TRUCK INVENTORY REPLENISHMENT PROCESS OPTIMIZATION AT REMONDIS SMART INFRA

INDUSTRIAL ENGINEERING & MANAGEMENT

MASTER THESIS
SPECIALIZATION PRODUCTION & LOGISTICS MANAGEMENT
ORIENTATION SUPPLY CHAIN & TRANSPORTATION MANAGEMENT

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MANAGEMENT SUMMARY

Context
Research is performed at the company called REMONDIS Smart Infra. Its primary business model revolves around building, renovating, cleaning, inspecting, and repairing the sewers and corresponding installations, such as barrages and pumping stations, that transport either wastewater from people's homes towards the municipal purification plants or rain- and surface-water away from crucial road infrastructure and structurally through various waterways, which is being adhered to across its four eldest establishments by its three main divisions: service and maintenance, construction and renovation, and cleaning and inspection. As REMONDIS Smart Infra continues to expand its number of establishments across the country, REMONDIS Smart Infra's ambition is to serve an increasing number of clients to become the eventual market leader in the Dutch sewage sector.

REMONDIS Smart Infra faces a resource capacity allocation problem concerning a completely exhausted resource capacity of its service and maintenance trucks due to the productive time of the service and maintenance mechanics being lower than the norm, which limits REMONDIS Smart Infra from achieving its ambition. The main contributor to this problem concerns the inefficient and ineffective inventory replenishment process for the service and maintenance trucks, which is a crucial process to enable the mechanics to properly perform the service and maintenance-related services. Currently, the mechanics spend a significant amount of time traveling towards and being at the warehouse to replenish their truck inventory. They cannot dedicate this time to providing value to any client. Optimizing the entire truck inventory replenishment process for the service and maintenance trucks in terms of efficiency and effectiveness has the potential to significantly improve the total productive time of mechanics per day and during that time mechanics would be capable of serving more clients.

Therefore, the research objective entails designing the entire inventory replenishment process for the service and maintenance trucks aiming to minimize the downtime of the corresponding mechanics caused by this process. So, the main research question to be answered is formulated as follows.

"How can the truck inventory replenishment process for the service and maintenance trucks of REMONDIS Smart Infra be optimized in terms of efficiency and effectiveness?"

Method
After clarifying and analysing REMONDIS Smart Infra's current truck inventory replenishment process by means of quantitative data analyses, interviews on expert opinions and a structured literature review, the optimization of REMONDIS Smart Infra's truck inventory replenishment process can be realised by designing an optimal replenishment system. Furthermore, the characteristics of this process greatly resemble one specific spare parts management issue known in literature as the repair kit problem. The repair kit problem determines which inventory items and how many parts of these items should be stored in truck inventory or "repair kit".

Scientific literature on the repair kit problem is required to define the optimal replenishment system for REMONDIS Smart Infra's truck inventory replenishment process. Such literature has to meet the requirements and assumptions that characterize this process. However, not all are included in relevant existing literature. The proposed formulation of the repair kit problem to be solved in this research adds to the repair kit literature in three ways. First, multiple kinds of service orders are considered, where each kind has unique inventory item requirements to be completed with the repair kit. Second, a periodic replenishment policy is developed, which is based on the return frequency and distance of the mechanics to the warehouse for truck inventory replenishment. Third, a combination of perfect or no advance demand information depending on the kind of service order to be performed is incorporated. To solve this repair kit problem and to complete this research's solution model, a greedy heuristic algorithm is proposed as solution procedure due to the tremendous state space involved, that makes it intractable to solve this problem formulation to optimality. The designed solution procedure derives near-optimal replenishment systems within reasonable runtime, where the optimal replenishment system is defined in terms of the optimal repair kit and optimal replenishment interval.

The optimal repair kit concerns the inventory items and their inventory levels to be stored in each service and maintenance truck that minimizes the sum of the expected holding, replenishment and penalty costs, which represents the expected total costs, given the optimal replenishment interval and achieves a certain target service rate. The optimal repair kit is meant to be an identical repair kit for each individual mechanic. In turn, the optimal replenishment interval concerns the number of workdays between two subsequent replenishments that results in the optimal repair kit with minimal average expected total costs per day. To define the optimal replenishment system for REMONDIS Smart Infra's truck inventory replenishment process, an experimental evaluation based on the replenishment interval and the ratio between the penalty costs and holding costs is performed aiming primarily for the minimal average expected total costs per workday and secondarily for a target service rate of at least 95%.

Results

When applying REMONDIS Smart Infra's historical data on inventory item requirements in combination with the experimental settings to the solution procedure, 20 experiments are performed, which determine the performance of REMONDIS Smart Infra's truck inventory replenishment process. Each experiment generates an optimal repair kit for that particular combination of experimental settings. Based on these different performances and the objectives defined, the optimal replenishment system specifically for REMONDIS Smart Infra's truck inventory replenishment process is established, which results in the expected total costs of €857.59 consisting of the expected holding, replenishment and penalty costs of €488.59, €118.00 and €251.00, respectively. The actual monetary investment value of the optimal repair kit is €2,793.88 per mechanic and its corresponding replenishment interval equals 5 workdays. This interval results in the average expected total costs of €171.52 per workday. The practical implication of this optimal replenishment system for REMONDIS Smart Infra's truck inventory replenishment process is that the mechanics should only visit the warehouse with a return frequency of once per workweek to replenish truck inventory according to the optimal repair kit, reducing their overall downtime by 66.70%.

Conclusions and recommendations

This research has developed a standard solution procedure in the form of a greedy heuristic algorithm that enables REMONDIS Smart Infra to derive its optimal replenishment system. The optimal repair kit and corresponding replenishment interval optimize its truck inventory replenishment process in terms of efficiency and effectiveness, as they significantly reduce the associated downtime of the service and maintenance mechanics. These downtime savings enable the mechanics' productivity to be increased, which, in turn, enables REMONDIS Smart Infra to increase the number of clients it serves. Furthermore, by providing REMONDIS Smart Infra with a standard solution procedure, which can create an optimal repair kit for any values assigned to the model parameters, REMONDIS Smart Infra will also be able to derive future optimal replenishment systems when more new clients are served as well as to validate and verify the resulting values for the service rate and investment values of the repair kit.

To realise a successful implementation of the optimal replenishment system within REMONDIS Smart Infra's truck inventory replenishment process, this research presents a total of seven recommendations. One recommends REMONDIS Smart Infra to actualise its data on the inventory levels stored in the service and maintenance trucks. Subsequently, REMONDIS Smart Infra should install the software program in which the standard solution procedure has been implemented, so the company itself can analyse and compare its results as well as use the procedure in further optimization. Another advises to train the S&M mechanics on the practical way of working with the optimal replenishment system. One more suggests to implement the recommended key performance indicators to monitor and evaluate the performance of the optimal replenishment system. Additionally, three key directions for potential future research are proposed to improve this research's practicality to REMONDIS Smart Infra's truck inventory replenishment process, which concern REMONDIS Smart Infra's problem context, the truck inventory replenishment process itself as well as the entire solution model. Future research can focus on optimizing the structure and layout of the truck interior, developing a replenishment technique on how to optimally store the optimal repair kit in truck inventory and examine the impact of the implementation that the optimal replenishment system will have on the operations of the warehouse manager in the replenishment process. Moreover, future research should look into specifying the optimal replenishment system per establishment, per client or per mechanic, reconsidering and eliminating other assumptions applied to the solution model, and further improving the efficiency of the solution procedure.

PREFACE

Hereby I present my master thesis “Truck inventory replenishment process optimization at REMONDIS Smart Infra”, which concludes the master Industrial Engineering and Management. The completion of this challenging thesis marks the end of an eventful, enlightening and enjoyable educational journey during this bachelor’s as well as the master’s degree programme at the University of Twente. I can fondly look back on this impactful five-year chapter of my life and I am utterly grateful to anyone who was in anyway part of it.

First of all, I want to thank Dennis Prak and Breno Alves Beirigo for their insights, time, support and enthusiasm as supervisors. Their critical and detailed feedback have improved the theoretical and practical relevance of this thesis. Furthermore, I want to emphasise the significance of their profound knowledge on the research topic, which, in turn, expanded my knowledge on this topic and enhanced my research capability to ensure the academic quality of this thesis. Not to mention, our light-hearted but serious meetings made the entire research process and experience truly memorable.

REMONDIS Smart Infra has provided me with many valuable and practical insights into its operations and processes alongside the opportunity to adequately perform this intriguing thesis for which I am grateful. Above all, I would like to thank all involved employees for their input, support and sincere excitement while I performed this thesis as well as for answering any of my thesis-related questions. A special thanks to Joep Bekkers, as the company supervisor, who has put in tremendous effort to support me and to provide detailed feedback to increase the practicality of this thesis to REMONDIS Smart Infra’s operations.

Finally, I would like to thank my family for their continuous and absolute support while I performed this thesis as well as during the entirety of my studies.

I hope you enjoy reading this thesis!

Lieke de Wit,
July 2023

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LIST OF ACRONYMS

ADI	–	Advance demand information
DP	–	Dynamic programming
EHC	–	Expected holding costs
EPC	–	Expected penalty costs
ERC	–	Expected replenishment costs
ETC	–	Expected total costs
KPI	–	Key performance indicator
MDP	–	Markov decision process
NJFR	–	Next job fill rate
NTFR	–	Next tour fill rate
RSI	–	REMONDIS Smart Infra
S&M	–	Service and maintenance
SO	–	Service order

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1. INTRODUCTION

The process of inventory optimization is a subset of inventory management which is commonly associated with designing and implementing an optimized process for maintaining and replenishing the right amount of inventory required to meet demand, keep logistics and storage costs low, and avoid common inventory issues such as stockouts, overstocking, and backorders (Muckstadt & Sapra, 2009) (Axsäter, 2015). More specifically, maximizing the company's profit margins and minimizing its loss (SAP, n.d.). This research addresses the process of inventory optimization from a relatively small and unexplored scientific standpoint, namely optimizing the replenishment process for REMONDIS Smart Infra's service truck inventory. Hence, this chapter poses the introduction to this relevant and valuable research for REMONDIS Smart Infra as well as other companies and organizations with similar operations to those of REMONDIS Smart Infra.

The introduction to this research discusses the company composition and business scope of REMONDIS Smart Infra considered in this research. Furthermore, the research motivation argues why performing this research is significant. Then, the problem statement formulates the core problem and research problem to be addressed in this research. Consequently, the research objective outlines exactly the ultimate goal to be achieved. Finally, the research design, which includes the research questions and research framework, is created as the conclusion to this chapter.

1.1 COMPANY INTRODUCTION: REMONDIS AND REMONDIS SMART INFRA

Research is performed at the company called REMONDIS Smart Infra (RSI), which is a subsidiary of REMONDIS. REMONDIS is an international recycling, service and water company. It has been founded in the 1930s in the German town of Lünen as a family-run business. In almost 90 years, REMONDIS has grown into a business, which is operational on four continents with approximately 900 establishments and more than 30,000 employees. REMONDIS provides its services to more than 30 million people through the many thousands of public and private sector clients (REMONDIS, n.d.) (REMONDIS, n.d.). Examples of which are the local authorities as well as the industrial, commercial and business customers. Each year REMONDIS generates a turnover of approximately 7.9 billion euros (REMONDIS Industrie Service GmbH & Co. KG, n.d.).

