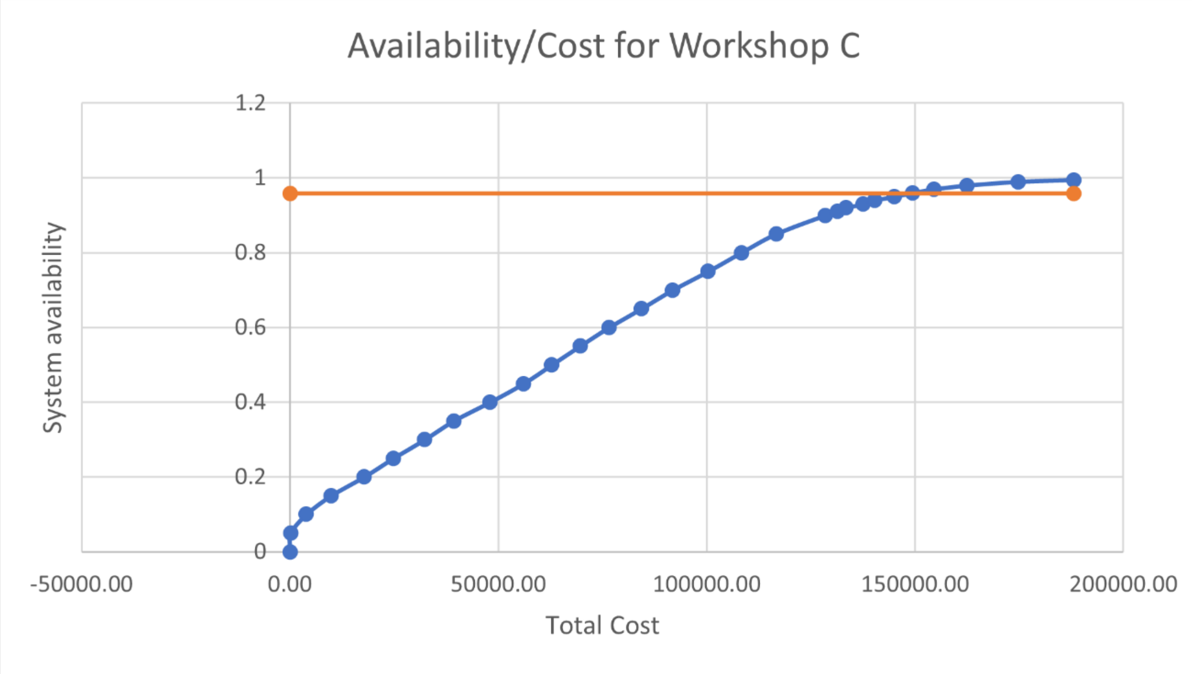
*Already optimal, no last iteration adjustments

Appendix C3: Single echelon (scenario 1) availability – cost visualisation

Availability/Cost graph for workshop B, scenario 1, single echelon.

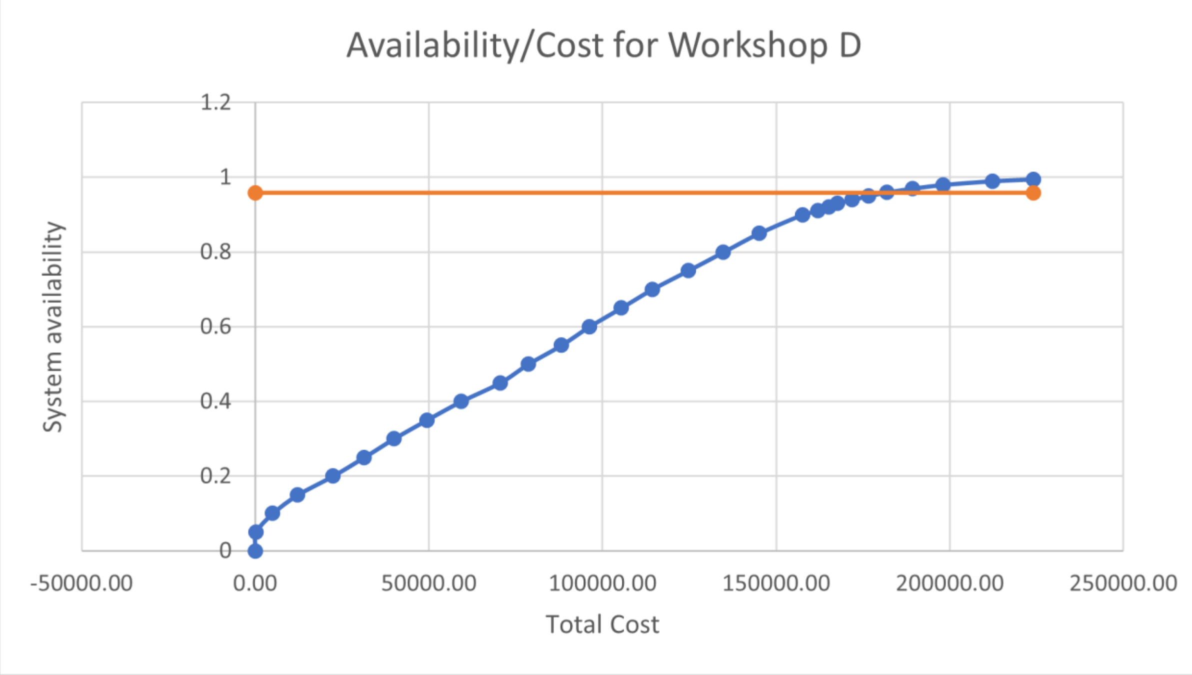


Availability/Cost graph for workshop C, scenario 1, single echelon.

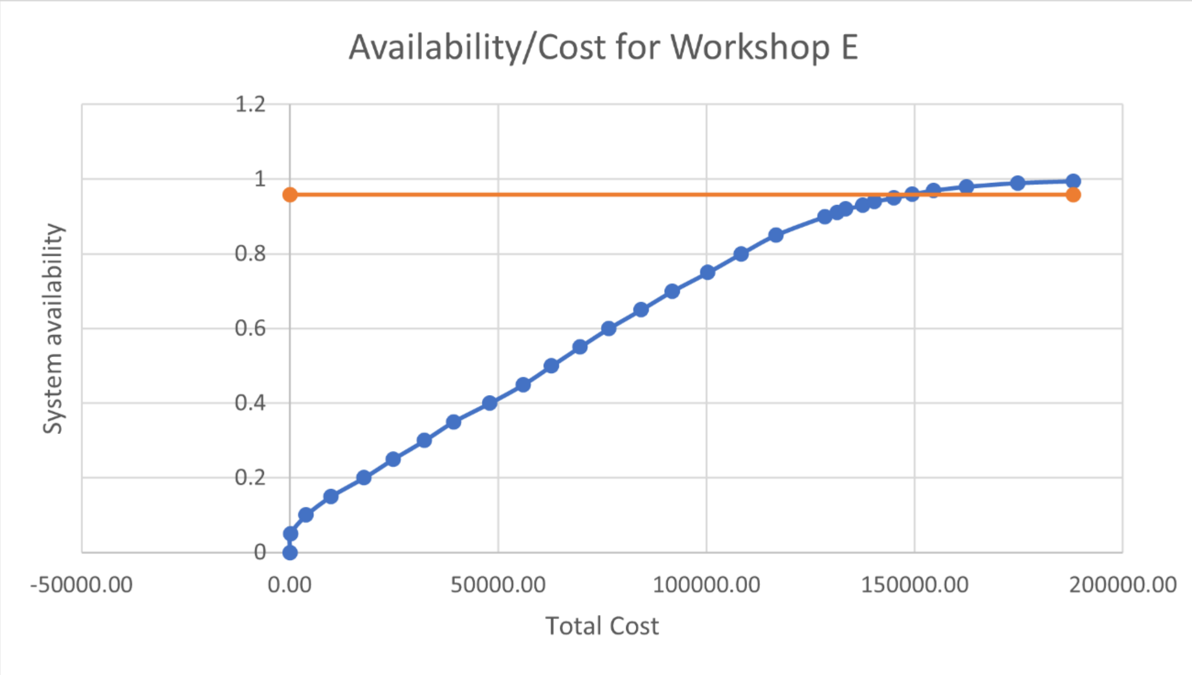


Appendix C3: Single echelon (scenario 1) availability – cost visualisation

Availability/Cost graph for workshop D, scenario 1, single echelon.

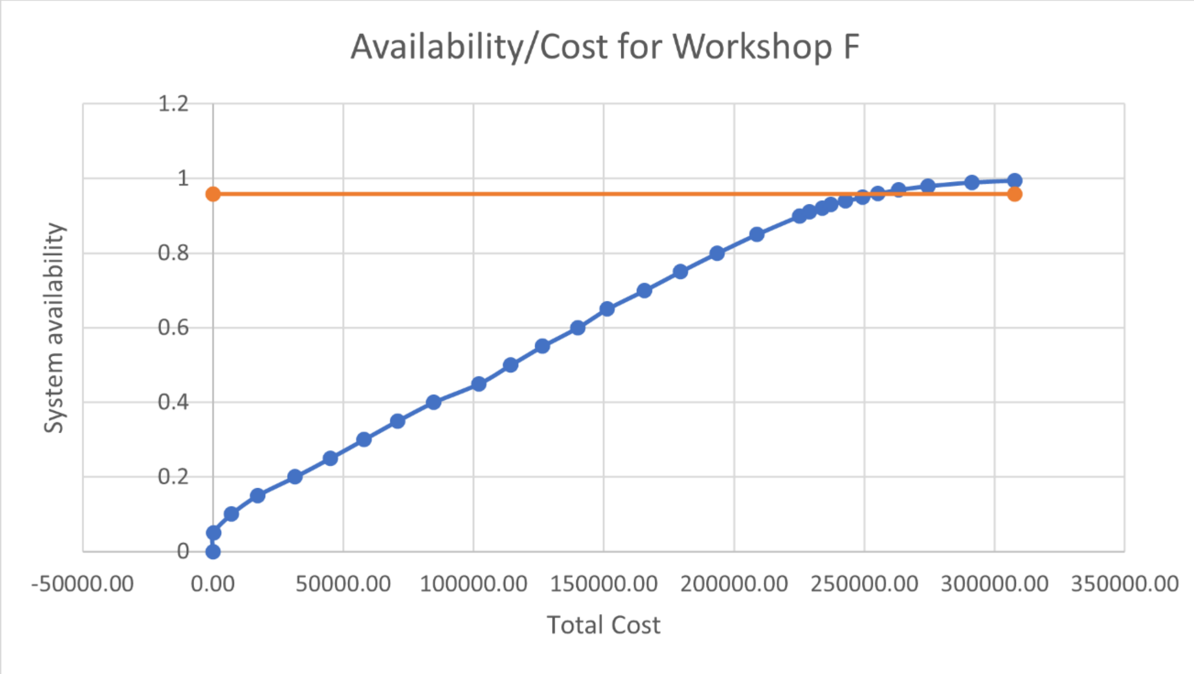


Availability/Cost graph for workshop E, scenario 1, single echelon.