1.1.1 Company composition

RSI is located within the REMONDIS Nederland division, which focuses on building, renovating, cleaning, inspecting, and repairing the sewers and corresponding installations, such as barrages and pumping stations, that transport either wastewater from people's homes towards the municipal purification plants or rain- and surface-water away from crucial road infrastructure and structurally through various waterways (REMONDIS Nederland, n.d.). Currently, RSI consist of the following three main divisions.

- Service and maintenance. This division is tasked with checking and maintaining the sewers and pumping stations. Such installations ought to meet supreme quality and safety requirements. In case any component is identified to be defective or does not meet the established requirements, the client will be notified about this defect (REMONDIS Nederland, n.d.).
- Construction and renovation. Here, new sewers and pumping stations are constructed in for example new housing estates. Also, this division performs renovations of such installations when requested by the client. Renovations are required when for example service and maintenance has detected defective pumps that need to be replaced (REMONDIS Nederland, n.d.).
- Cleaning and inspection. This division is tasked with cleaning the sewers, pumping stations, and purification plants. With the assistance of digital recording equipment, sewer systems and their condition are inspected. As a result of periodically inspecting and cleaning installations, the reliability of installations can be guaranteed and unnecessary costs are prevented (REMONDIS Nederland, n.d.).

1.1.2 Business scope

The boundaries of the research impact on RSI have been established at its four eldest establishments, namely Ermelo, Hardenberg, Leek, and Lichtenvoorde, as RSI has eight establishments across the Netherlands in total. Subsequently, the main research tasks are performed from the establishment in Lichtenvoorde to the largest extent.

For each of the main divisions, mechanics with the right qualifications utilize the corresponding types of trucks that require replenishment of specific inventory, such as mechanical equipment, support tools, and commodities, according to the orders which are distinctive for that main division. Therefore, this research focuses on the replenishment process at each included establishment's local warehouse involving the trucks used only for the service and maintenance (S&M) services of RSI.

1.2 RESEARCH MOTIVATION

Over the last couple of years, RSI has expanded and keeps expanding its number of establishments as well as its influence and expertise across the Netherlands. The company has come across more diverse competitors in the Dutch sewage sector, having to compete for clients and their demand for certain kinds of sewage-related services. As the competitiveness in the sewage sector intensifies, RSI remains steadfast in its ambition to serve an increasing number of clients, public as well as private, to become the eventual market leader in this sector.

RSI faces certain impediments in achieving its ambition. These impediments concern on the one hand the inaccurate pricing of the tender submitted to potential clients due to the inaccurate calculation of execution costs, which, in turn, might be explained by either the potential lack of quality and effort from the calculator or the inflexible and inaccurate resource pricing in the software system. On the other hand, RSI is dealing with a completely exhausted resource capacity of its S&M trucks and mechanics as a result of either a deficiency in the respective resource capacity or the productive time of the S&M mechanics being lower than the norm.
This research focuses on the resource capacity allocation problem that RSI faces caused by either the suboptimal resource capacity itself or the mismanagement of its resources, including the S&M mechanics and trucks. The relations between these diverse problems regarding the resource capacity allocation problem are outlined in Figure 1-1. This figure indicates that the core problem to be solved in this research concerns the overall productive time of the mechanics. In the subsequent paragraphs, it will be thoroughly argued why with respect to RSI's other problems.

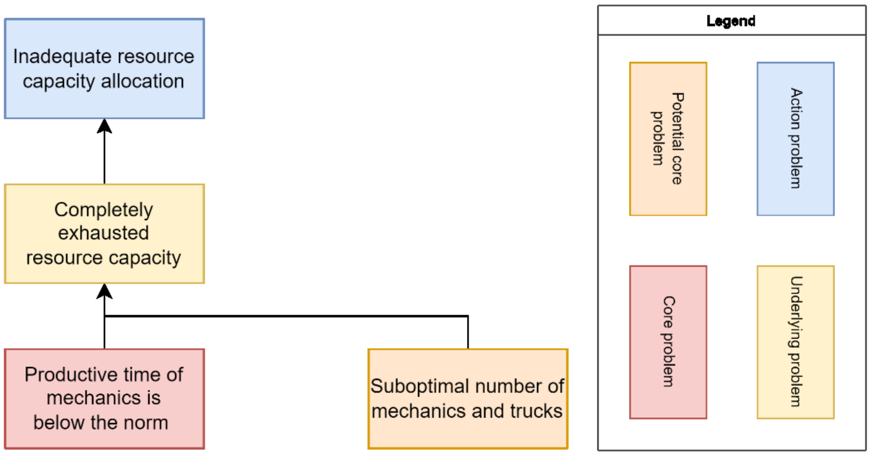

Figure 1-1 Problem cluster.

1.2.1 Problem 1: Inaccurate pricing of the tender

One way to secure more clients is to improve the accuracy of the tender provided to a potential client in order to obtain the right to provide the corresponding demanded services. A tender is formally defined as "an unconditional offer of money or service in satisfaction of an obligation made to save a penalty or forfeiture for non-payment or non-performance" (tender, n.d.). This would require increased accuracy in RSI's calculation of the execution costs for the services included in the obtainable bid. The accuracy of the calculation depends on the quality and effort put in by the calculator as well as the accuracy of the resource pricing in the software system.

Due to the current unpredictable times and resource scarcity, the pricing of resources is required to be adaptable and accurate to prevent creating a severely over- or under-priced tender. In case of an over-priced tender, the client will never select RSI's tender over a competitor's tender. When proposing an under-priced tender and being selected by the client, RSI could make a huge loss providing the agreed-upon services. Improvements in the adaptability of resource pricing to increase its accuracy would require constant updates and maintenance from either a responsible employee or an enhanced feature within the software system. As this research does not have the authority and competence to affect this matter, it will be disregarded.

1.2.2 Problem 2: Inadequate resource capacity allocation

Even if RSI would implement a solution to increase its accuracy in resource pricing, RSI's operations would not have the capacity to serve the increasing number of clients that the more accurate tenders would acquire. At the moment, the resource capacity – mechanics and trucks – is completely exhausted, especially for the S&M division, meaning that it takes considerable effort and dedication to even manage to serve its current clients. To make the ambition of extending its clientele conceivable, RSI could increase its workforce and acquire more resources by hiring new mechanics and purchasing more trucks and commodities. However, this would require a large monetary investment on RSI's part, which should only be done after careful consideration and evaluation on effectiveness and profitability. Furthermore, this matter is also affected by the unpredictable times and resource scarcity as well as the current labour shortages resulting in additional monetary and operational complications.

1.2.2.1 Mechanics' productive time

According to RSI's board of directors, the productive time of the S&M mechanics is lower than the norm that RSI enforces. The productive time is defined as the actual time per day in which these mechanics provide the services valuable for RSI's clients, as formulated in the agreed-upon contracts resulting from the proposed and selected tenders. Moreover, productivity is measured as the total amount of time that mechanics spent on direct orders that are related to service contracts in a predefined time horizon, which is usually defined as a workweek. These measurements are based on the data registration on service orders (SOs) and booked working hours in the software system.

1.2.2.2 Truck inventory replenishment process

Many potential causes contribute to this problem, such as travel time between client locations, social and educational briefings, and occasional impediments. Yet, the main contributor to this problem concerns the process of truck inventory replenishment by the mechanic and the warehouse manager, which is a crucial process to enable the mechanics to properly perform the S&M-related services. Currently, the mechanics spend a significant amount of their time traveling towards and at the warehouse to replenish the inventory of their trucks, which they cannot dedicate to providing value to any client. Historical data shows that mechanics return on average 3 times per workweek to the warehouse for truck inventory replenishments resulting in a time loss of 34.64 hours per workweek over all S&M mechanics regarding the replenishment of their truck inventory only. Including the travel time to return to and from the warehouse, a total time loss of 132.74 hours per workweek over all S&M mechanics is inflicted.

When the entire truck inventory replenishment process for the S&M trucks is optimized in terms of efficiency and effectiveness, the total productive time of mechanics per day has the potential to significantly improve and during that time mechanics would be capable of serving more clients. As a result, this indirectly creates additional capacity for realizing RSI's ambition for an increasing clientele whether or not RSI board of directors decides to invest in expanding the workforce. So, that is the problem that this research is going to focus on.

Just to clarify in terms of terminology, this research's main focus lies on the optimization of RSI's inventory management of the S&M trucks and the corresponding operational process stages involved.

1.3 PROBLEM STATEMENT

Based upon the selected problem as introduced under Section 1.2 and as indicated in the problem cluster presented in Figure 1-1, the core problem to be addressed in this research is to be formally formulated. Moreover, the main research question for this research to answer, will subsequently be outlined as the research problem.

1.3.1 Core problem

In order for the core problem to be formally formulated, the core problem should take the form of an action problem. An action problem can be described as a perceived discrepancy between norm and reality (Heerkens & van Winden, 2017). This discrepancy regarding the actual time in which the S&M mechanics provide valuable services for RSI's clients is phrased as follows.

"The productive time of service and maintenance mechanics is significantly below the norm of REMONDIS Smart Infra."

As previously stated in Section 1.2, this core problem can have several causes ranging from travel time between client locations to educational briefings. However, the proper cause to be addressed to solve the core problem is stated in the following way.

"Inefficient and ineffective truck inventory replenishment process for service and maintenance trucks."

The other causes potentially influencing the core problem are outside the scope of this research because certain causes are currently still required to perform the client services accordingly or they occur completely unforeseen. In other words, these causes can currently be considered a necessary evil. Therefore, these causes will be included in and counted as productive time. This assumption is justified, as certain actions are deemed causes but they are inherently necessary to perform the services correctly and properly for the clients. Work meetings and travel time towards and between client locations can be considered examples of such actions.

1.3.2 Research problem

A research problem is a specific issue or gap in existing knowledge that is aimed to be addressed in research, which can be viewed from a practical or theoretical perspective (McCombes & George, 2022). In this research, the research problem concerns a practical problem expressed as the main research question to be answered.

"How can the truck inventory replenishment process for the service and maintenance trucks of REMONDIS Smart Infra be optimized in terms of efficiency and effectiveness?"

Answering this main research question requires the ultimate research objective and the formulation of the research design to be defined, which includes formulating the research questions and establishing the research framework.

1.4 RESEARCH OBJECTIVE

As briefly touched upon in Sections 1.2 and 1.3, the goal of this research is to optimize RSI's truck inventory replenishment process. However, this statement does not exactly define what that means for RSI and what this research intends to achieve.

By optimizing the truck inventory replenishment process, the intention is to maximize a mechanic's productive time in which the mechanic provides the actual services deemed valuable to the clients. In other words, the aim is to minimize the downtime caused by replenishing the inventory of the S&M trucks. Subsequently, the main research objective can be outlined as follows.

"Designing the entire inventory replenishment process for the service and maintenance trucks aiming to minimize the downtime of the corresponding mechanics caused by this process."

Stating the entire truck inventory replenishment process means any aspect that is involved in this process will be considered in this research and potentially optimized. This holds for the frequency with which the mechanics drop by the warehouse for replenishing their truck inventory as well as the total quantity stored of certain items in the trucks.

1.5 RESEARCH DESIGN

In order to systematically perform this research, the research design is formulated. A research design entails the overall strategy that is selected to integrate the different components of this research in a coherent and logical way, thereby, ensuring the research problem will be effectively addressed; it constitutes the blueprint for the collection, measurement, and analysis of data (Kirshenblatt-Gimblett, 2006). To do so, the research questions for the different research components are phrased and the research framework combining these components is accordingly constructed.

1.5.1 Research questions

Answering the main research question requires the research to be partitioned into different components, as it concerns a complex problem depending on the acquisition of various knowledge dispositions. Consequently, the following research questions have to be answered.