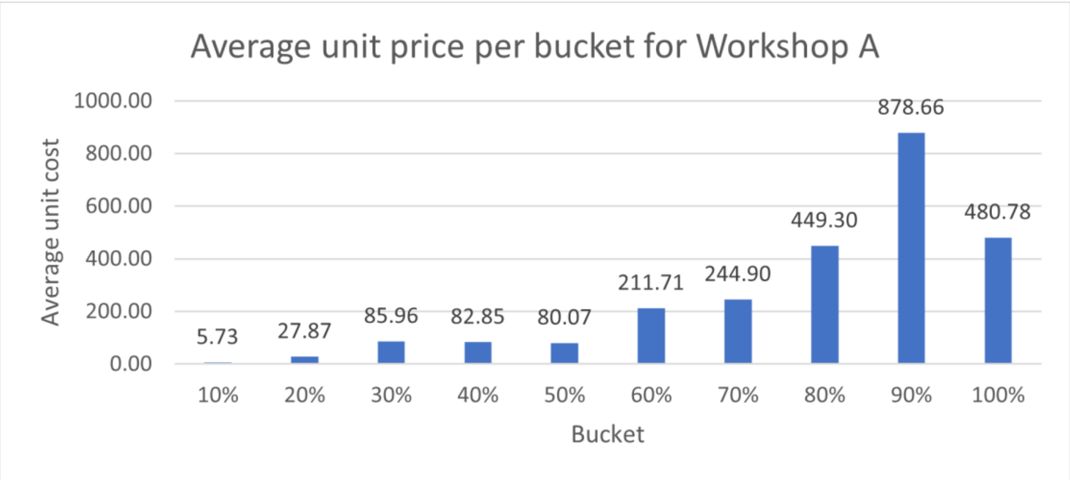
Appendix C3: Single echelon (scenario 1) availability – cost visualisation

Availability/Cost graph for workshop F, scenario 1, single echelon.



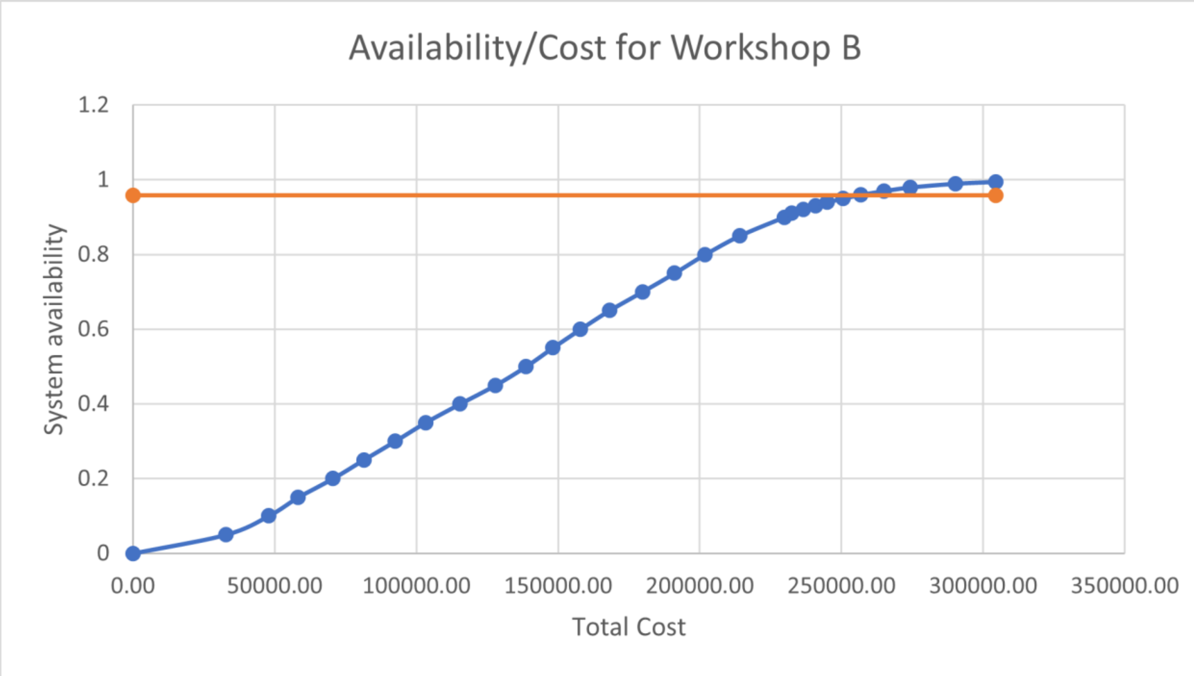
Appendix C4: Single echelon (scenario 2) availability – cost visualisation

Average price per bucket, workshop A, single echelon, scenario 2.

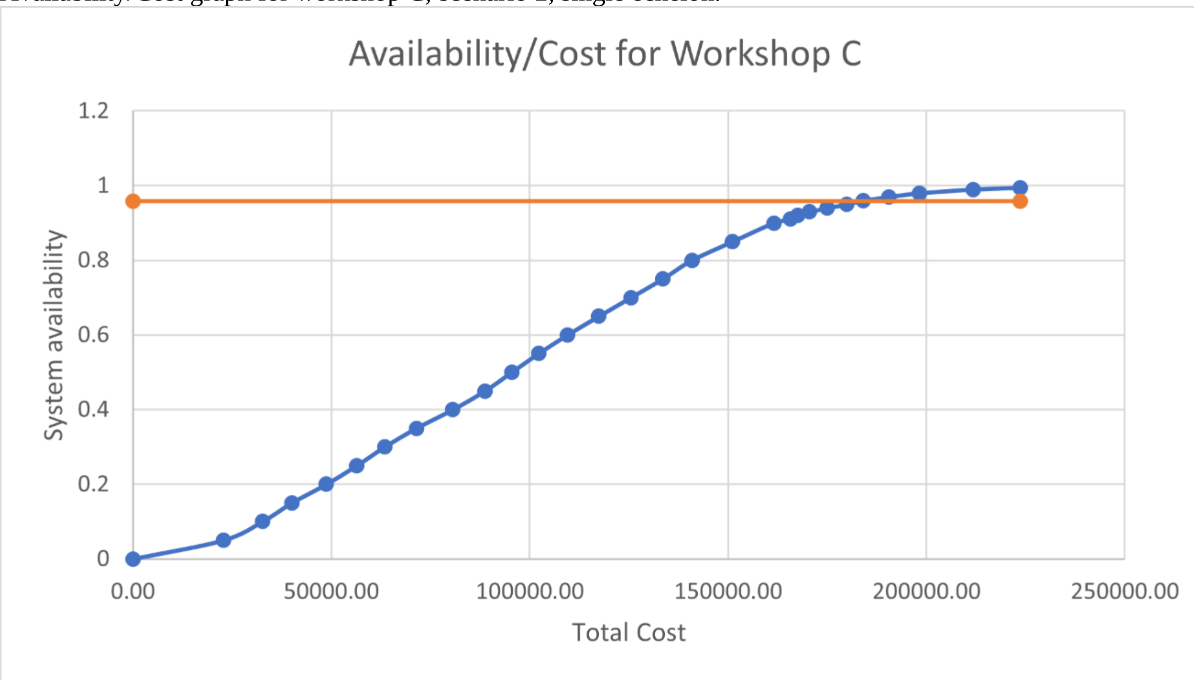


Appendix C4: Single echelon (scenario 2) availability – cost visualisation

Availability/Cost graph for workshop B, scenario 2, single echelon.

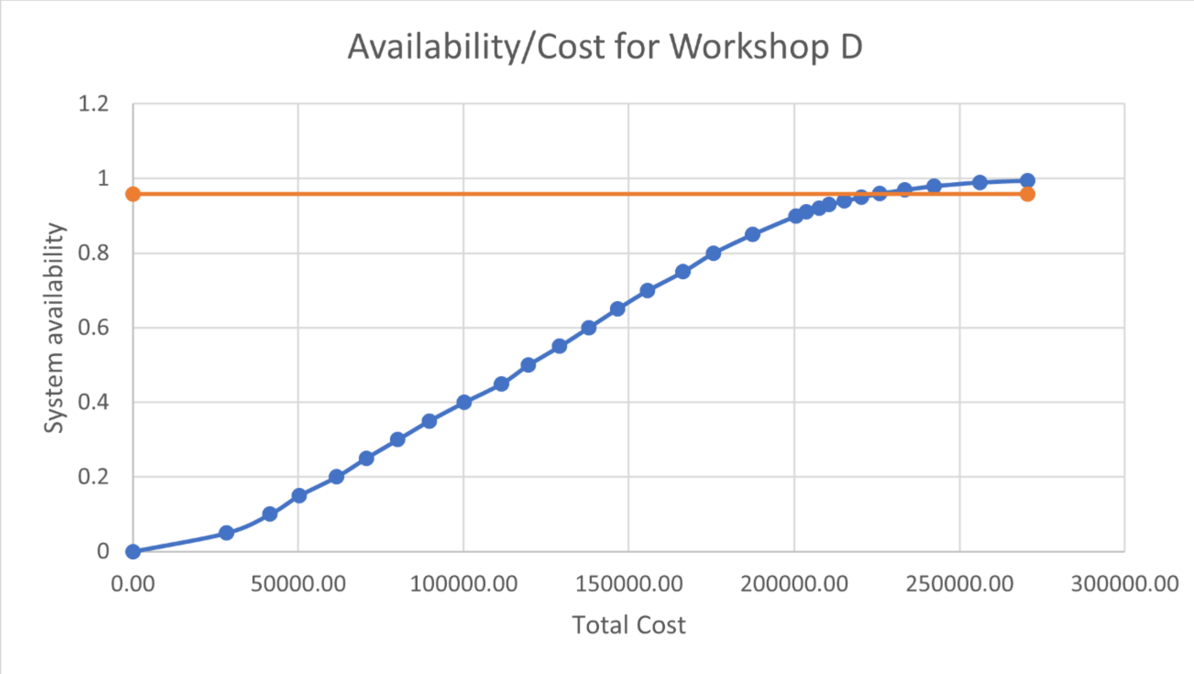


Availability/Cost graph for workshop C, scenario 2, single echelon.

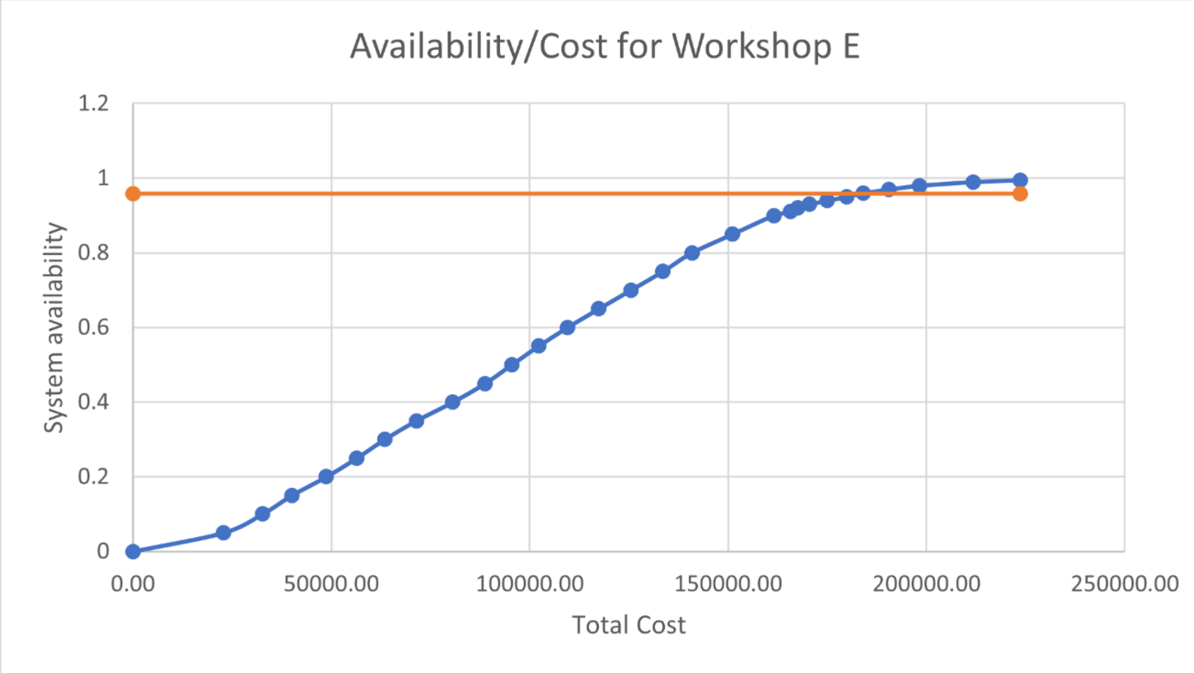


Appendix C4: Single echelon (scenario 2) availability – cost visualisation

Availability/Cost graph for workshop D, scenario 2, single echelon.