1. **How is the current inventory replenishment process for service and maintenance trucks organized?**
   - 1.1. What are the stages included in the current truck inventory replenishment process?
   - 1.2. What replenishment technique is currently applied?
     - *1.2.1. How are the service and maintenance trucks currently being replenished?*
     - *1.2.2. What is the current return frequency of the service and maintenance trucks to the warehouse?*
   - 1.3. In what way is inventory currently stored in the service and maintenance trucks?
     - *1.3.1. What kind of inventory is currently stored in the trucks?*
     - *1.3.2. In which quantities is the inventory currently in stock in the trucks?*
     - *1.3.3. How is the inventory currently stored in the trucks?*
   - 1.4. What key performance indicators (KPIs) are currently used to measure the efficiency and effectiveness of the truck inventory replenishment process?

The second chapter is going to provide the answers to the first research question and corresponding sub-questions. To design the optimized inventory replenishment process for the service and maintenance trucks of RSI, the current inventory replenishment process for these trucks should be known and constructed. Furthermore, it is relevant to know the KPIs that RSI currently uses to measure the efficiency and effectiveness of the truck inventory replenishment process. This will be the offset for this research and indicate the possible areas for improvement in the entire process toward optimization in terms of efficiency and effectiveness – maximizing the mechanics' productive time.

2. **What information is available in literature regarding truck inventory replenishment processes, replenishment techniques and truck inventory management?**
   - 2.1. What truck inventory replenishment processes exist in literature, and which fit with service and maintenance trucks?
   - 2.2. What replenishment techniques exist in literature, and which are applicable to service and maintenance trucks?
   - 2.3. What are suitable methods to manage the inventory in service and maintenance trucks?
   - 2.4. What optimization techniques for inventory replenishment processes for service and maintenance trucks are available in the literature?

In the third chapter, a comprehensive literature review will be performed in order to answer the second research question as well as its sub-questions. The literature review is going to provide essential insights into the processes, techniques, and methods, which are applicable to S&M trucks, to be potentially used in the optimization of the entire truck inventory replenishment process. Furthermore, a specific search for optimization techniques for the inventory replenishment process applicable to the S&M trucks will be performed as is the main objective of this research. All gathered insights will be combined into a literature model and upheld in the upcoming chapter.

3. **How should the optimized inventory replenishment process for service and maintenance trucks be designed?**
   3.1. Which data is required to design the optimized truck inventory replenishment process?
   3.2. How can the found literature be applied to the development of the solution design for the optimized truck inventory replenishment process?
   3.3. What should the solution design for optimizing the truck inventory replenishment process look like?

The fourth chapter is concerned with answering the third research question and all its sub-questions. This chapter is concerned with constructing the solution design for optimizing the truck inventory replenishment process. First, the data required to design the optimized truck inventory replenishment process for RSI should be determined and gathered. Then, the found literature in the previous chapter is assessed on its applicability to the development of the solution design. Subsequently, the solution design for optimizing RSI's truck inventory replenishment process is constructed in its entirety.

4. **How does the optimized inventory replenishment process for service and maintenance trucks perform under experimental settings?**
   4.1. Which initial numerical results can be derived from the solution design?
   4.2. Which experimental settings should be considered?
   4.3. How does the solution design for optimizing the truck inventory replenishment process perform under experimental settings?
   4.4. What should the optimized inventory replenishment process for service and maintenance trucks look like?
      4.4.1. What should the return frequency of the service and maintenance trucks to the warehouse be?
      4.4.2. In what way should inventory be stored in the service and maintenance trucks?
         4.4.2.1. What kind of inventory should be stored in the trucks?
         4.4.2.2. In which quantities should the inventory be in stock in the trucks?
      4.4.3. What KPIs should be used to measure the efficiency and effectiveness of the truck inventory replenishment process?

Now that the solution design has been constructed, the optimized inventory replenishment process can be developed, which will be done by testing the solution design, as the fourth research question and its sub-questions suggest. The fifth chapter starts by deriving the initial numerical results for the inventory replenishment process for the S&M trucks and, in turn, formulating the different experimental settings based on these initial numerical results in order to validate this developed solution design. Using these experimental settings, the performance of the solution design should be determined resulting in different truck inventory replenishment processes being derived. In turn, these truck inventory replenishment processes are evaluated based on their efficiency and effectiveness. The truck inventory replenishment process deemed the most efficient and effective will be defined as the optimized inventory replenishment process for the S&M trucks of RSI.

5. **Which conclusions can be drawn, and recommendations can be made from the optimized inventory replenishment process for service and maintenance trucks and the corresponding experimental results?**
   5.1. What can be concluded from the performance of optimized truck inventory replenishment process?
   5.2. What are the recommendations for implementing the optimized truck inventory replenishment process?
   5.3. What can be proposed as future research for RSI's truck inventory replenishment process?

Finally, the sixth chapter concludes and presents the recommendations for this research regarding the performance and implementation of the optimized inventory replenishment process for the S&M trucks of RSI. Furthermore, potential future research for RSI's truck inventory replenishment process is proposed.

1.5.2 Research framework

As can be observed from the reasoning for each research question, this research focuses on quantitative as well as qualitative analyses, which are all somehow related to each other by contributing to answering the main research question and solving the core problem. Figure 1-2 shows and summarizes the cohesion between the chapters, research questions, inputs, and outputs. The inputs concern the information or data to be collected, measured, or analysed while the outputs present exactly what each research question contributes to solving the research problem. Therefore, this research framework is somewhat alike to a conceptual framework.

Take away from this figure the time span and direction in which this research intends to solve RSI's core problem across the chapters of this research. For instance, the next two upcoming chapters aim to provide a detailed data-driven overview of the current problem context and a collection of scientific literature to support the optimization and solution to this context.

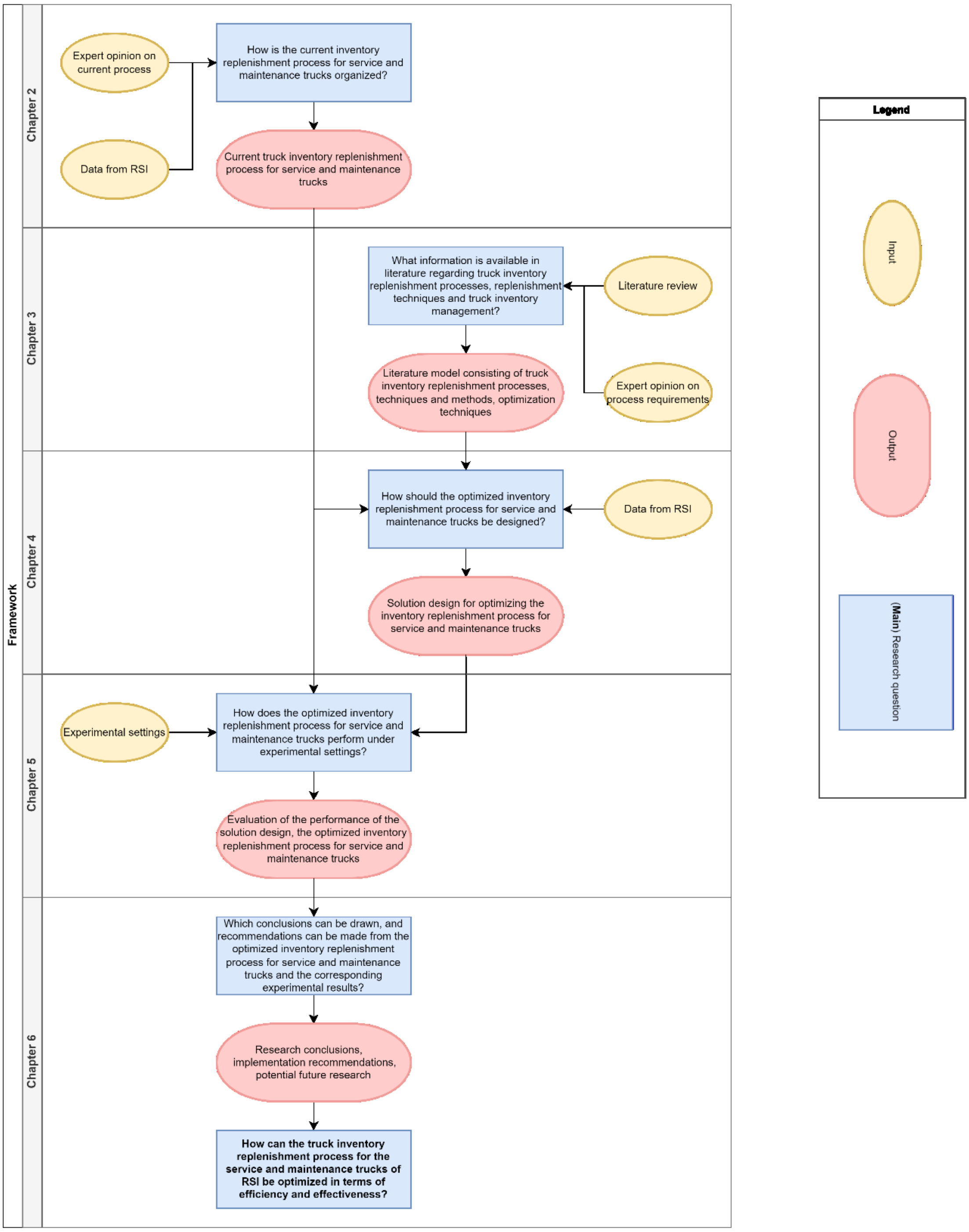

Figure 1-2 Research framework of the research questions to be answered throughout this research.

2. CONTEXT ANALYSIS

The aim of this chapter is to provide insight into the current situation at RSI concerning its inventory replenishment process for the S&M trucks. By performing a context analysis, the significance of this research is illustrated with regards to the consequences of having no efficient and effective truck inventory replenishment process. This entails providing a clear overview of the available relevant data depicting a consistent and realistic view of the impact on RSI's current situation. In turn, the context analysis intends to answer the following research question.

1. *How is the current inventory replenishment process for service and maintenance trucks organized?*

The answer to this research question is realised by outlining RSI's problem context in terms of the stages in the current truck inventory replenishment process, what replenishment technique is currently applied and how the truck inventory is currently managed. Furthermore, this chapter defines the KPIs that RSI currently uses to measure the efficiency and effectiveness of its truck inventory replenishment process.

2.1 CURRENT TRUCK INVENTORY REPLENISHMENT PROCESS

To kick-off this chapter, this section sketches an overview of the stages required to replenish the S&M trucks of RSI. Furthermore, it defines the key users in this inventory replenishment process and identifies potential bottlenecks and areas for improvement regarding efficiency and effectiveness in the corresponding process. Hence, this section intends to answer the following sub-question.

1.1. *What are the stages included in the current truck inventory replenishment process?*

According to the warehouse manager and the functional manager, Figure 2-1 depicts the stages in the inventory replenishment process for the S&M trucks in the way that they are currently performed, as validated and verified by joint discussion and review. In this flowchart, the start and end nodes to this process are respectively indicated as well as the stakeholder involved in each stage (🠉) and the medium in which each stage takes place (⇣).

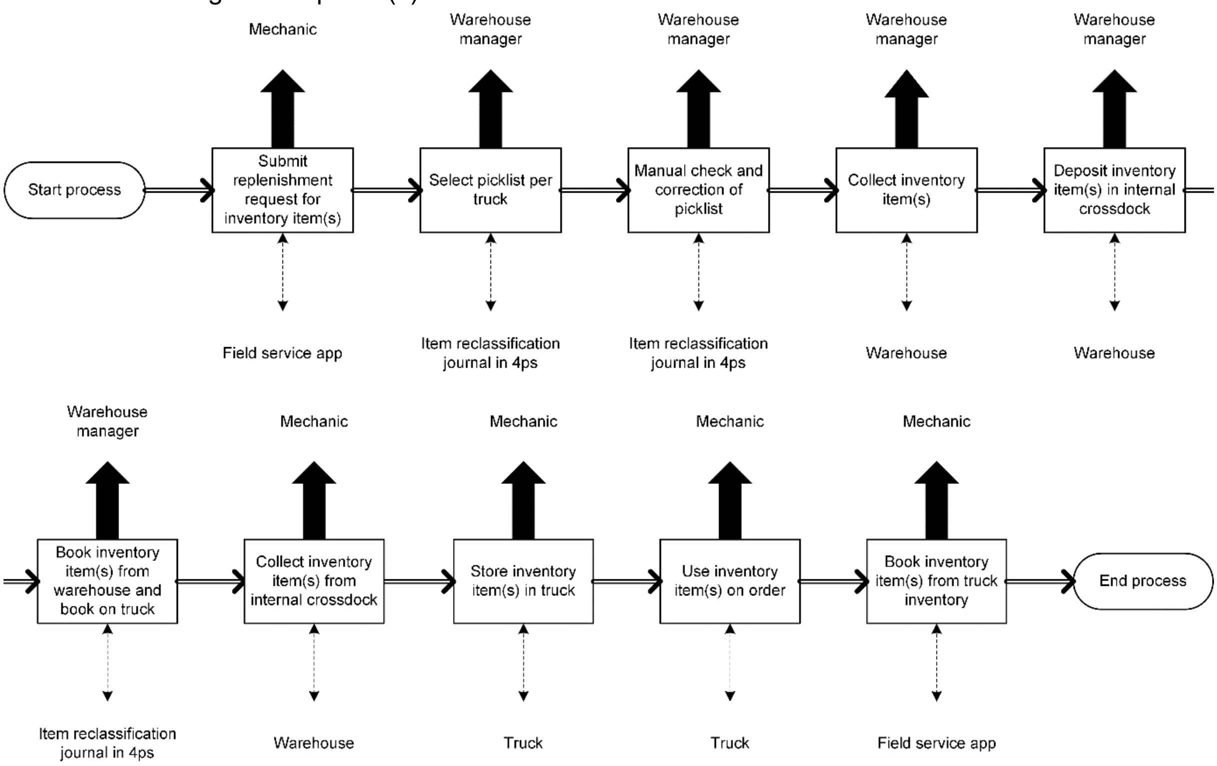

Figure 2-1 Current truck inventory replenishment process at RSI including stages, stakeholders and mediums.

Each stage in this truck inventory replenishment process is performed by either an S&M mechanic or the warehouse manager, so they are the stakeholders to be considered in this process and will be impacted the most by any change or optimization in this process. RSI has 46 S&M mechanics across their eldest establishments and these mechanics make use of 51 trucks to perform the SOs agreed upon in the service contracts with RSI's clients. Establishing the size of the workforce is crucial for defining which mechanics and trucks should be included in the optimization and for which relevant data should be gathered to obtain a realistic outline of the current state of the entire inventory replenishment process for the S&M trucks.

Furthermore, each establishment has their own warehouse, where each warehouse is managed by either a warehouse manager or an appointed work planner in case no warehouse manager is present at the respective establishment. The involvement of the warehouse managers in this research will be essential due to their knowledge and expertise on this process and their significant influence on its efficient and effective execution.

To clarify the current truck inventory replenishment process and how it is performed at RSI, each stage in the process is explained in detail.

1. **Submit replenishment request for inventory item(s)**: When an S&M mechanic needs certain inventory items, such as mechanical equipment, support tools, and commodities, in case the mechanic has used the item during an SO or lacks that item in their truck inventory, the mechanic places an inventory replenishment request in the field service app on their tablet.
2. **Select picklist per truck**: All replenishment requests submitted by the S&M mechanics are received by the warehouse manager in the item reclassification journal in RSI's software system. From this item reclassification journal, the warehouse manager selects a picklist per truck, which means that the warehouse manager filters this journal on a specific truck number and this creates a selection of inventory items requested by the mechanic who utilizes that truck.
3. **Manual check and correction of picklist**: Once the picklist for a specific truck has been selected, the warehouse manager checks the picklist on whether reasonable requests for inventory items have been made by the corresponding mechanic. Here, the warehouse manager mainly checks the kind and quantity of items requested. The warehouse manager will correct the respective picklist in the item reclassification journal in case of any anomalies or errors.
4. **Collect inventory item(s)**: The approved inventory items on the picklist for a specific truck are now collected by the warehouse manager from the different storage locations within the warehouse.
5. **Deposit inventory item(s) in internal crossdock**: Subsequently, the warehouse manager delivers the collected inventory items to the internal crossdock within the warehouse and deposits them in the rack assigned to the truck for which the inventory items were requested.
6. **Book inventory item(s) from warehouse and book on truck**: The following action undertaken by the warehouse manager entails booking the collected and deposited inventory items from warehouse inventory onto truck inventory of a specific truck in the item reclassification journal of the software system.
7. **Collect inventory item(s) from internal crossdock**: Once the requested inventory items are located in the internal crossdock, the S&M mechanic should travel to the warehouse and the mechanic can retrieve the inventory items as requested.
8. **Store inventory item(s) in truck**: Then, the mechanic physically stores these inventory items in their truck in their corresponding truck inventory according to their own insights and perceptions.
9. **Use inventory item(s) on order**: As a result of this replenishment process, the S&M mechanic is able to use these inventory items on future SOs when a respective SO requires them to provide the required services to RSI's clients.
10. **Book inventory item(s) from truck inventory**: Finally, the S&M mechanic should book the used inventory item(s) from their truck inventory in the field service app on their tablet. These inventory items are to be booked related to the SO for which the mechanic used the respective inventory item(s).

Analysing the stages as described above, the truck inventory replenishment process can be defined as a continuous circular process. For instance, when an inventory item has been booked from truck inventory because it has been used on a SO, the S&M mechanic will need a replenishment of the respective inventory item. So, the mechanic will submit a replenishment request for this item in the field service app, thus resuming the current truck inventory replenishment process.

Moreover, the truck inventory replenishment process, as it is currently performed according to the previously-described stages, has the potential for various issues to occur, which can contribute to the inefficiency and ineffectiveness of the process as a whole and incur monetary implications regarding investments in truck inventory. Likewise, these issues are in part also responsible for the incurrence of the downtime of the S&M mechanics regarding this process. In chronological order, these potential issues entail the following.

- At the moment, S&M mechanics are constantly placing replenishment requests according to their own insights and perceptions on what inventory levels they need to attain for certain inventory items, which likely results in varying inventory levels between S&M trucks and return frequencies to the warehouse for replenishment of truck inventory.
- The manual check and correction of a truck's picklist by the warehouse manager is exclusively based on the insights and perceptions of the warehouse manager on the required truck inventory levels of certain inventory items. This also affects the inventory levels in the S&M trucks and the return frequency of the mechanics to the warehouse for truck inventory replenishment.
- There is currently no guideline or indication for the S&M mechanics when to return to the warehouse to collect their requested inventory items from the internal crossdock. This can lead to unnecessary visits on the one hand in case the inventory items have not been deposited in the crossdock yet. On the other hand, it can result in trucks lacking certain inventory items to perform the SOs when the mechanic does not visit the warehouse in time.
- Furthermore, the S&M mechanics do not have a procedure on how to exactly store the inventory items in their trucks. There is a predefined layout and structure within the trucks but their truck inventory can get out of control in terms of the quantity of items stored as well as deviating from the predefined layout and structure, as their trucks are not periodically being checked. A lack of overview of the actual inventory levels in the S&M trucks is the inevitable consequence. However, this does vary significantly per establishment and depending on the characteristics of the mechanics.

The most crucial stage to address in the entire truck inventory replenishment process is already the very first one (1). When should an inventory replenishment of an S&M truck exactly be triggered? Currently, the S&M mechanics simply decide this and subsequently return to the warehouse for replenishment of their truck inventory according to their own insights, which occurs either when a mechanic arrives at an order and the required item is not in their truck inventory or when a mechanic intends to precautionary replenish that item. It might require (re)designing an inventory policy or replenishment system to optimize the truck inventory replenishment process of RSI.

2.2 CURRENT REPLENISHMENT TECHNIQUE

This section clarifies certain crucial details from the current truck inventory replenishment process with respect to its potential for optimization in terms of efficiency and effectiveness. Phrased differently, this section intends to specify exactly how and how often the S&M trucks are currently replenished, which entails answering the following sub-question.

1.2. What replenishment technique is currently applied?

At first, the current method applied in replenishing the inventory of the S&M trucks is described based on the expertise of the warehouse manager and functional manager. Subsequently, the current return frequency of the S&M trucks to the warehouse for replenishment of their truck inventory is derived based on actual data from tracing and assessing the routes of the trucks.

2.2.1 Current method of truck replenishment

In order to define and explain the current method of inventory replenishment applied to the S&M trucks, the following sub-question is going to be answered in this section.

1.2.1.How are the service and maintenance trucks currently being replenished?

Simply put, there is no systematic method or technique applied in the replenishment of inventory in the S&M trucks aside from the quick manual check by the warehouse manager. As can be observed from Figure 2-1, no methodology is outlined defining how the inventory items in S&M trucks should be replenished. Potential for optimization through the implementation of such a replenishment technique is absolutely present and became apparent from sketching the stages in the truck inventory replenishment process as well as the corresponding discussions with the warehouse manager and functional manager.

2.2.1.1 Kinds of SOs

However, RSI mainly bases the inventory replenishments of its S&M trucks on the SOs that are expected to be performed in the near future, partially according to its annual planning. The majority of these SOs are either maintenance, malfunction or incidental orders, so truck inventory and the corresponding inventory levels should be based on the inventory requirements for each kind of SO.

- **Maintenance order**: An SO which entails the periodic inspection and evaluation of the pumps, pumping stations and other related installations, where the mechanics carefully check and monitor the condition of these installations and occasionally replace or repair small parts. This kind of orders is always part of a service contract with a client. A maintenance SO and its inventory item requirements are known 3 to 5 workdays in advance.
- **Malfunction order**: An SO where a pumping station or any related installation has broken down and has to be fixed immediately due to potentially serious consequences. Usually such an order is included within a service contract. A malfunction SO and its inventory item requirements are known only 1 to 2 hours in advance.
- **Incidental order**: An incidental SO is usually performed outside of a service contract and can entail providing any kind of service that the client requires, such as a maintenance or repair. An incidental SO and its inventory item requirements are known 1 to 3 workdays in advance.

Over the year 2022, 46.13%, 52.83% and 1.05% of the SOs were maintenance, malfunction and incidental orders, respectively. These values indicate that maintenance and malfunction orders are the most prevalent in a typical workday or -week of the S&M mechanics. Therefore, these kinds of SOs most likely also result in the majority of returns to the warehouse for truck inventory replenishment according to a ratio similar to the aforementioned percentages.

2.2.1.2 Typical workday and workweek for S&M mechanic

Speaking of a typical workday or -week for an S&M mechanic, they can be depicted in the following way after a thorough data analysis over the workdays and workweeks of 2022. An S&M mechanic performs on average 7.3 SOs per day and 33.46 SOs per week with a standard deviation of 3.23 and 11.39, respectively, as presented in Figure 2-2. Naturally, the variance and width of the box plot in general is larger for the number of SOs performed per week than per day. On a typical workday or in a typical workweek, the S&M mechanic performs a wide variety of SOs, where each day and each week differs slightly due to uncertainties involved, especially in case of malfunction orders. However, the ratio between the kinds of SOs performed corresponds to the percentages given in the previous paragraph.