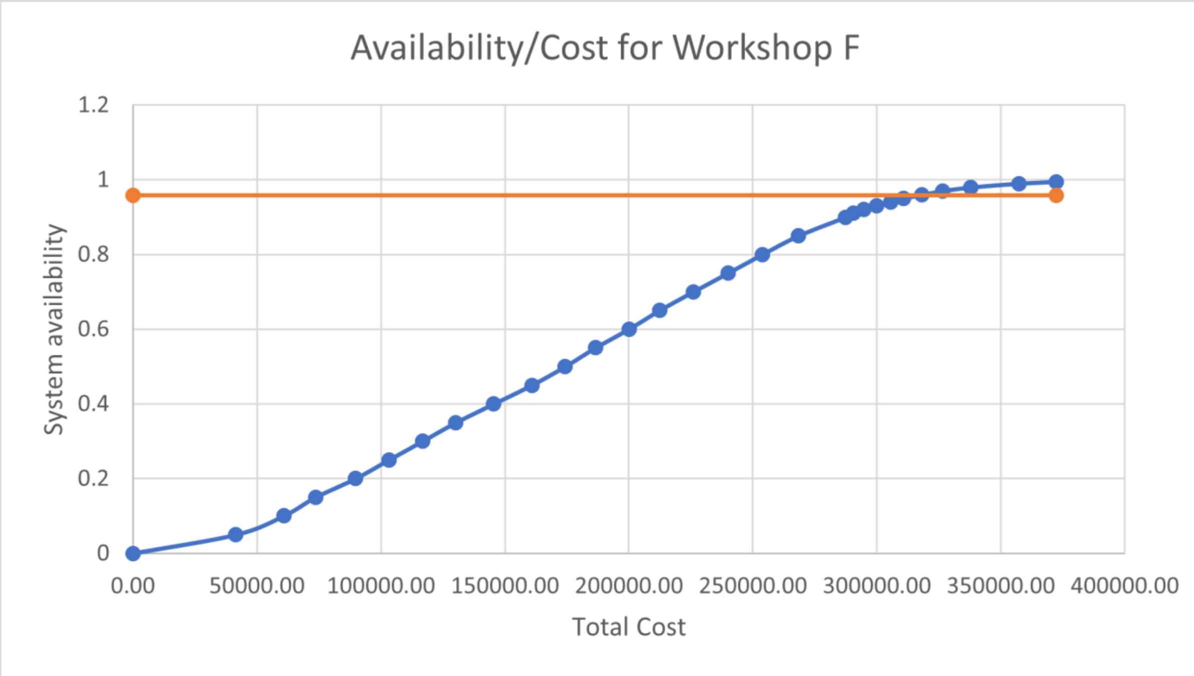


Availability/Cost graph for workshop E, scenario 2, single echelon.



Appendix C4: Single echelon (scenario 2) availability – cost visualisation

Availability/Cost graph for workshop F, scenario 2, single echelon.



Appendix C5: Last iteration threshold adjustments

Workshop	Iteration #	Att. avail.	Last iteration	New item	New avail.	Cost savings
A	974	96.4941%	Complete rear axle	Complete transmission	96.4454%	268.54
B	1010	96.4519%	Complete rear axle	*	-	-
C	745	96.6382%	Vehicle door left or right front or rear	Front bumper complete	96.4406%	1274.49
D	897	96.6185%	Vehicle door left or right front or rear	Rim	96.4411%	1223.10
E	745	96.6382%	Vehicle door left or right front or rear	Front bumper complete	96.4406%	1274.49
F	1230	96.4534%	Side window left or right front or rear	*	-	-

* Item was already optimal

Appendix C6: Iterations (scen. 1, WS A)

#	PN	Delta	Avail.	Cost	SumBO
1	1	0.07472678	3.776%	1.35	292.95
2	35	0.04297038	3.800%	2.35	292.30
3	3	0.03503703	3.825%	2.89	291.65
4	9	0.03443481	3.868%	4.54	290.65
5	9	0.03442977	3.911%	4.54	289.65
6	9	0.03440143	3.955%	4.54	288.65
7	9	0.03429514	3.997%	4.54	287.66
8	9	0.03399620	4.040%	4.54	286.67
9	9	0.03332357	4.082%	4.54	285.70
10	1	0.03228234	4.093%	1.35	285.42
11	9	0.03206240	4.133%	4.54	284.49
12	9	0.03003553	4.171%	4.54	283.62
13	7	0.02749082	4.198%	3.68	282.97
14	9	0.02718523	4.233%	4.54	282.18
15	9	0.02362236	4.263%	4.54	281.50
16	13	0.02261942	4.299%	5.85	280.65
17	25	0.02224868	4.338%	6.15	279.78
18	2	0.02102449	4.366%	4.81	279.13
19	9	0.01961413	4.392%	4.54	278.56
20	35	0.01856342	4.404%	2.35	278.28
21	20	0.01689468	4.446%	8.68	277.34
22	25	0.01565643	4.474%	6.15	276.72
23	9	0.01551480	4.495%	4.54	276.27
24	3	0.01513617	4.507%	2.89	275.99
25	11	0.01513056	4.537%	6.69	275.35
26	13	0.01493734	4.562%	5.85	274.79
27	22	0.01451739	4.606%	10.10	273.85
28	20	0.01378330	4.642%	8.68	273.09
29	7	0.01187617	4.655%	3.68	272.81
30	22	0.01184382	4.691%	10.10	272.04
31	9	0.01167168	4.708%	4.54	271.70
32	1	0.01017586	4.712%	1.35	271.61
33	20	0.00946194	4.737%	8.68	271.09
34	15	0.00915486	4.785%	16.62	270.12
35	2	0.00908269	4.798%	4.81	269.84
36	25	0.00878950	4.815%	6.15	269.49
37	9	0.00834591	4.826%	4.54	269.25
38	15	0.00823673	4.870%	16.62	268.37
39	22	0.00813053	4.896%	10.10	267.85
40	43	0.00812591	4.939%	16.85	266.97
41	13	0.00773538	4.954%	5.85	266.68
42	26	0.00663683	4.974%	9.56	266.28
43	15	0.00657900	5.009%	16.62	265.58
44	11	0.00653648	5.023%	6.69	265.30
45	44	0.00617394	5.075%	24.93	264.31
46	35	0.00585146	5.080%	2.35	264.22
47	44	0.00576882	5.128%	24.93	263.30
48	43	0.00571821	5.160%	16.85	262.69
49	9	0.00567341	5.168%	4.54	262.52
50	20	0.00546068	5.184%	8.68	262.22
51	28	0.00535929	5.218%	18.88	261.57
52	4	0.00525092	5.265%	26.07	260.70
53	44	0.00492484	5.307%	24.93	259.91
54	3	0.00477114	5.312%	2.89	259.82
55	22	0.00469230	5.328%	10.10	259.52
56	15	0.00458358	5.354%	16.62	259.03
57	42	0.00446919	5.366%	8.02	258.81
58	8	0.00445945	5.427%	35.06	257.81
59	8	0.00445880	5.487%	35.06	256.81
60	8	0.00445513	5.548%	35.06	255.81
61	8	0.00444136	5.608%	35.06	254.81
62	8	0.00440265	5.668%	35.06	253.82
63	8	0.00431554	5.726%	35.06	252.86
64	30	0.00415655	5.764%	24.34	252.21
65	8	0.00415221	5.820%	35.06	251.28
66	34	0.00411323	5.858%	24.60	250.63
67	25	0.00402079	5.868%	6.15	250.47
68	8	0.00388972	5.921%	35.06	249.60
69	44	0.00375263	5.957%	24.93	249.00
70	7	0.00374354	5.962%	3.68	248.91
71	4	0.00369508	5.999%	26.07	248.30
72	9	0.00366904	6.006%	4.54	248.19
73	8	0.00352060	6.055%	35.06	247.40
74	13	0.00323415	6.062%	5.85	247.28
75	43	0.00321020	6.083%	16.85	246.93
76	38	0.00313671	6.123%	32.26	246.29
77	33	0.00308983	6.163%	32.75	245.64
78	8	0.00305919	6.207%	35.06	244.95
79	2	0.00286299	6.212%	4.81	244.87
80	37	0.00281228	6.253%	35.98	244.22
81	15	0.00278216	6.271%	16.62	243.92
82	20	0.00268203	6.281%	8.68	243.77
83	12	0.00257443	6.322%	39.30	243.13
84	8	0.00254011	6.359%	35.06	242.56
85	44	0.00253159	6.385%	24.93	242.15
86	1	0.00250000	6.386%	1.35	242.13
87	14	0.00249124	6.449%	60.01	241.18
88	27	0.00237115	6.491%	42.67	240.53
89	28	0.00231524	6.509%	18.88	240.25
90	22	0.00230464	6.519%	10.10	240.10
91	9	0.00225971	6.523%	4.54	240.03
92	14	0.00213347	6.578%	60.01	239.22
93	4	0.00207441	6.601%	26.07	238.87
94	11	0.00206039	6.607%	6.69	238.78
95	6	0.00203346	6.676%	76.62	237.79
96	8	0.00200923	6.707%	35.06	237.34
97	6	0.00199205	6.776%	76.62	236.36
98	41	0.00198646	6.842%	75.26	235.40
99	6	0.00187561	6.908%	76.62	234.48
100	50	0.00181890	6.987%	85.96	233.48
101	50	0.00181882	7.066%	85.96	232.48
102	50	0.00181829	7.144%	85.96	231.48
103	50	0.00181608	7.223%	85.96	230.49
104	50	0.00180919	7.302%	85.96	229.49
105	30	0.00179565	7.322%	24.34	229.21
106	50	0.00179195	7.400%	85.96	228.23
107	34	0.00177693	7.421%	24.60	227.95
108	50	0.00175603	7.498%	85.96	226.98
109	10	0.00174959	7.572%	85.44	226.03
110	41	0.00170118	7.635%	75.26	225.21
111	50	0.00169190	7.710%	85.96	224.28
112	6	0.00165728	7.775%	76.62	223.46
113	29	0.00164883	7.793%	21.74	223.24
114	40	0.00163218	7.869%	91.59	222.28
115	50	0.00159170	7.942%	85.96	221.40
116	26	0.00157898	7.949%	9.56	221.31
117	14	0.00157444	7.998%	60.01	220.70
118	25	0.00153710	8.003%	6.15	220.64
119	44	0.00151405	8.022%	24.93	220.40
120	8	0.00151153	8.050%	35.06	220.06
121	10	0.00149833	8.117%	85.44	219.24
122	36	0.00149492	8.197%	100.00	218.29
123	15	0.00148113	8.210%	16.62	218.13
124	43	0.00146852	8.223%	16.85	217.97
125	50	0.00145252	8.291%	85.96	217.17
126	35	0.00143759	8.293%	2.35	217.15
127	40	0.00139777	8.363%	91.59	216.33
128	32	0.00135716	8.450%	114.44	215.34
129	38	0.00135507	8.474%	32.26	215.06
130	6	0.00135025	8.531%	76.62	214.40
131	33	0.00133482	8.555%	32.75	214.12
132	9	0.00132707	8.558%	4.54	214.08
133	31	0.00131402	8.578%	27.28	213.85
134	32	0.00131112	8.664%	114.44	212.89
135	36	0.00128023	8.736%	100.00	212.07
136	50	0.00127856	8.799%	85.96	211.37
137	41	0.00125543	8.853%	75.26	210.77
138	51	0.00123461	8.971%	126.65	209.77
139	51	0.00123461	9.089%	126.65	208.77