Remarkably, a significantly smaller number of SOs is performed on a workday when a malfunction order or incidental order is one of the SOs performed on that day. This can be explained by the fact that malfunction and incidental orders usually take twice the time of a maintenance order to complete. As RSI's guideline for the completion of a maintenance order is 45 minutes, the duration of a malfunction and incidental order should approximately be 1.5 hours. The actual duration of an SO might occasionally be prolonged due to unforeseen circumstances or hindrances but this is not the standard.

Also, some mechanics performed a particularly small number of SOs on a certain day (1) or in a certain week (12) due to illness or other personal circumstances. The corresponding values can be considered outliers because performing between 5 and 10 SOs per day is considered business as usual, which has been confirmed by the planners of these SOs.

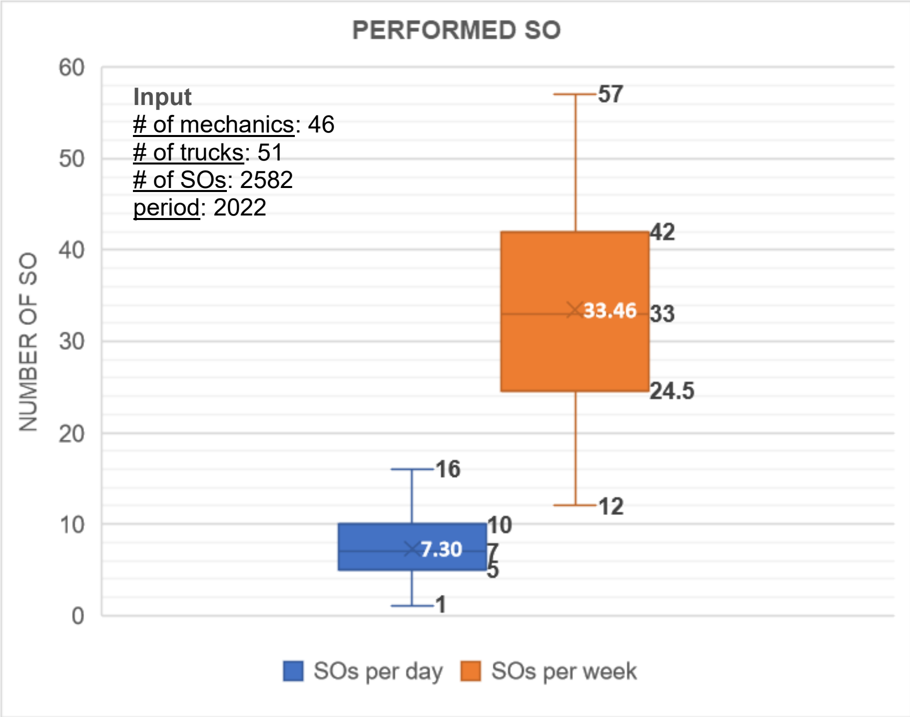

Figure 2-2 Number of SOs performed per day and per week by each S&M mechanic on average over all 2,582 SOs performed in 2022 by the 46 S&M mechanics using 51 trucks.

On a typical workday, an S&M mechanic performs a sequence of maintenance, malfunction and incidental SOs in the form of a tour. An instance of such a typical tour is depicted in Figure 2-3. It can be observed that the mechanic started from their home and first performed a sequence of nearby maintenance SOs according to an area of maintenance SOs to which the planner has scheduled them. At the end of that day, a malfunction SO arose to which this mechanic was scheduled. Once the mechanic completed the malfunction SO, they returned home with their S&M truck.

The 15 SOs performed and depicted in Figure 2-3 have been connected by direct line segments to create uniformity and a standardization in distance measurement. Therefore, the distances between these SOs are depicted and can be measured in the Euclidean plane by the Euclidean distance, as the Euclidean distance is one of the most widely used distance metrics and requires the inclusion of specific features, which have all been met by observations in this tour presented in Figure 2-3 (Turing, n.d.).

As can be seen in Figure 2-3, S&M mechanics are typically scheduled to perform maintenance and incidental SOs, which are located usually within a 10-kilometre radius of their residence. The only rare exception can be made for malfunction SOs due to their high urgency to be immediately dealt with. The planners of these SOs aim to schedule the nearest available S&M mechanic to that malfunction SO. However, this is not always feasible, when no mechanic is considered to be near the SO – the Euclidean distance is greater than 10 kilometres – or no nearby mechanic is directly available to perform that SO. So, an S&M mechanic has to occasionally travel more than 10 kilometres from their residence but this does not occur regularly or systematically.

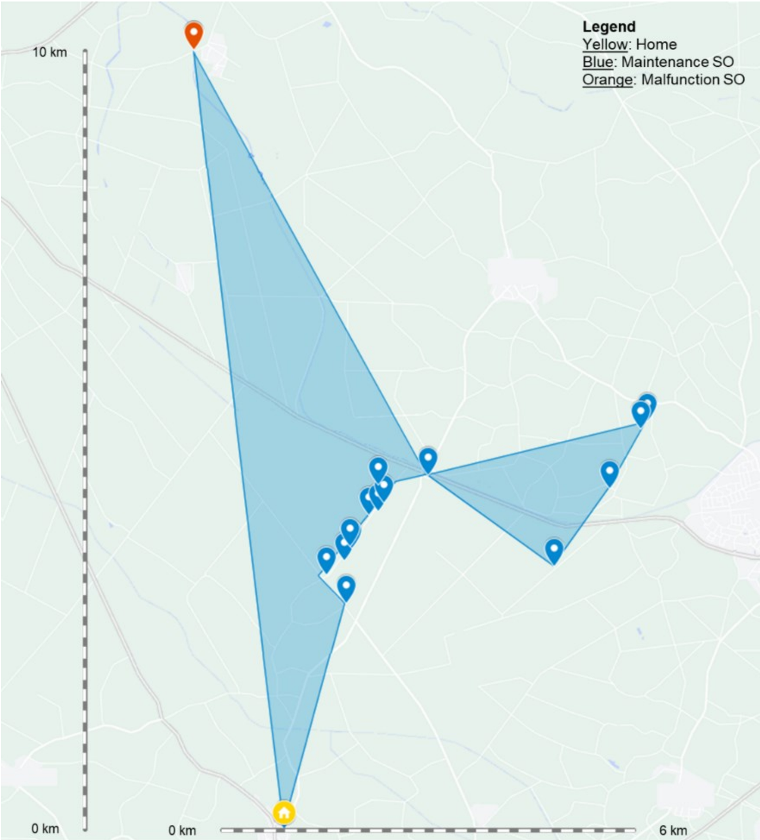

Figure 2-3 Typical tour of an S&M mechanic on a single workday – excluding visit to the warehouse.

2.2.1.3 Inventory requirements

Now, insight into the inventory requirements for future SOs is essential in defining how the S&M trucks should be replenished. As the service contracts that RSI concludes almost always concern long-term contracts of at least multiple years, inventory items used in previously-performed SOs provide an accurate overview of the inventory requirements for future SOs. Based on a thorough data analysis of RSI's software system – also called a database research, an overview of inventory items used in previously-performed maintenance, malfunction and incidental SOs has been derived. In this analysis, the inventory items included entail items that have been used on SOs, which are included within a service contract, completed in the year 2022 and performed by the S&M mechanics from one of the four eldest establishments of RSI with their S&M trucks.

Table 2-1 below depicts the top ten most frequently demanded inventory items on maintenance, malfunction and incidental orders by the S&M mechanics. This table depicts the inventory requirements according to the most commonly performed SOs over the last year by stating the inventory item numbers, where each number corresponds to a different inventory item, as well as the total quantity of each inventory item demanded over 2022. Also, this table presents the average quantity and variance of an item demanded over the SOs in which that specific item has actually been used, so the average quantity of an inventory item that a mechanic would need for an SO that requires that item. Next to that, the maximum number of parts that a single SO can demand of each inventory item is listed. Furthermore, the average quantity and variance of an item demanded over all 2,582 SOs performed in 2022 has been calculated to indicate the likelihood that any SO would require that specific item.

The respective variances related to both averages represent the width of the potential demand for each inventory item. The smaller the variance in demand for a specific item, the higher the certainty on the potential demand of future SOs for that item.

For instance, item 9998 has been used 951 times in total, 1.08 times on each SO it has been actually used with a corresponding variance of 0.72 and 0.37 times over all 2,582 SOs performed in 2022 with a respective variance of 0.60. The maximum demand for item 9998 on a single SO is equal to 15 parts of that item.

In turn, Figure 2-4 presents how many inventory items have had a certain total demand over 2022. This figure shows that the gross of inventory items has only been used between 1 or 10 times in total over the entirety of 2022. Specifically, 426 out of 537 items are included in that total demand interval, which comes down to a share of 79.3% of inventory items. Furthermore, the top ten most frequently used inventory items, as stated in Table 2-1, can also be clearly identified in the right tail of this figure.

Table 2-1 Demand for the top ten most frequently used inventory items from RSI's 537 inventory items for the 2,582 SOs over 2022.

ItemNr.	Total demand	Average demand on actual SO	Variance demand on actual SO	Maximum demand per SO	Average total demand	Variance total demand
9998	951	1.08	0.72	15	0.37	0.60
2245	580	4.87	14.48	35	0.22	1.73
2246	491	8.05	15.68	16	0.19	1.86
3629	437	1.63	0.67	6	0.17	1.84
2333	219	2.61	1.16	6	0.08	0.29
2207	188	3.75	3.47	10	0.07	0.33
2240	173	1.01	0.01	2	0.07	0.06
2244	164	6.31	13.26	20	0.06	0.56
2457	157	1.00	0.00	1	0.06	0.06
4228	141	2.66	5.65	14	0.05	0.26