#	PN	Delta	Avail.	Cost	SumBO
140	51	0.00123461	9.207%	126.65	207.77
141	51	0.00123461	9.325%	126.65	206.77
142	51	0.00123461	9.443%	126.65	205.77
143	51	0.00123461	9.561%	126.65	204.77
144	51	0.00123461	9.680%	126.65	203.77
145	51	0.00123459	9.798%	126.65	202.77
146	51	0.00123452	9.916%	126.65	201.77
147	51	0.00123434	10.034%	126.65	200.77
148	51	0.00123389	10.152%	126.65	199.77
149	51	0.00123287	10.269%	126.65	198.77
150	51	0.00123073	10.387%	126.65	197.77
151	51	0.00122663	10.504%	126.65	196.78
152	51	0.00121930	10.621%	126.65	195.79
153	37	0.00121492	10.651%	35.98	195.51
154	51	0.00120709	10.767%	126.65	194.53
155	32	0.00119604	10.864%	114.44	193.66
156	51	0.00118801	10.979%	126.65	192.70
157	3	0.00117217	10.981%	2.89	192.67
158	51	0.00115995	11.093%	126.65	191.73
159	20	0.00113834	11.100%	8.68	191.67
160	13	0.00112421	11.105%	5.85	191.63
161	51	0.00112098	11.214%	126.65	190.72
162	12	0.00111217	11.245%	39.30	190.44
163	10	0.00110573	11.314%	85.44	189.84
164	39	0.00110140	11.396%	101.29	189.12
165	50	0.00108087	11.465%	85.96	188.53
166	8	0.00108083	11.493%	35.06	188.29
167	51	0.00106970	11.599%	126.65	187.42
168	40	0.00103152	11.670%	91.59	186.82
169	27	0.00102435	11.703%	42.67	186.54
170	51	0.00100560	11.804%	126.65	185.72
171	6	0.00100485	11.863%	76.62	185.23
172	32	0.00100424	11.952%	114.44	184.49
173	14	0.00099213	11.998%	60.01	184.11
174	22	0.00097816	12.005%	10.10	184.05
175	4	0.00094895	12.024%	26.07	183.89
176	36	0.00094478	12.098%	100.00	183.29
177	51	0.00092930	12.193%	126.65	182.54
178	7	0.00091971	12.196%	3.68	182.51
179	50	0.00087494	12.255%	85.96	182.03
180	51	0.00084258	12.342%	126.65	181.35
181	44	0.00080743	12.358%	24.93	181.22
182	41	0.00079110	12.406%	75.26	180.84
183	32	0.00076449	12.476%	114.44	180.28
184	51	0.00074833	12.554%	126.65	179.68
185	9	0.00074417	12.557%	4.54	179.65
186	8	0.00073473	12.578%	35.06	179.49
187	28	0.00072980	12.589%	18.88	179.40
188	2	0.00070338	12.592%	4.81	179.38
189	15	0.00069811	12.601%	16.62	179.30
190	10	0.00069677	12.649%	85.44	178.92
191	6	0.00068103	12.692%	76.62	178.59
192	50	0.00067693	12.740%	85.96	178.22
193	51	0.00065015	12.808%	126.65	177.69
194	40	0.00065001	12.858%	91.59	177.31
195	36	0.00059535	12.907%	100.00	176.93
196	30	0.00056602	12.918%	24.34	176.84
197	43	0.00056140	12.926%	16.85	176.78
198	34	0.00056012	12.937%	24.60	176.69
199	42	0.00055670	12.941%	8.02	176.66
200	51	0.00055197	13.000%	126.65	176.22
201	39	0.00054856	13.047%	101.29	175.86
202	14	0.00053720	13.074%	60.01	175.66
203	32	0.00052474	13.124%	114.44	175.27
204	21	0.00051706	13.282%	302.41	174.27
205	21	0.00051706	13.439%	302.41	173.27
206	21	0.00051706	13.597%	302.41	172.27
207	21	0.00051703	13.754%	302.41	171.27
208	21	0.00051694	13.912%	302.41	170.27
209	21	0.00051662	14.069%	302.41	169.27
210	21	0.00051573	14.226%	302.41	168.28

#	PN	Delta	Avail.	Cost	SumBO
211	21	0.00051361	14.383%	302.41	167.28
212	21	0.00050920	14.538%	302.41	166.30
213	11	0.00050620	14.541%	6.69	166.28
214	25	0.00050222	14.544%	6.15	166.26
215	1	0.00050108	14.544%	1.35	166.25
216	21	0.00050103	14.697%	302.41	165.28
217	50	0.00050014	14.738%	85.96	165.01
218	21	0.00048741	14.887%	302.41	164.07
219	19	0.00048013	15.065%	325.67	163.07
220	19	0.00048013	15.244%	325.67	162.07
221	19	0.00048012	15.423%	325.67	161.07
222	19	0.00048010	15.601%	325.67	160.07
223	19	0.00048001	15.780%	325.67	159.07
224	19	0.00047972	15.958%	325.67	158.07
225	19	0.00047889	16.137%	325.67	157.07
226	19	0.00047692	16.314%	325.67	156.08
227	8	0.00047516	16.331%	35.06	155.97
228	19	0.00047283	16.507%	325.67	154.98
229	21	0.00046678	16.666%	302.41	154.08
230	19	0.00046524	16.841%	325.67	153.11
231	51	0.00045757	16.904%	126.65	152.74
232	19	0.00045260	17.075%	325.67	151.80
233	21	0.00043813	17.227%	302.41	150.95
234	19	0.00043344	17.392%	325.67	150.05
235	41	0.00042835	17.428%	75.26	149.84
236	38	0.00042714	17.443%	32.26	149.76
237	20	0.00042366	17.447%	8.68	149.73
238	6	0.00042082	17.484%	76.62	149.53
239	33	0.00042076	17.499%	32.75	149.44
240	19	0.00040684	17.655%	325.67	148.59
241	21	0.00040140	17.798%	302.41	147.81
242	9	0.00039903	17.800%	4.54	147.80
243	44	0.00038682	17.811%	24.93	147.74
244	37	0.00038296	17.826%	35.98	147.65
245	10	0.00037727	17.863%	85.44	147.45
246	19	0.00037273	18.008%	325.67	146.67
247	51	0.00037015	18.062%	126.65	146.37
248	22	0.00036405	18.067%	10.10	146.35
249	4	0.00036277	18.078%	26.07	146.29
250	21	0.00035767	18.207%	302.41	145.59
251	50	0.00035282	18.242%	85.96	145.40
252	40	0.00035195	18.280%	91.59	145.19
253	12	0.00035057	18.296%	39.30	145.11
254	49	0.00034956	18.469%	410.60	144.19
255	13	0.00033298	18.471%	5.85	144.18
256	19	0.00033212	18.603%	325.67	143.48
257	32	0.00032494	18.647%	114.44	143.25
258	27	0.00032289	18.664%	42.67	143.16
259	36	0.00032236	18.702%	100.00	142.95
260	21	0.00030908	18.817%	302.41	142.35
261	15	0.00029416	18.823%	16.62	142.32
262	8	0.00029264	18.835%	35.06	142.26
263	51	0.00029211	18.880%	126.65	142.02
264	35	0.00028814	18.881%	2.35	142.02
265	19	0.00028701	18.997%	325.67	141.42
266	48	0.00027792	19.176%	516.44	140.50
267	49	0.00027141	19.315%	410.60	139.79
268	26	0.00026184	19.318%	9.56	139.77
269	21	0.00025847	19.416%	302.41	139.27
270	14	0.00025286	19.435%	60.01	139.17
271	46	0.00024395	19.759%	640.97	138.17
272	46	0.00024395	20.083%	640.97	137.17
273	46	0.00024395	20.407%	640.97	136.17
274	46	0.00024395	20.731%	640.97	135.17
275	46	0.00024395	21.055%	640.97	134.17
276	46	0.00024395	21.379%	640.97	133.17
277	46	0.00024395	21.703%	640.97	132.17
278	46	0.00024395	22.027%	640.97	131.17
279	46	0.00024395	22.351%	640.97	130.17
280	46	0.00024395	22.674%	640.97	129.17
281	46	0.00024395	22.998%	640.97	128.17

#	PN	Delta	Avail.	Cost	SumBO
282	46	0.00024395	23.322%	640.97	127.17
283	46	0.00024395	23.646%	640.97	126.17
284	46	0.00024395	23.970%	640.97	125.17
285	46	0.00024395	24.294%	640.97	124.17
286	46	0.00024395	24.618%	640.97	123.17
287	46	0.00024394	24.942%	640.97	122.17
288	46	0.00024394	25.266%	640.97	121.17
289	46	0.00024393	25.590%	640.97	120.17
290	46	0.00024390	25.914%	640.97	119.18
291	46	0.00024386	26.237%	640.97	118.18
292	46	0.00024377	26.561%	640.97	117.18
293	46	0.00024361	26.885%	640.97	116.18
294	46	0.00024332	27.208%	640.97	115.18
295	46	0.00024285	27.530%	640.97	114.18
296	46	0.00024210	27.852%	640.97	113.19
297	46	0.00024094	28.171%	640.97	112.20
298	19	0.00024001	28.315%	325.67	111.70
299	46	0.00023923	28.634%	640.97	110.72
300	6	0.00023786	28.668%	76.62	110.61
301	16	0.00023783	29.005%	657.46	109.61
302	16	0.00023783	29.342%	657.46	108.61
303	16	0.00023782	29.680%	657.46	107.61
304	16	0.00023778	30.017%	657.46	106.61
305	50	0.00023772	30.056%	85.96	106.48
306	16	0.00023762	30.394%	657.46	105.48
307	16	0.00023716	30.730%	657.46	104.48
308	46	0.00023678	31.070%	640.97	103.51
309	16	0.00023601	31.408%	657.46	102.52
310	3	0.00023494	31.410%	2.89	102.51
311	16	0.00023354	31.745%	657.46	101.53
312	46	0.00023340	32.087%	640.97	100.57
313	16	0.00022892	32.419%	657.46	99.61
314	46	0.00022890	32.757%	640.97	98.67
315	51	0.00022483	32.817%	126.65	98.49
316	46	0.00022308	33.148%	640.97	97.58
317	16	0.00022121	33.476%	657.46	96.65
318	46	0.00021582	33.799%	640.97	95.76
319	48	0.00021579	34.044%	516.44	95.05
320	18	0.00021056	34.406%	741.18	94.05
321	16	0.00020965	34.726%	657.46	93.17
322	21	0.00020885	34.868%	302.41	92.77
323	18	0.00020801	35.231%	741.18	91.78
324	46	0.00020701	35.554%	640.97	90.93
325	29	0.00020538	35.564%	21.74	90.90
326	9	0.00020489	35.566%	4.54	90.90
327	39	0.00020304	35.613%	101.29	90.77
328	41	0.00020163	35.648%	75.26	90.67
329	18	0.00020006	36.001%	741.18	89.72
330	46	0.00019665	36.311%	640.97	88.91
331	19	0.00019393	36.460%	325.67	88.51
332	16	0.00019389	36.770%	657.46	87.69
333	46	0.00018481	37.066%	640.97	86.94
334	7	0.00018434	37.068%	3.68	86.93
335	18	0.00018349	37.401%	741.18	86.06
336	43	0.00018343	37.408%	16.85	86.04
337	32	0.00018223	37.458%	114.44	85.91
338	28	0.00017930	37.467%	18.88	85.89
339	10	0.00017758	37.503%	85.44	85.79
340	16	0.00017418	37.787%	657.46	85.06
341	49	0.00017372	37.961%	410.60	84.60
342	8	0.00017186	37.976%	35.06	84.56
343	46	0.00017165	38.257%	640.97	83.86
344	51	0.00016876	38.310%	126.65	83.72
345	44	0.00016775	38.320%	24.93	83.70
346	23	0.00016772	38.721%	926.01	82.70
347	40	0.00016567	38.758%	91.59	82.61
348	31	0.00016368	38.769%	27.28	82.58
349	21	0.00016290	38.893%	302.41	82.26
350	23	0.00016203	39.281%	926.01	81.30
351	18	0.00015759	39.582%	741.18	80.56
352	46	0.00015743	39.849%	640.97	79.91