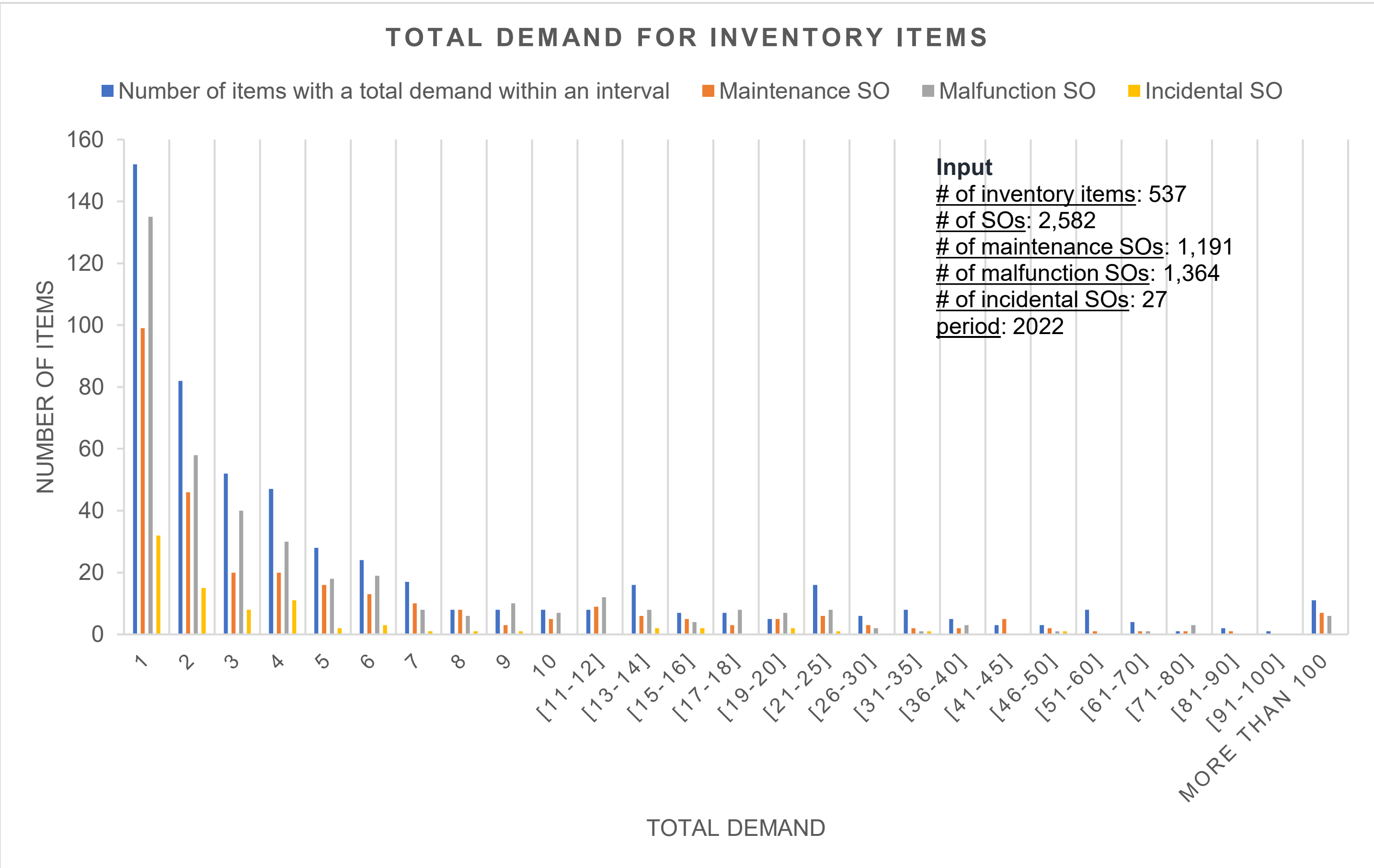

Figure 2-4 Number of times each inventory item is used in 2022 (yearly total demand) for each of RSI's 537 inventory items over the 2,582 SOs performed in 2022 of which 1,191, 1,364 and 27 are maintenance, malfunction and incidental SOs, respectively.

Table 2-2 summarizes the values for the inventory requirements for RSI's 537 inventory items in terms of the minimum, average and maximum values over all items. Note that the minimum values for the "Average total demand" and "Variance total demand" are not actual equal to 0. In fact, these values are so small that rounded to two decimals they seem equal to 0. However, the minimum value for the "Variance demand on actual SO" is in fact equal to 0.

Table 2-2 Summary inventory requirements for RSI's 537 inventory items over the 2,582 SOs performed in 2022.

Measure characteristic	Minimum	Average	Maximum
Total demand	1.00	14.52	951.00
Average demand on actual SO	1.00	1.68	20.00
Variance demand on actual SO	0.00	2.40	548.97
Maximum demand per SO	1.00	2.43	64.00
Average total demand	0.00	0.01	0.37
Variance total demand	0.00	0.03	1.86

Furthermore, the different kinds of SOs require different inventory items for their completion. Therefore, a distinction is made between the inventory requirements for the different kinds of SOs. Figure 2-4 also displays the inventory requirements according to the performed maintenance, malfunction and incidental SOs over the last year, separately and respectively, using the same structure as the total demand for all 2,582 SOs. Again, the gross of inventory items per kind of SO is demanded between 1 or 10 times over the entirety of 2022.

However, there are also significant differences in the requirements per kind of SO. This can be explained by a large difference in the number of different inventory items demanded by these kinds of SOs, especially between maintenance and malfunction SOs on the one hand and incidental SOs on the other hand. For instance, 100, 135 and 30 different inventory items are each demanded once by maintenance, malfunction and incidental SOs over the entirety of 2022, respectively. Subsequently, 45, 60 and 15 different inventory items are each demanded twice by maintenance, malfunction and incidental SOs over the entirety of 2022, respectively.

A continuous trend is identified in which the incidental SOs always demand the smallest number of different inventory items, whereas the maintenance and malfunction SOs are the kinds of SOs that interchange for the top spot within certain intervals. This trend makes sense, as the number of incidental SOs performed is significantly lower than the number of maintenance and malfunction SOs performed over 2022. In turn, the opportunity to demand a large variety of inventory items is significantly smaller in comparison to the other kinds of SOs. When comparing the average number of times each inventory item has been used in 2022 – the average total demand – over the different kinds of SOs, significant differences in the inventory requirements per SO can be observed regardless of the total number of SOs performed by each kind in 2022. For instance, the probability that inventory item 3629 will be required by a maintenance SO is equal to 16.0% while for a malfunction or incidental SO, this probability for item 3629 is equal to 17.5% and 33.3%, respectively.

A thorough analysis of the inventory requirements shows that dependency between these required inventory items to complete the SOs cannot be immediately ruled out. Demand for different inventory items on the same SO can be dependent. Relevant statistical measures would be able to confirm or deny these dependencies. Subsequently, the correlation between the usage of different inventory items on SOs has been outlined and calculated, where 288,369 correlation coefficients between the 537 inventory items were identified.

The correlation coefficient (R-value) is a statistical measure of the strength of a linear relationship between two variables, which in this case concerns two inventory items. Its values can range from -1 to 1. A correlation coefficient of -1 describes a perfect negative, or inverse, correlation with values for one variable rising as those for the other decline, and vice versa. A coefficient of 1 shows a perfect positive correlation, or a direct relationship. So, as one variable increases in its values, the other variable also increases in its values. A correlation coefficient of 0 means there is no linear relationship (Fernando, 2021; Ratner, 2009).

In order to determine whether a correlation between two inventory items is significant, so whether the usage of two inventory items on an SO is actually dependent, a statistical hypothesis test is performed. The null hypothesis of this test presumes that the correlation coefficient is not significantly different from 0, so no significant linear relationship (correlation) exists between inventory item x and inventory item y. In turn, the alternative hypothesis of this test states that the correlation coefficient is significantly different from 0, which means that a significant linear relationship (correlation) between inventory items x and y exists (Illowsky & Dean, 2021). The corresponding significance level to determine whether or not to reject the null hypothesis is set to $\alpha < 0.05$.

Figure 2-5 presents the results of this hypothesis test in which the number of correlations – combinations of inventory items, which are defined as significant, are distributed in intervals. In total, 1,814 significant correlations between 447 out of 537 inventory items have been identified by the hypothesis test with varying correlation coefficients (R-values). Most of these significant correlations have a correlation coefficient between -0.06 and 0.47, specifically 78.1% of significant correlations fall within this joined interval. The corresponding R-values included in this interval seem to represent a relatively weak or moderate linear relationship between inventory items, as they are closer to 0 than 1 (Ratner, 2009). However, even weak correlations can be statistically significant, as is acknowledged in Figure 2-5.

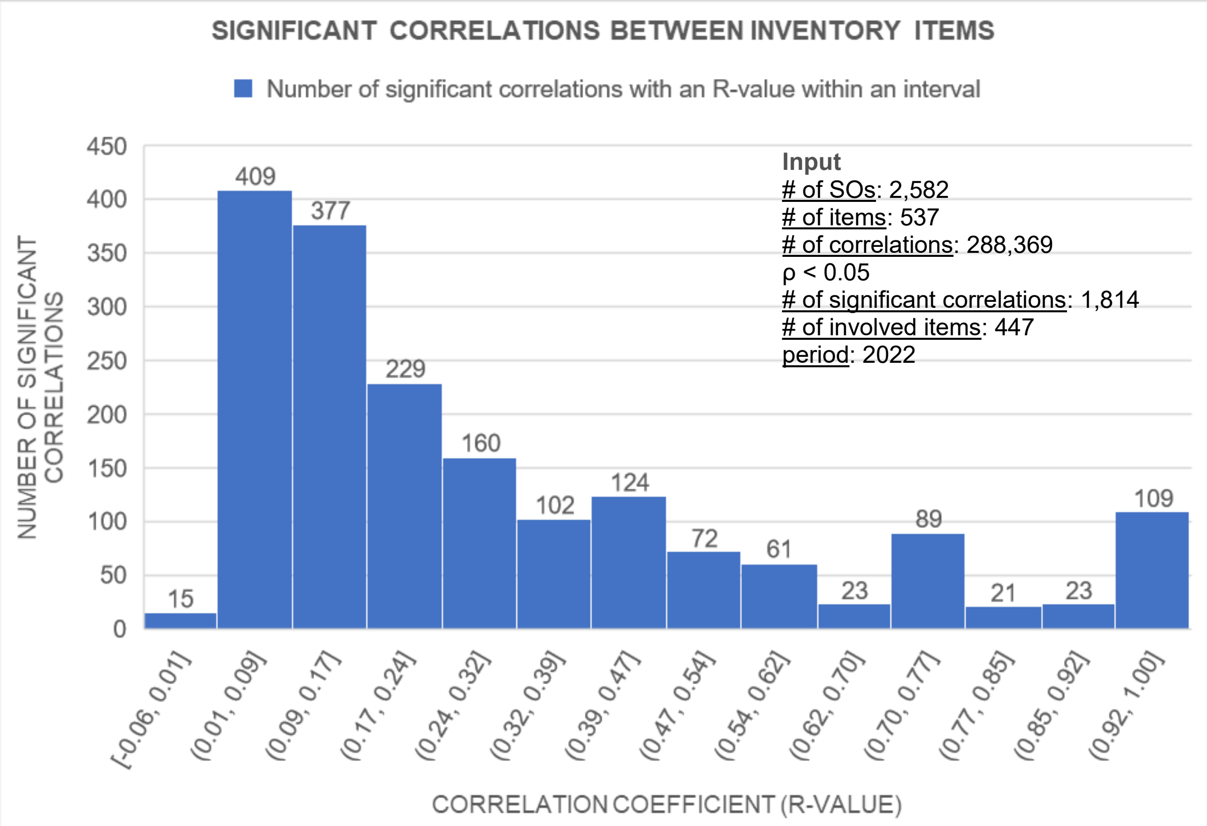

Figure 2-5 1,814 significant correlations out of a total of 288,369 correlations between 447 out of 537 inventory items over the 2,582 SOs performed in 2022.

Towards the right tail of the interval distribution, as presented in Figure 2-5, the strength of the linear relationship between the different inventory items increases until a perfect positive linear relationship is achieved. Remarkably, 88 out of the 1,814 combinations of inventory items have a perfect positive correlation, which means that their R-values are exactly equal to 1. Table 2-3 shows 10 examples of these combinations of inventory items with perfect positive correlation, which also all have a p-value equal to 0 (Beers, 2023). Practically, this means that when one of the two inventory items is required by an SO, the other inventory item will automatically always be required by that SO as well in order for that SO to be completed. Many of these perfect positive correlations concern complementary inventory items, which belong together based on their physical properties. For instance, inventory items 1780 and 1778 are a tee and plastic (HdPE) tube, respectively, with identical diameters making them a perfect fit to be used together on an SO that demands at least one of them.

Table 2-3 Examples of 10 out of 88 combinations of inventory items with perfect positive correlation.