#	PN	Delta	Avail.	Cost	SumBO
353	50	0.00015309	39.883%	85.96	79.83
354	36	0.00015174	39.921%	100.00	79.73
355	16	0.00015144	40.183%	657.46	79.09
356	19	0.00015127	40.311%	325.67	78.78
357	23	0.00014781	40.675%	926.01	77.90
358	25	0.00014289	40.677%	6.15	77.90
359	46	0.00014246	40.923%	640.97	77.31
360	2	0.00014098	40.925%	4.81	77.31
361	20	0.00014006	40.928%	8.68	77.30
362	30	0.00013906	40.937%	24.34	77.28
363	48	0.00013812	41.126%	516.44	76.82
364	34	0.00013761	41.135%	24.60	76.80
365	17	0.00013065	41.545%	1154.14	75.84
366	46	0.00012710	41.768%	640.97	75.32
367	16	0.00012708	41.996%	657.46	74.78
368	18	0.00012523	42.250%	741.18	74.19
369	23	0.00012410	42.567%	926.01	73.45
370	51	0.00012355	42.610%	126.65	73.35
371	6	0.00012351	42.636%	76.62	73.29
372	21	0.00012260	42.737%	302.41	73.06
373	22	0.00012036	42.741%	10.10	73.05
374	4	0.00011853	42.749%	26.07	73.03
375	47	0.00011585	43.462%	1349.75	72.03
376	47	0.00011585	44.174%	1349.75	71.03
377	47	0.00011585	44.887%	1349.75	70.03
378	47	0.00011585	45.599%	1349.75	69.03
379	47	0.00011585	46.312%	1349.75	68.03
380	47	0.00011585	47.024%	1349.75	67.03
381	47	0.00011585	47.737%	1349.75	66.03
382	47	0.00011585	48.449%	1349.75	65.03
383	47	0.00011585	49.162%	1349.75	64.03
384	47	0.00011585	49.874%	1349.75	63.03
385	47	0.00011585	50.587%	1349.75	62.03
386	47	0.00011585	51.299%	1349.75	61.03
387	47	0.00011585	52.012%	1349.75	60.03
388	47	0.00011585	52.724%	1349.75	59.03
389	47	0.00011585	53.437%	1349.75	58.03
390	47	0.00011585	54.149%	1349.75	57.03
391	47	0.00011584	54.862%	1349.75	56.03
392	47	0.00011584	55.574%	1349.75	55.03
393	47	0.00011584	56.286%	1349.75	54.03
394	47	0.00011583	56.999%	1349.75	53.03
395	47	0.00011580	57.711%	1349.75	52.03
396	47	0.00011576	58.423%	1349.75	51.03
397	47	0.00011568	59.134%	1349.75	50.03
398	47	0.00011555	59.845%	1349.75	49.03
399	47	0.00011533	60.554%	1349.75	48.04
400	47	0.00011497	61.262%	1349.75	47.05
401	17	0.00011454	61.792%	1154.14	46.20
402	47	0.00011442	62.502%	1349.75	45.21
403	19	0.00011385	62.651%	325.67	44.98
404	47	0.00011361	63.358%	1349.75	43.99
405	47	0.00011244	64.057%	1349.75	43.02
406	15	0.00011183	64.064%	16.62	43.01
407	46	0.00011175	64.365%	640.97	42.55
408	47	0.00011084	65.058%	1349.75	41.60
409	24	0.00010926	65.768%	1430.79	40.60
410	24	0.00010904	66.476%	1430.79	39.60
411	47	0.00010870	67.170%	1349.75	38.66
412	24	0.00010813	67.879%	1430.79	37.67
413	47	0.00010594	68.563%	1349.75	36.76
414	24	0.00010559	69.263%	1430.79	35.79
415	38	0.00010494	69.278%	32.26	35.77
416	14	0.00010477	69.305%	60.01	35.73
417	33	0.00010337	69.320%	32.75	35.71
418	16	0.00010272	69.625%	657.46	35.28
419	47	0.00010249	70.296%	1349.75	34.39
420	11	0.00010146	70.299%	6.69	34.39
421	9	0.00010088	70.301%	4.54	34.38
422	24	0.00010031	70.976%	1430.79	33.47
423	47	0.00009831	71.626%	1349.75	32.62

#	PN	Delta	Avail.	Cost	SumBO
424	46	0.00009677	71.916%	640.97	32.22
425	8	0.00009637	71.932%	35.06	32.20
426	23	0.00009448	72.340%	926.01	31.64
427	50	0.00009431	72.378%	85.96	31.59
428	37	0.00009409	72.394%	35.98	31.57
429	47	0.00009339	73.018%	1349.75	30.76
430	32	0.00009304	73.068%	114.44	30.69
431	5	0.00009282	73.846%	1681.28	29.69
432	49	0.00009232	74.025%	410.60	29.45
433	45	0.00009224	74.813%	1691.90	28.45
434	5	0.00009170	75.592%	1681.28	27.47
435	24	0.00009152	76.248%	1430.79	26.63
436	18	0.00009151	76.582%	741.18	26.20
437	45	0.00009112	77.379%	1691.90	25.21
438	21	0.00008902	77.513%	302.41	25.04
439	51	0.00008822	77.569%	126.65	24.97
440	5	0.00008819	78.337%	1681.28	24.02
441	47	0.00008776	78.966%	1349.75	23.26
442	17	0.00008769	79.485%	1154.14	22.61
443	45	0.00008764	80.273%	1691.90	21.67
444	12	0.00008613	80.290%	39.30	21.64
445	13	0.00008572	80.293%	5.85	21.64
446	1	0.00008464	80.293%	1.35	21.64
447	41	0.00008354	80.326%	75.26	21.60
448	19	0.00008266	80.465%	325.67	21.43
449	46	0.00008250	80.741%	640.97	21.09
450	47	0.00008152	81.339%	1349.75	20.39
451	5	0.00008089	82.071%	1681.28	19.52
452	45	0.00008038	82.809%	1691.90	18.65
453	16	0.00007988	83.091%	657.46	18.31
454	27	0.00007933	83.109%	42.67	18.29
455	24	0.00007930	83.728%	1430.79	17.56
456	47	0.00007476	84.292%	1349.75	16.92
457	10	0.00007358	84.326%	85.44	16.88
458	48	0.00007340	84.531%	516.44	16.63
459	5	0.00006947	85.179%	1681.28	15.89
460	46	0.00006923	85.424%	640.97	15.60
461	45	0.00006904	86.078%	1691.90	14.86
462	40	0.00006864	86.112%	91.59	14.82
463	47	0.00006765	86.634%	1349.75	14.23
464	44	0.00006633	86.643%	24.93	14.22
465	23	0.00006485	86.979%	926.01	13.84
466	24	0.00006475	87.504%	1430.79	13.25
467	36	0.00006287	87.540%	100.00	13.21
468	21	0.00006236	87.646%	302.41	13.08
469	51	0.00006146	87.689%	126.65	13.04
470	18	0.00006141	87.946%	741.18	12.74
471	47	0.00006036	88.419%	1349.75	12.22
472	16	0.00005973	88.643%	657.46	11.97
473	6	0.00005919	88.668%	76.62	11.94
474	39	0.00005907	88.702%	101.29	11.90
475	19	0.00005791	88.810%	325.67	11.78
476	17	0.00005785	89.192%	1154.14	11.36
477	46	0.00005716	89.403%	640.97	11.12
478	50	0.00005565	89.431%	85.96	11.09
479	5	0.00005521	89.971%	1681.28	10.50
480	45	0.00005486	90.514%	1691.90	9.90
481	47	0.00005307	90.940%	1349.75	9.45
482	43	0.00005219	90.945%	16.85	9.44
483	8	0.00005168	90.955%	35.06	9.43
484	24	0.00004960	91.373%	1430.79	8.98
485	35	0.00004867	91.374%	2.35	8.97
487	42	0.00004726	91.378%	8.02	8.97
488	46	0.00004644	91.553%	640.97	8.97
489	47	0.00004595	91.924%	1349.75	8.78
490	32	0.00004349	91.953%	114.44	8.38
491	16	0.00004293	92.120%	657.46	8.35
492	21	0.00004217	92.195%	302.41	8.17
493	51	0.00004178	92.226%	126.65	8.09
494	20	0.00004159	92.229%	8.68	8.06
495	49	0.00004144	92.329%	410.60	8.05
#	**PN**	**Delta**	**Avail.**	**Cost**	**SumBO**
496	5	0.00004034	92.734%	1681.28	7.51
497	23	0.00004016	92.956%	926.01	7.27
498	45	0.00004009	93.363%	1691.90	6.84
499	3	0.00003968	93.364%	2.89	6.84
500	47	0.00003918	93.685%	1349.75	6.50
501	19	0.00003916	93.762%	325.67	6.42
502	15	0.00003867	93.766%	16.62	6.42
503	14	0.00003866	93.780%	60.01	6.40
504	18	0.00003789	93.949%	741.18	6.22
505	46	0.00003711	94.092%	640.97	6.07
506	25	0.00003595	94.094%	6.15	6.07
507	28	0.00003594	94.098%	18.88	6.06
508	22	0.00003574	94.100%	10.10	6.06
509	24	0.00003557	94.409%	1430.79	5.74
510	4	0.00003372	94.414%	26.07	5.73
511	26	0.00003317	94.416%	9.56	5.73
512	17	0.00003299	94.647%	1154.14	5.48
513	48	0.00003295	94.750%	516.44	5.38
514	47	0.00003287	95.023%	1349.75	5.09
515	50	0.00003148	95.039%	85.96	5.07
516	7	0.00003114	95.040%	3.68	5.07
517	41	0.00003083	95.054%	75.26	5.06
518	16	0.00002968	95.173%	657.46	4.93
519	46	0.00002917	95.287%	640.97	4.81
520	30	0.00002787	95.292%	24.34	4.81
521	51	0.00002773	95.313%	126.65	4.79
522	34	0.00002758	95.317%	24.60	4.78
523	21	0.00002754	95.368%	302.41	4.73
524	10	0.00002715	95.382%	85.44	4.71
525	47	0.00002714	95.608%	1349.75	4.48
526	5	0.00002707	95.888%	1681.28	4.19
527	45	0.00002690	96.169%	1691.90	3.90
528	8	0.00002690	96.17%	35.06	3.89
529	6	0.00002653	96.19%	76.62	3.88
530	19	0.00002629	96.24%	325.67	3.87
531	40	0.00002557	96.25%	91.59	3.81
532	44	0.00002533	96.26%	24.93	3.81
533	24	0.00002407	96.47%	1430.79	3.59

Appendix D: Two-echelon results

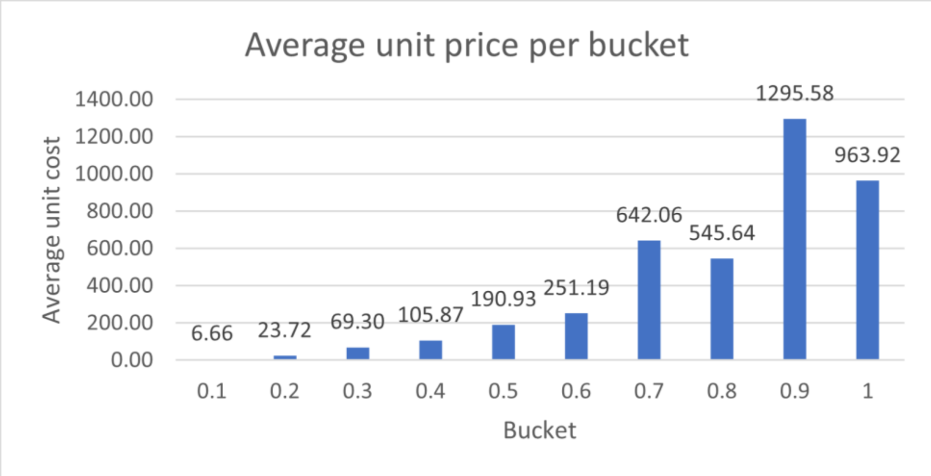
Appendix D1: Two-echelon inventory composition (scenario 1)

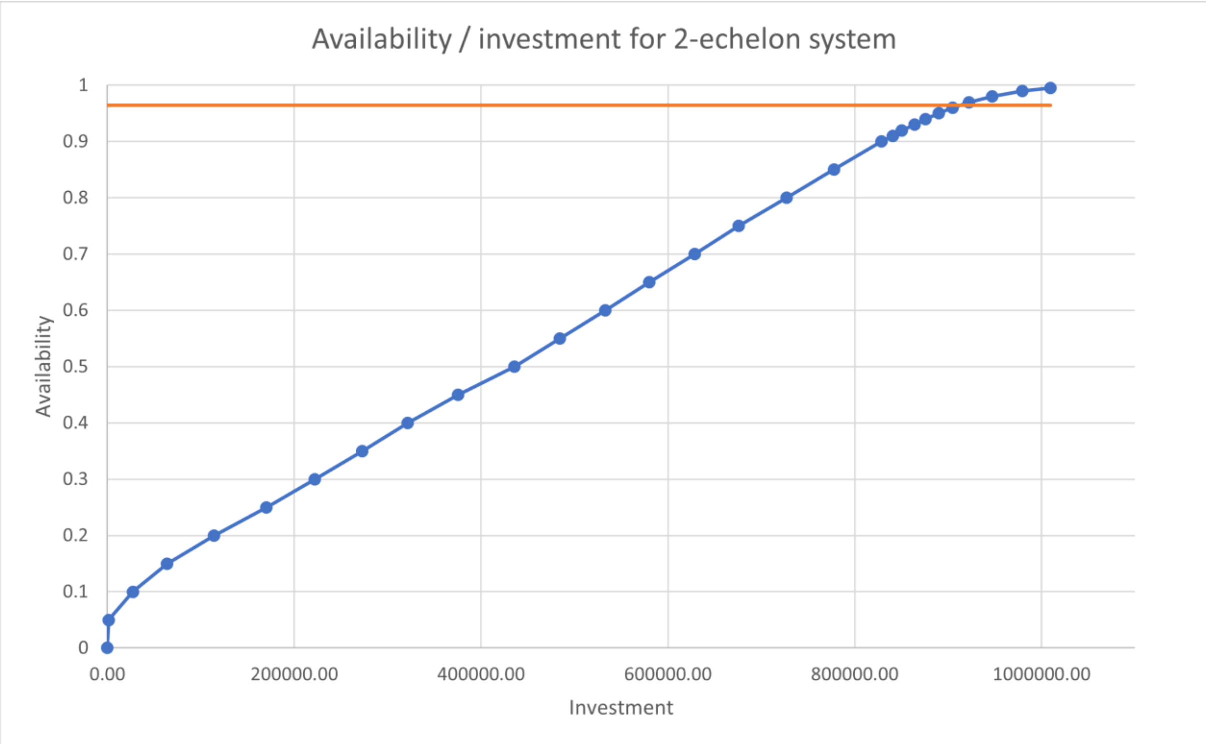
Component	Depot	A	B	C	D	E	F	Total
Oil Filter	10	2	2	2	2	2	2	22
Air Filter Element	10	2	2	1	2	1	2	20
Fuel Filter	10	2	2	2	2	2	2	22
Valve cover	15	2	2	2	2	2	2	27
Engine	14	0	0	0	0	0	0	14
Turbo charger	37	1	2	1	1	1	2	45
Intercooler	10	2	2	2	2	2	2	22
Set of injectors	66	4	4	3	4	3	5	89
Glow plugs	68	5	5	4	5	4	6	97
Fuel injection high pressure pump	21	1	1	1	1	1	1	27
Oil pan	10	2	2	1	2	1	2	20
Coolant radiator	9	1	1	1	1	1	1	15
Coolant pump	14	2	2	2	2	2	2	26
Engine flywheel	22	1	1	1	1	1	1	28
Exhaust gas system	24	2	3	2	2	2	3	38
Complete transmission	86	1	1	1	1	1	2	93
Complete transfer case	20	0	0	0	0	0	0	20
Steering box	36	1	1 (+1)	1	1	1	1	42 (+1)
Spring front	96	2	2	1	2	1	2	106
Shock absorber front	20	2	2	2	2	2	3	33
Spring rear	97	2	2	1	2	1	2	107
Shock absorber rear	19	2	2	2	2	2	3	32
Complete rear axle	30	0	0	0	0	0	1	31
Complete front axle	44 (-1)	1	1	1	1	1	1	50 (-1)
Wheel bearing front axle	15	2	2	2	2	2	3	28
Wheel bearing rear axle	6	1	1	1	1	1	1	12
Fuel tank	9	1	1	1	1	1	1	15
Brake shoes / brake pad front axle	9	1	1	1	1	1	2	16
Brake shoes / brake pad rear axle	4	1	1	1	1	1	1	10
Brake drum / brake disk front axle	9	1	1	1	1	1	1	15
Brake drum / brake disk rear axle	4	1	1	1	1	1	1	10
Brake calliper	32	1	1	1	1	1	2	39
Compressor	9	1	1	1	1	1	1	15
Evaporator	9	1	1	1	1	1	1	15
Pump	10	2	2	2	2	2	2	22
Alternator	21	1	1	1	1	1	1	27
Starter	9	1	1	1	1	1	1	15
Power steering pump	9	1	1	1	1	1	1	15
ECU for motor management	11	1	1	0	1	0	1	15
Windshield	21	1	1	1	1	1	1	27
Front bumper complete	22	1	1	1	1	1	1	28
Rear bumper complete	4	1	1	1	1	1	1	10
Headlamp complete	15	2	2	2	2	2	2	27
Mirror left or right complete including house and glasses	27	3	3	2	2	2	3	42
Windshield(s) (set of armoured glass)	34	0	0	0	0	0	1	35
Side window left or right front or rear	213	5	5	3	4	3	9	242
Vehicle door left or right front or rear	204	5	5	3	4	3	9	233
Driver's seat	18	0	0	0	0	0	0	18
Co-driver seat	18	0	0	0	0	0	0	18
Tire	75	2	2	2	2	2	3	88
Rim	144	3	3	2	3	2	4	161

Appendix D2: Two-echelon inventory composition (scenario 2)