ItemNr.1	ItemNr.2	p-value	R-value
2098	1369	0.000	1
4438	2248	0.000	1
1780	1778	0.000	1
4228	3631	0.000	1
3084	2593	0.000	1
4552	1830	0.000	1
3887	3724	0.000	1
4116	4107	0.000	1

In conclusion, only 1,814 out of 288,369 correlations between the 537 inventory items are deemed significant according to varying degrees defined by the strength of the respective linear relationship. Merely 0.6% of inventory item combinations actually experience dependency to a certain extent when it comes to their inventory requirements for an SO. Therefore, the demand for different inventory items on the same SO is considered to be independent in this research for all inventory items.

2.2.2 Current return frequency

To express the seriousness of an inefficient and ineffective truck inventory replenishment process, the current frequency with which the S&M mechanics return to the warehouse for truck inventory replenishment should be signified. Therefore, the sub-question formulated below will be answered.

> *1.2.2. What is the current return frequency of the service and maintenance trucks to the warehouse?*

From the truck routing data gathered over the year 2022 as well as over all of RSI's S&M mechanics across RSI's four eldest establishments, a dataset has been created that shows how many times an S&M mechanic has visited the warehouse of at least one of the establishments for the replenishment of their truck inventory over all the workdays of the mechanic. Such returns to the warehouse are triggered by actually arriving at an SO and not having the required inventory item in truck inventory to complete the SO or for precautionary replenishment of that inventory item. Here, no distinction can be made between necessary and unnecessary returns, so whether an S&M mechanic returned to the warehouse out of emergency or precaution cannot be said based on the available data.

Using this dataset, the average return frequency per mechanic per workday, over all mechanics per workday and over all mechanics per workweek can be determined. This results in each mechanic currently returning to the warehouse 0.6 times per day and 3 times per week on average for the replenishment of their truck inventory.

During the data analysis, however, a striking observation has been made that the return frequency of the S&M mechanics differs between certain establishments significantly. Hence, the average return frequency over all mechanics per establishment per workday is calculated, which is displayed in Table 2-4. So, a mechanic at establishment 1 returns to the warehouse for truck inventory replenishment 0.68 times per workday and 3.40 times per workweek on average. The difference in the average return frequency is especially large between establishment 2 and the others.

Table 2-4 Average return frequency per workday and per workweek for each S&M mechanic in 2022 over all S&M mechanics per establishment of RSI.

Establishment	1	2	3	4
Return frequency per workday	0.68	0.36	0.62	0.66
Return frequency per workweek	3.40	1.79	3.09	3.31

Figure 2-3 displays the data on the return frequency per establishment from Table 2-4 in a box plot to clearly indicate the significant difference between establishment 2 and RSI's other establishments.

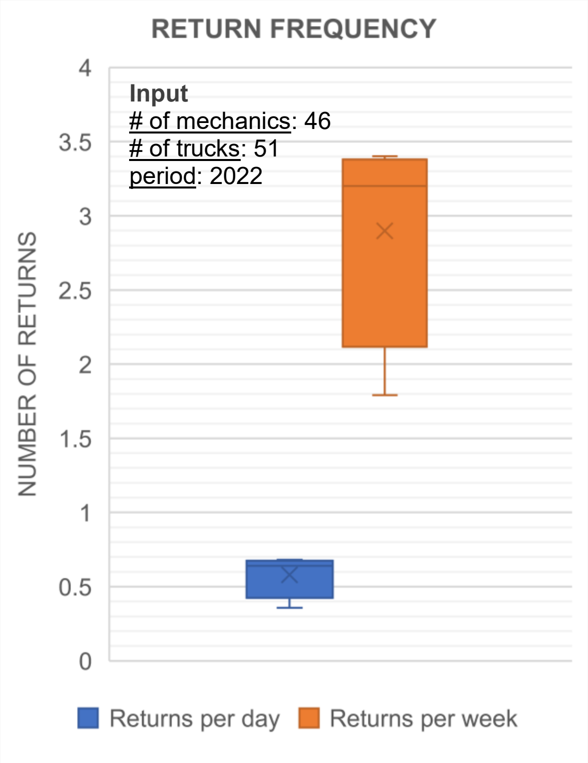

Figure 2-3 Return frequency (per day/week) for each S&M mechanic on average in 2022 over all S&M mechanics.

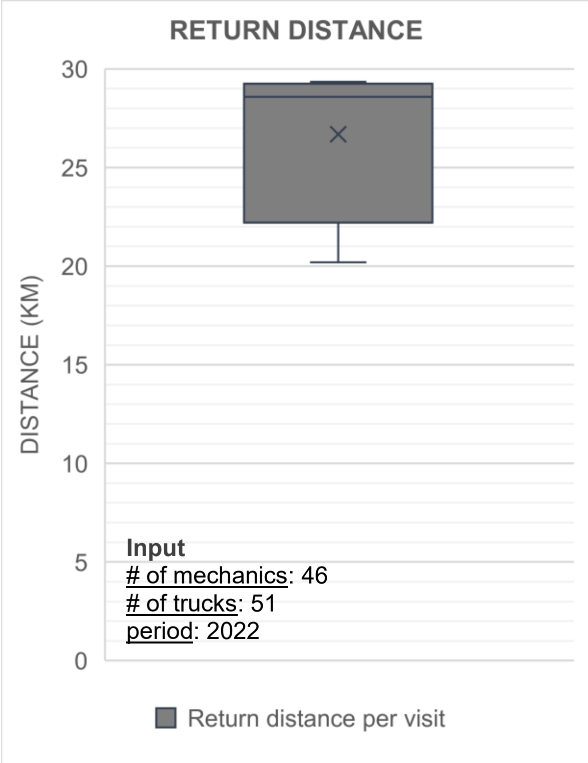

Figure 2-4 Return distance (per day/week) for each S&M mechanic on average in 2022 over all S&M mechanics.

Additionally, the number of times S&M mechanics return to their establishment in general also differs per establishment but this also depends on the distance between the mechanics' residence compared to the establishment, as most mechanics can take their trucks home and do not necessarily need to return to the establishment after a workday. Moreover, the culture as well as the sphere among the S&M mechanics influences whether certain mechanics are more likely to visit the establishment more often. Nevertheless, the return frequency of the S&M mechanics – as previously calculated – can exclusively be explained by visits to the warehouse to replenish their truck inventory.

Furthermore, the truck routing data also indicate the distance each mechanic has travelled with their truck to return to the warehouse for the replenishment of their truck inventory, which is defined as the return distance. Based on this data, the average return distance per mechanic per visit and over all mechanics per visit can be calculated. As a result, the average distance travelled by the S&M mechanics with their trucks to a warehouse for the replenishment of truck inventory is 24.86 kilometres.

Once again, a large difference between the establishments is observed but this time in the return distance of their mechanics. Table 2-5 displays the average kilometres travelled over all mechanics per establishment for each visit to the warehouse. For instance, a mechanic at establishment 1 travels 20.20 kilometres on average to return to the warehouse for truck inventory replenishment. Now, the difference in the average return distance is substantial between establishment 1 and the others.

Table 2-5 Average return distance per visit of each S&M mechanic to the warehouse in 2022 over all S&M mechanics per establishment of RSI.

Establishment	1	2	3	4
Return distance per visit (km)	20.20	28.91	29.36	28.26

In turn, Figure 2-4 displays the data on the return distance per establishment from Table 2-5 to present a clear overview of the significant difference between establishment 1 and RSI's other establishments.

A remark should be made that certain visits to the warehouse were registered with a distance of 0 kilometres. These visits have been excluded from the dataset for determining the return distance as well as the return frequency because these visits are just small movements or repositionings of the S&M

trucks directly around the warehouse and do not represent actual separate visits to the warehouse for the replenishment of truck inventory. It also does not happen that a truck is returned to the warehouse anyway and at that moment a so-called free replenishment could be performed, as the S&M mechanics take their truck home after a workday.

2.3 CURRENT TRUCK INVENTORY MANAGEMENT

Now, insight is required into how truck inventory is currently being managed, as it is a crucial component of the truck inventory replenishment process. This considers the actual kinds of inventory and corresponding quantities stored in the S&M trucks as well as how these inventory items are currently stored in the trucks. In short, this section is focussed on addressing what and how much inventory is actually present in the trucks in combination with its management. Therefore, the following sub-question should be answered.

1.3. In what way is inventory currently stored in the service and maintenance trucks?

The following two sections discuss the kinds and quantities of current truck inventory based on historical stock data regarding truck inventory and the way in which the corresponding inventory items are currently stored based on the current layouts and structure within the trucks.

2.3.1 Current kinds and quantities of inventory

This section defines the current state of the inventory levels in RSI's S&M trucks and identifies which inventory items have exactly been stored in these trucks. Therefore, the following two sub-questions will be subsequently and simultaneously answered.

1.3.1. What kind of inventory is currently stored in the trucks?
1.3.2. In which quantities is the inventory currently in stock in the trucks?

2.3.1.1 Items and quantities stored in truck inventory

By performing a historical data analysis in RSI's software system on truck inventory, the average quantity of each inventory item stored over all S&M trucks and over each month as well as the entirety of 2022 has been mapped completely. Any item that has been stored at least once in an S&M truck in the past year is included in this analysis. Table 2-6 highlights the values corresponding to the top 10 inventory items stored in the S&M trucks, which corresponds to items that have been stored in the trucks in the greatest quantities according to their yearly average.

Essentially, this table depicts the results of this analysis, where the numbers of inventory items that have been stored in the S&M trucks are stated first. In the subsequent columns, the values for the average quantities of the respective inventory items are presented, which are differentiated by (an abbreviation of) each month of 2022 as well as over the entire year of 2022.

Table 2-6 Average quantity of 10 out of 909 inventory items stored in the highest quantities over all S&M trucks in 2022.

	Average inventory per month												Average inventory per year
ItemNr.	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**2022**
4201	9.25	200	150	0	100	0	250	100	200	300	100	0	117.44
4361	300	0	160	150	0	49.5	49.7	0	25	100	133	100	88.97
2081	65.3	-1.50	99.5	100	200	98	0	0	92.5	-1	99.5	49	66.78
2399	0	0	100	0	0	100	300	50	0	99	100	0	62.42
4202	0	0	200	0	0	100	0	100	149	100	100	0	62.42
2334	88.2	100	83.3	16	57.1	17.5	100	47.1	72	38.1	110	10.5	61.65
2244	43.4	75	128	100	0	98.5	41.1	28.6	41.2	43.8	33.3	66.7	58.27
2335	0	0	0	0	66.7	0	115	150	0	100	200	-1	52.58
2246	24.4	39.3	16.7	100	42.9	44.4	61.1	58	36.4	47.7	68.9	31.8	47.62
4116	5.67	0	200	0	100	1	0	200	0	-1	0	37.3	45.24

From the table outlined above, the following observations can be made. First and foremost, certain averages have a value of zero or even a negative value. This means that the registration of truck inventory at RSI has its flaws, as an average inventory level cannot be nonpositive under any circumstances. According to the current truck inventory replenishment process, as depicted in Figure 2-1, the stage in which such flaws are present, entails the “Book inventory item(s) from warehouse and book on truck”-stage. What exactly occurs, is that the respective inventory item has never been properly booked on the truck in the software system while that item has actually been stored in the truck and used by the mechanic to complete an SO. Furthermore, no check or sensor exists in the entire process to detect or correct any of these discrepancies between the actual truck inventory and the corresponding values registered in the software system, as they arise from these stages in the process. Moreover, the positive average inventory levels, that at first glance seem accurate, might in fact be rightly skewed because of the faulty registration.