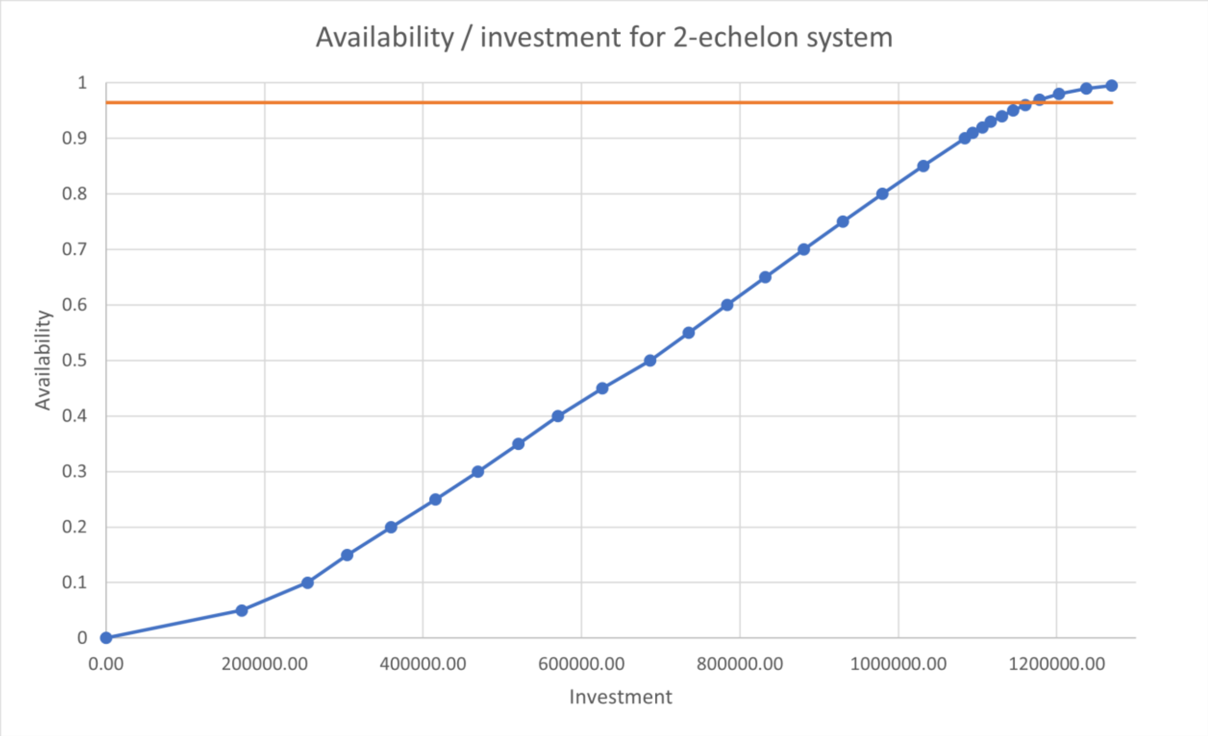
Component	Depot	A	B	C	D	E	F	Total
Oil Filter	58	5	5	4	5	4	6	87
Air Filter Element	57	5	5	4	4	4	5	84
Fuel Filter	57	5	5	4	5	4	6	86
Valve cover	15	2	2	2	2	2	2	27
Engine	14	0	0	0	0	0	0	14
Turbo charger	37	1	2	1	1	1	2	45
Intercooler	10	2	2	2	2	2	2	22
Set of injectors	66	4	4	3	4	3	5	89
Glow plugs	97	6	6	5	6	5	7	132
Fuel injection high pressure pump	21	1	1	1	1	1	1	27
Oil pan	10	2	2	1	2	1	2	20
Coolant radiator	9	1	1	1	1	1	1	15
Coolant pump	14	2	2	2	2	2	2	26
Engine flywheel	22	1	1	1	1	1	1	28
Exhaust gas system	34	3	3	2	3	2	3	50
Complete transmission	86	1	1	1	1	1	2	93
Complete transfer case	20	0	0	0	0	0	0	20
Steering box	36	1	1	1	1	1	1	42
Spring front	251	10	11	7	9	7	16	311
Shock absorber front	51	4	4	3	4	3	5	74
Spring rear	252	10	11	7	9	7	16	312
Shock absorber rear	51	4	4	3	4	3	5	74
Complete rear axle	30	0	0	0	0	0	1	31
Complete front axle	44	1	1	1	1	1	1	50
Wheel bearing front axle	25	3	3	3	3	3	3	43
Wheel bearing rear axle	16	2	2	2	2	2	2	28
Fuel tank	9	1	1	1	1	1	1	15
Brake shoes / brake pad front axle	33	3	3	2	3	2	3	49
Brake shoes / brake pad rear axle	28	3	3	2	3	2	3	44
Brake drum / brake disk front axle	33	3	3	2	3	2	3	49
Brake drum / brake disk rear axle	28	3	3	2	2	2	3	43
Brake calliper	87	3	3	2	3	2	3	103
Compressor	13	1	1	1	1	1	2	20
Evaporator	9	1	1	1	1	1	1	15
Pump	10	2	2	2	2	2	2	22
Alternator	37	1	1	1	1	1	2	44
Starter	14	2	2	1	1	1	2	23
Power steering pump	9	1	1	1	1	1	1	15
ECU for motor management	11	1	1	1	1	1	1	17
Windshield	21	1	1	1	1	1	1	27
Front bumper complete	22	1	1	1	1	1	1	28
Rear bumper complete	4	1	1	1	1	1	1	10
Headlamp complete	15	2	2	2	2	2	2	27
Mirror left or right complete including house and glasses	27	3	3	2	2	2	3	42
Windshield(s) (set of armoured glass)	34	0	0	0	0	0	1	35
Side window left or right front or rear	213	5	5	3	4	3	9	242
Vehicle door left or right front or rear	205	5	5	3	4	3	9	234
Driver's seat	18	0	0	0	0	0	0	18
Co-driver seat	19 (-1)	0	0	0	0	0	0	19 (-1)
Tire	598	133	139	96	121	96	179	1362
Rim	144 (+1)	3	3	2	3	2	4	161 (+1)

Appendix D3: Two-echelon (scenario 1) availability – cost visualisation





Appendix D4: Two-echelon (scenario 2) availability – cost visualisation



Appendix D5: Two-echelon adjusted inventory composition (scenario 1)

Component	Depot	A	B	C	D	E	F	Total
Oil Filter	10	2	2	2	2	2	2	22
Air Filter Element	10	2	2	1	2	1	2	20
Fuel Filter	10	2	2	2	2	2	2	22
Valve cover	15	2	2	2	2	2	2	27
Engine	9	1	1	1	1	1	1	15
Turbo charger	37	1	1	1	1	1	2	44
Intercooler	10	2	2	2	2	2	2	22
Set of injectors	66	4	4	3	4	3	5	89
Glow plugs	68	5	5	4	5	4	6	97
Fuel injection high pressure pump	21	1	1	1	1	1	1	27
Oil pan	10	2	2	1	2	1	2	20
Coolant radiator	9	1	1	1	1	1	1	15
Coolant pump	14	2	2	2	2	2	2	26
Engine flywheel	22	1	1	1	1	1	1	28
Exhaust gas system	24	2	3	2	2	2	3	38
Complete transmission	81	2	2	1	2	1	4	93
Complete transfer case	16	1	1	1	1	1	1	22
Steering box	34 (-1)	1	1	1	1	1	2	41 (-1)
Spring front	90	3	3	2	3	2	5	108
Shock absorber front	20	2	2	2	2	2	3	33
Spring rear	90	3	3	2	3	2	5	108
Shock absorber rear	19	2	2	2	2	2	3	32
Complete rear axle	25	1	1	1	1	1	2	32
Complete front axle	41	1	1	1	1	1	3	49
Wheel bearing front axle	15	2	2	2	2	2	3	28
Wheel bearing rear axle	6	1	1	1	1	1	1	12
Fuel tank	9	1	1	1	1	1	1	15
Brake shoes / brake pad front axle	9	1	1	1	1	1	2	16
Brake shoes / brake pad rear axle	3	1	1	1	1	1	1	9
Brake drum / brake disk front axle	9	1	1	1	1	1	1	15
Brake drum / brake disk rear axle	2	1	1	1	1	1	1	8
Brake calliper	32	1	1	1	1	1	2	39
Compressor	9	1	1	1	1	1	1	15
Evaporator	9	1	1	1	1	1	1	15
Pump	10	2	2	2	2	2	2	22
Alternator	21	1	1	1	1	1	1	27
Starter	9	1	1	1	1	1	1	15
Power steering pump	9	1	1	1	1	1	1	15
ECU for motor management	8	1	1	1	1	1	1	14
Windshield	21	1	1	1	1	1	1	27
Front bumper complete	22	1	1	1	1	1	1	28
Rear bumper complete	3	1	1	1	1	1	1	9
Headlamp complete	15	2	2	2	2	2	2	27
Mirror left or right complete including house and glasses	27	2	3	2	2	2	3	41
Windshield(s) (set of armoured glass)	29	1	1	1	1	1	2	36
Side window left or right front or rear	202	7	7	5	6	5	11	243
Vehicle door left or right front or rear	195	6	7	4	6	4	11	233
Driver's seat	13 (+1)	1	1	1	1	1	1	19 (+1)
Co-driver seat	14	1	1	1	1	1	1	20
Tire	72	3	3	2	3	2	4	89
Rim	138	4	4	3	4	3	7	163

Appendix D6: Two-echelon adjusted inventory composition (scenario 2)

Component	Depot	A	B	C	D	E	F	Total
Oil Filter	58	5	5	4	5	4	6	87
Air Filter Element	57	5	5	4	4	4	5	84
Fuel Filter	57	5	5	4	5	4	6	86
Valve cover	15	2	2	2	2	2	2	27
Engine	9	1	1	1	1	1	1	15
Turbo charger	37	1	2	1	1	1	2	45
Intercooler	10	2	2	2	2	2	2	22
Set of injectors	66	4	4	3	4	3	5	89
Glow plugs	97	6	6	5	6	5	7	132
Fuel injection high pressure pump	21	1	1	1	1	1	1	27
Oil pan	10	2	2	1	2	1	2	20
Coolant radiator	9	1	1	1	1	1	1	15
Coolant pump	14	2	2	2	2	2	2	26
Engine flywheel	22	1	1	1	1	1	1	28
Exhaust gas system	34	3	3	2	3	2	3	50
Complete transmission	81	2	2	2	2	2	4	95
Complete transfer case	16	1	1	1	1	1	1	22
Steering box	34	1	1	1	1	1	2	41
Spring front	251	10	11	7	9	7	16	311
Shock absorber front	51	4	4	3	4	3	5	74
Spring rear	252	10	11	7	9	7	16	312
Shock absorber rear	51	4	4	3	4	3	5	74
Complete rear axle	25	1	1	1	1	1	2	32
Complete front axle	41 (-1)	1	1	1	1	1	3	49 (-1)
Wheel bearing front axle	25	3	3	3	3	3	3	43
Wheel bearing rear axle	16	2	2	2	2	2	2	28
Fuel tank	9	1	1	1	1	1	1	15
Brake shoes / brake pad front axle	33	3	3	2	3	2	3	49
Brake shoes / brake pad rear axle	28	3	3	2	3	2	3	44
Brake drum / brake disk front axle	33	3	3	2	3	2	3	49
Brake drum / brake disk rear axle	28	3	3	2	2	2	3	43
Brake calliper	86	3	3	2	3	2	4	103
Compressor	13	1	1	1	1	1	2	20
Evaporator	9	1	1	1	1	1	1	15
Pump	10	2	2	2	2	2	2	22
Alternator	37	1	1	1	1	1	2	44
Starter	14	2	2	1	1	1	2	23
Power steering pump	9	1	1	1	1	1	1	15
ECU for motor management	9	1	1	1	1	1	1	15
Windshield	21	1	1	1	1	1	1	27
Front bumper complete	22	1	1	1	1	1	1	28
Rear bumper complete	3	1	1	1	1	1	1	9
Headlamp complete	15	2	2	2	2	2	2	27
Mirror left or right complete including house and glasses	27	3	3	2	2	2	3	42
Windshield(s) (set of armoured glass)	29	1	1	1	1	1	2	36
Side window left or right front or rear	203	7	7	5	6	5	11	244
Vehicle door left or right front or rear	196	6	7	4	6 (+1)	4	11	234 (+1)
Driver's seat	13	1	1	1	1	1	1	19
Co-driver seat	14	1	1	1	1	1	1	20
Tire	597	133	139	96	121	96	179	1361
Rim	138	4	4	3	4	3	7	163

Appendix E: Model analysis

Appendix E1: Investment required for several levels of availability.

Single echelon, scenario 1			
Days of availability	**Indexed investment (millions)**	**Ratio**	**Availability**
350	1.135	1 : 14.6	95.8988%
352	1.155	1 : 14.4	96.4515%
354	1.180	1 : 14.1	97.0016%
356	1.208	1 : 13.8	97.5493%
358	1.240	1 : 13.4	98.0903%
360	1.283	1 : 13.0	98.6389%
362	1.343	1 : 12.4	99.1803%
364	1.463	1 : 11.4	99.7268%

Single echelon, scenario 2			
Days of availability	**Indexed investment (millions)**	**Ratio**	**Availability**
350	1.407	1 : 11.8	95.9097%
352	1.429	1 : 11.6	96.4468%
354	1.454	1 : 11.4	96.9910%
356	1.483	1 : 11.2	97.5450%
358	1.518	1 : 11.0	98.0875%
360	1.561	1 : 10.7	98.6376%
362	1.627	1 : 10.2	99.1831%
364	1.752	1 : 9.5	99.7282%

Two echelon, scenario 1			
Days of availability	**Indexed investment (millions)**	**Ratio**	**Availability**
350	0.911	1 : 18.3	95.89%
352	0.920	1 : 18.1	96.44%
354	0.929	1 : 17.9	96.99%
356	0.941	1 : 17.7	97.54%
358	0.954	1 : 17.4	98.09%
360	0.969	1 : 17.2	98.63%
362	0.992	1 : 16.8	99.18%
364	1.034	1 : 16.1	99.73%

Two echelon, scenario 2			
Days of availability	**Indexed investment (millions)**	**Ratio**	**Availability**
350	1.165	1 : 14.3	95.8978%
352	1.175	1 : 14.2	96.4395%
354	1.185	1 : 14.0	96.9863%
356	1.197	1 : 13.9	97.5391%
358	1.210	1 : 13.7	98.0840%
360	1.227	1 : 13.5	98.6322%
362	1.250	1 : 13.3	99.1785%
364	1.295	1 : 12.8	99.7261%

Appendix E2: Availability across workshops for varying degrees of allowed unavailability

Single echelon scenario 1						
A	**B**	**C**	**D**	**E**	**F**	**Average**
95.89%	95.91%	95.89%	95.89%	95.89%	95.91%	95.90%
96.44%	96.46%	96.44%	96.45%	96.44%	96.47%	96.45%
96.99%	97.01%	96.99%	97.03%	96.99%	97.00%	97.00%
97.55%	97.54%	97.56%	97.56%	97.56%	97.54%	97.55%
98.09%	98.11%	98.09%	98.09%	98.09%	98.08%	98.09%
98.65%	98.64%	98.64%	98.63%	98.64%	98.63%	98.64%
99.18%	99.18%	99.18%	99.19%	99.18%	99.18%	99.18%
99.73%	99.73%	99.73%	99.73%	99.73%	99.73%	99.73%

Single echelon scenario 2						
A	**B**	**C**	**D**	**E**	**F**	**Average**
95.94%	95.92%	95.89%	95.91%	95.89%	95.90%	95.91%
96.45%	96.45%	96.44%	96.44%	96.44%	96.45%	96.45%
96.99%	96.99%	96.99%	96.99%	96.99%	97.00%	96.99%
97.57%	97.54%	97.54%	97.54%	97.54%	97.54%	97.55%
98.08%	98.08%	98.10%	98.08%	98.10%	98.09%	98.09%
98.63%	98.63%	98.63%	98.63%	98.63%	98.66%	98.64%
99.18%	99.19%	99.18%	99.18%	99.18%	99.18%	99.18%
99.73%	99.73%	99.73%	99.73%	99.73%	99.73%	99.73%

Two-echelon scenario 1						
A	**B**	**C**	**D**	**E**	**F**	**Average**
95.28%	95.46%	95.04%	95.73%	95.04%	97.68%	95.89%
95.89%	96.05%	95.62%	96.28%	95.62%	98.13%	96.44%
96.48%	96.68%	96.30%	96.69%	96.30%	98.51%	96.99%
97.09%	97.20%	97.02%	97.34%	97.02%	98.80%	97.54%
97.73%	97.83%	97.63%	97.97%	97.63%	99.12%	98.09%
98.44%	98.31%	98.47%	98.40%	98.47%	99.35%	98.63%
99.06%	98.98%	99.05%	99.02%	99.05%	99.66%	99.18%
99.69%	99.68%	99.67%	99.65%	99.67%	99.90%	99.73%

Two-echelon scenario 1						
A	**B**	**C**	**D**	**E**	**F**	**Average**
95.32%	95.58%	94.93%	95.62%	94.93%	97.77%	95.90%
95.84%	96.08%	95.73%	96.10%	95.73%	98.13%	96.44%
96.78%	96.92%	96.24%	96.59%	96.24%	98.24%	96.99%
97.11%	97.32%	96.94%	97.30%	96.94%	98.81%	97.54%
97.71%	97.85%	97.90%	97.86%	97.51%	99.10%	98.08%
98.47%	98.39%	98.38%	98.38%	98.38%	99.37%	98.63%
99.05%	99.01%	99.04%	99.00%	99.04%	99.67%	99.18%
99.69%	99.68%	99.70%	99.71%	99.70%	99.83%	99.73%

Appendix E3: Investment ratio across workshops for varying levels of demand

Multiplication factor	**Investment (Millions)**	**Ratio**	**Investment (Millions)**	**Ratio**
0.5	0.599	27.74	0.466	35.69
0.75	0.883	18.83	0.692	24.03
1	1.155	14.39	0.911	18.25
1.25	1.424	11.67	1.149	14.47
1.5	1.690	9.84	1.384	12.01

Appendix E4: Item cost and share of total investment, single echelon.

Items with a share of investment above 5% are highlighted.

Item	Scenario 1		Scenario 2	
	Cost	% of total	Cost	% of total
Oil Filter	47.39344	0.004%	174.6787	0.012%
Air Filter Element	154.0107	0.013%	567.9144	0.049%
Fuel Filter	98.19245	0.009%	355.2256	0.031%
Valve cover	1042.812	0.090%	1042.812	0.090%
Engine	75657.75	6.550%	75657.75	6.550%
Turbo charger	5133.377	0.444%	5133.377	0.444%
Intercooler	125.1462	0.011%	125.1462	0.011%
Set of injectors	4172.461	0.361%	4207.524	0.364%
Glow plugs	608.4623	0.053%	803.7152	0.070%
Fuel injection high pressure pump	3759.546	0.325%	3759.546	0.325%
Oil pan	207.3162	0.018%	207.3162	0.018%
Coolant radiator	982.6203	0.085%	982.6203	0.085%
Coolant pump	251.6637	0.022%	251.6637	0.022%
Engine flywheel	2820.338	0.244%	2880.345	0.249%
Exhaust gas system	947.2371	0.082%	1229.746	0.106%
Complete transmission	75608.45	6.546%	76923.37	6.659%
Complete transfer case	33470.16	2.898%	33470.16	2.898%
Steering box	40023.53	3.465%	40023.53	3.465%
Spring front	44616.58	3.863%	116263.6	10.065%
Shock absorber front	442.6635	0.038%	920.0457	0.080%
Spring rear	41732.09	3.613%	107959.1	9.346%
Shock absorber rear	515.1515	0.045%	1050.505	0.091%
Complete rear axle	39818.4	3.447%	39818.4	3.447%
Complete front axle	85847.36	7.432%	88708.94	7.680%
Wheel bearing front axle	270.7258	0.023%	387.6302	0.034%
Wheel bearing rear axle	200.8584	0.017%	420.8462	0.036%
Fuel tank	1066.861	0.092%	1066.861	0.092%
Brake shoes / brake pad front axle	528.6612	0.046%	1378.295	0.119%
Brake shoes / brake pad rear axle	282.6485	0.024%	1369.758	0.119%
Brake drum / brake disk front axle	657.2896	0.057%	1752.772	0.152%
Brake drum / brake disk rear axle	354.6674	0.031%	1718.773	0.149%
Brake calliper	6751.779	0.585%	15677.86	1.357%
Compressor	851.462	0.074%	1113.45	0.096%
Evaporator	664.2133	0.058%	664.2133	0.058%
Pump	82.41861	0.007%	82.41861	0.007%
Alternator	4300	0.372%	6600	0.571%
Starter	899.5137	0.078%	1259.319	0.109%
Power steering pump	838.7372	0.073%	838.7372	0.073%
ECU for motor management	2329.742	0.202%	2532.328	0.219%
Windshield	4029.997	0.349%	4029.997	0.349%
Front bumper complete	3311.249	0.287%	3461.76	0.300%
Rear bumper complete	128.3422	0.011%	128.3422	0.011%
Headlamp complete	690.7058	0.060%	690.7058	0.060%
Mirror left or right complete including house and glasses	1520.946	0.132%	1570.813	0.136%
Windshield(s) (set of armoured glass)	76135.66	6.591%	76135.66	6.591%
Side window left or right front or rear	176907.7	15.315%	178830.7	15.482%
Vehicle door left or right front or rear	350933.7	30.381%	350933.7	30.381%
Driver's seat	14976.67	1.297%	14976.67	1.297%
Co-driver seat	11907.26	1.031%	11907.26	1.031%
Tire	10315.79	0.893%	120952.6	10.471%
Rim	26089.66	2.259%	26216.31	2.270%

Appendix E5: Item cost and share of total investment, two echelon.

Items with a share of investment above 5% are highlighted.

Item	Scenario 1		Scenario 2	
	Cost	% of total	Cost	% of total
Oil Filter	29.79016	0.003%	117.8065485	0.010%
Air Filter Element	96.25668	0.008%	404.2780749	0.035%
Fuel Filter	63.53629	0.006%	248.3691403	0.022%
Valve cover	703.8981	0.061%	703.8981143	0.061%
Engine	25219.25	2.183%	25219.25134	2.183%
Turbo charger	3371.173	0.292%	3447.790599	0.298%
Intercooler	80.97695	0.007%	80.97695218	0.007%
Set of injectors	3120.58	0.270%	3120.580417	0.270%
Glow plugs	440.4541	0.038%	599.380805	0.052%
Fuel injection high pressure pump	2306.994	0.200%	2306.99409	0.200%
Oil pan	133.7524	0.012%	133.7523845	0.012%
Coolant radiator	589.5722	0.051%	589.5721925	0.051%
Coolant pump	152.1687	0.013%	152.1687463	0.013%
Engine flywheel	1680.201	0.145%	1680.201395	0.145%
Exhaust gas system	631.4914	0.055%	830.9097164	0.072%
Complete transmission	61144.22	5.293%	62459.15033	5.407%
Complete transfer case	25391.16	2.198%	25391.15927	2.198%
Steering box	29647.06	2.567%	30388.23529	2.631%
Spring front	35172.19	3.045%	101282.8877	8.768%
Shock absorber front	286.4293	0.025%	642.2960253	0.056%
Spring rear	32659.89	2.827%	94350.80214	8.168%
Shock absorber rear	323.2323	0.028%	747.4747475	0.065%
Complete rear axle	29632.3	2.565%	29632.29821	2.565%
Complete front axle	70108.68	6.069%	68677.88723	5.946%
Wheel bearing front axle	172.2801	0.015%	264.5729743	0.023%
Wheel bearing rear axle	114.7762	0.010%	267.8112393	0.023%
Fuel tank	640.1163	0.055%	640.1163336	0.055%
Brake shoes / brake pad front axle	302.0921	0.026%	925.1571442	0.080%
Brake shoes / brake pad rear axle	195.6797	0.017%	956.6563467	0.083%
Brake drum / brake disk front axle	365.1609	0.032%	1192.85893	0.103%
Brake drum / brake disk rear axle	218.2569	0.019%	1173.130688	0.102%
Brake calliper	4463.041	0.386%	11787.00472	1.020%
Compressor	491.2281	0.043%	654.9707602	0.057%
Evaporator	369.0074	0.032%	369.0074116	0.032%
Pump	51.80599	0.004%	51.80598555	0.004%
Alternator	2700	0.234%	4400	0.381%
Starter	539.7082	0.047%	827.5526159	0.072%
Power steering pump	483.8869	0.042%	483.8868562	0.042%
ECU for motor management	1418.104	0.123%	1519.396754	0.132%
Windshield	2472.952	0.214%	2472.952435	0.214%
Front bumper complete	2107.158	0.182%	2107.15827	0.182%
Rear bumper complete	72.19251	0.006%	72.19251337	0.006%
Headlamp complete	454.8551	0.039%	454.8550521	0.039%
Mirror left or right complete including house and glasses	1022.275	0.089%	1047.208931	0.091%
Windshield(s) (set of armoured glass)	60908.53	5.273%	60908.528	5.273%
Side window left or right front or rear	155755.7	13.484%	156396.6976	13.540%
Vehicle door left or right front or rear	314490.6	27.226%	317190.1054	27.460%
Driver's seat	10328.74	0.894%	9812.299465	0.849%
Co-driver seat	8211.902	0.711%	8211.902305	0.711%
Tire	7650.877	0.662%	116998.2456	10.129%
Rim	20643.76	1.787%	20643.76114	1.787%