In addition, certain inventory items of a small size and cheap value are stored in greater quantities for ease of use and storage, as smaller and lighter items can be easily put away without any consequence for the load of the truck inventory. An example concerns inventory item 4201, which concerns a ferrule used to fasten and seal electric wires. This explains why such inventory items should make up the majority of top listings, as the risk of storing large and expensive items in the S&M trucks is significantly greater in comparison. However, no indication is given in the available data for the baseline inventory of these and other items, so what storage quantities of the different inventory items should be aimed for in the S&M trucks. This results in the hoarding of small cheap items and a lack of larger expensive but frequently-used items. So, no real structure currently exists for RSI’s truck inventory management, for instance, in terms of a min-max inventory or other replenishment system.

Overall, shortcomings exist in RSI’s registration of the truck inventory data, as concluded in the previous paragraphs. In turn, no reliable and accurate statements can be made based on that data regarding what kind of inventory items and corresponding quantities have actually been stored over the past year in the S&M trucks. Also, RSI has no monetary control over the cheap as well as expensive inventory items that are actually stored in the S&M trucks as a result of the current truck inventory data. Therefore, RSI should take immediate action to ensure its data quality regarding its truck inventory management. Moreover, a replenishment system should be designed for the inventory of the S&M trucks to define in what way truck inventory should be optimally stored, which will be developed in this research.

2.3.1.2 Cost-price of truck inventory

Even though the current truck inventory levels and a corresponding replenishment technique cannot be accurately determined, the total cost-price for storing these inventory items in the S&M trucks can contribute to defining the holding costs. Holding costs can be formally defined as those costs associated with storing inventory that remains unsold or unused in this case (Tuovila, 2023). This way the impact of storing a specific inventory item in truck inventory can be numerically assessed, as inventory requires a large amount of cash outlay, and decisions about inventory spending can reduce the amount of cash available for other purposes. In turn, defining the cost-price and later on the holding costs for the inventory items will assist in RSI’s monetary control over the inventory items to be stored in the S&M trucks.

The intention is to present the cost-price for each inventory item, that can be required or demanded by an SO, individually, which stands for a single quantity value for each of the 537 inventory items. Figure 2-6 shows how many inventory items have a single quantity cost-price that falls within a certain cost-price interval, where the values on the horizontal axis represent the upper bound of each interval. For instance, 173 different inventory items have a cost-price between €0 and €1.

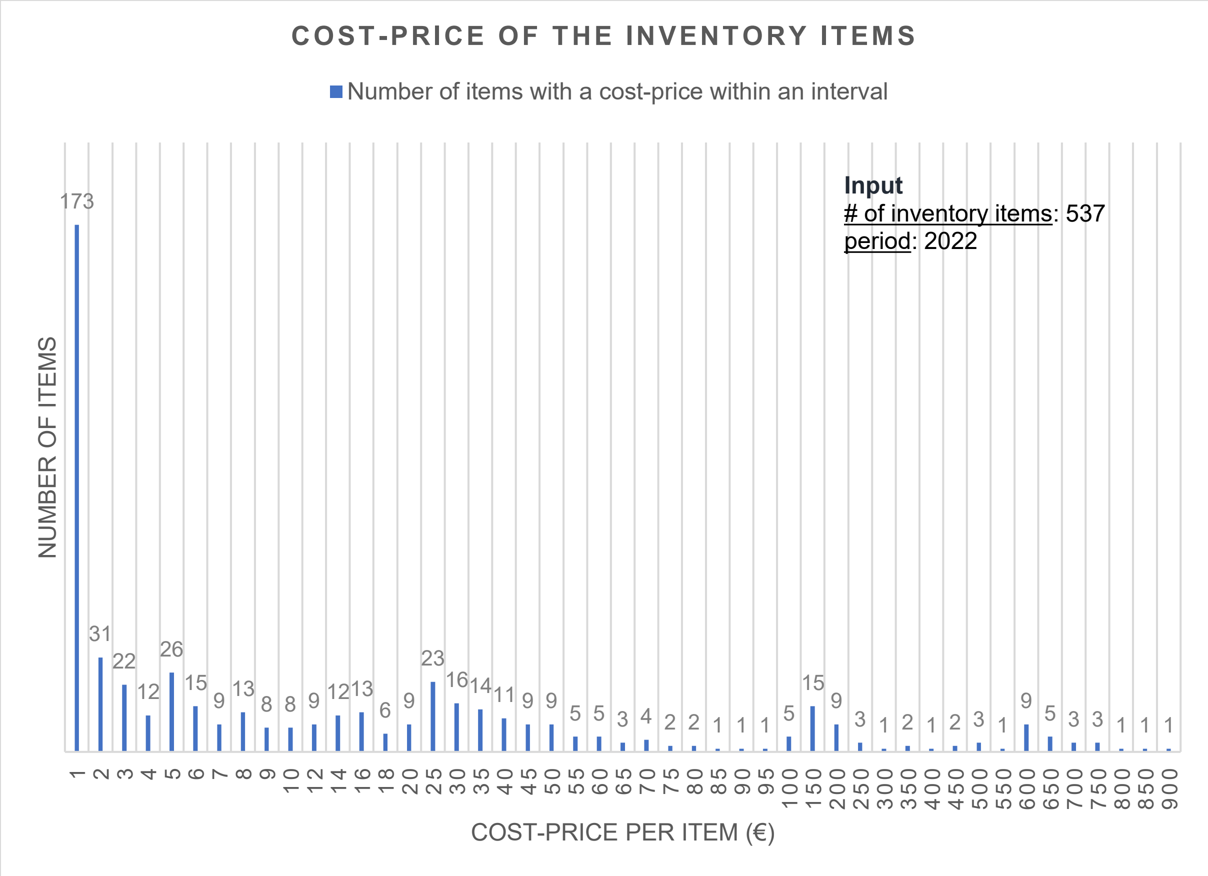

Figure 2-6 Cost-price per inventory item (€) of RSI's 537 inventory items.

Remarkably, almost one-third of all inventory items are cheap, so having a single quantity cost-price of €1 or even cheaper. These cheaper items are mostly bolts, nuts and washers, which are often used in combination, but also safety fuses, plastic tubes and other small consumables. For instance, inventory items 1541, 2205 and 2245 have a cost-price of €0.95, €0.39 and €0.02, and have been used 25, 94 and 580 times on the 2,582 SOs performed in 2022, respectively. However, some incredibly expensive items also exist. In this case, 60 different inventory items cost more than €100, which concern electronic print boards, pumps and control cabinets, among others. Here, inventory items 2296, 3035 and 4538 have cost-price of €588.00, €567.80 and €207.75, and have each been used 1 time on the 2,582 SOs performed in 2022, respectively.

Considering the price variability between the inventory items, as outlined in the previous paragraph, a trend can be identified regarding the cost-price of an inventory item and the total number of times it has been used on the SOs performed in 2022. Cheaper items are used significantly more often in a year than expensive items. So, a negative linear relationship or trade-off exists between the cost-price and total usage of an inventory item in a year. Then, the replenishment system to be developed should consider and define which inventory items in which levels to generally store in the S&M trucks while taking this trade-off into account. This allows for the assessment of the average monetary value that is to be stored in an S&M truck. Unfortunately, the average value that is currently stored in a truck cannot be determined due to the inaccurate current truck inventory levels, as concluded in the previous section.

2.3.2 Current method of truck inventory storage

In order to define the way in which the inventory items are currently stored within the S&M trucks by the respective mechanics as well as to identify potential for optimization in the inventory management of the inventory items within the S&M trucks, the sub-question that is formulated as follows will be answered.

1.3.3. How is the inventory currently stored in the trucks?

When examining the interior of the inventory of a typical S&M truck, which is depicted in Figure 2-7 and Figure 2-8, the following structure and layout in the storage of inventory items can be defined, where certain areas of the truck storage can be accessed through the side door or from the backdoor.

Side door

- **Rack**: Most inventory items, as identified and discussed in the previous sections, are stored in the rack directly opposite of the side door. Such items are usually relatively small in size but can absolutely differ. Each kind of inventory items is assigned to their own drawer in the rack depending on their size, such as the measuring tools, electronics, fuses, magnetic switches, floats, bolts and screws and other general tools. There are 10 small, 4 medium and 4 large drawers included in this rack.
- **Cabinet**: This storage unit is used to store work clothes as well as the fuel tank and is therefore located immediately next to the side door as well as attached to the outer wall of the truck.
- **Hooks**: Directly to the right of the side door are multiple hooks, where the S&M mechanic can hang their jackets and safety gear as well as some commonly used tools, such as screwdrivers and socket wrenches.
- **Open area**: the open area immediately accessible from the side door functions as the main room for the mechanic to move around to select and grab the inventory items they intend to use on a particular SO. Furthermore, larger and heavier items, such as pumps or pipes but also buckets and other large tools, are located here, mostly right in front of the water hose installation in the back of the open area. However, as indicated by the current kinds of inventory in Section 2.3.1, such inventory items are not commonly and casually stored in the S&M trucks due to their size and monetary value. That is why such items do not have a fixed allocated storage location within the truck and are rather stored in this area.

Backdoor

- **Water hose installation**: When opening the back door of the S&M truck, the most prominent storage unit is the water hose installation, which consists of a water tank, different kinds of hoses and an electronic control system. Moreover, various cleaning tools, such as shovels and brooms, are stored on the sides of this installation.
- **Upper rack**: The upper rack is located right above the water hose installation. In this storage unit, the S&M mechanic is free to store any inventory items they require to perform their SOs. Usually, the items stored here do not have a drawer assigned to them in the rack and are therefore stored in crates to maintain some form of structure and distinction between the kinds of items.

Figure 2-7 Typical S&M truck used in practice.

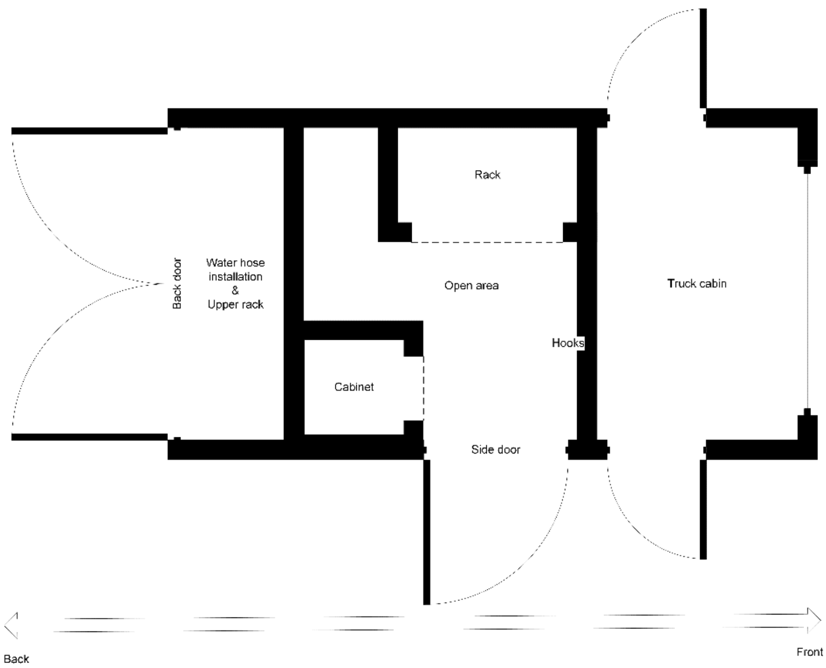

Figure 2-8 Schematic depiction of the interior of an average S&M truck used in 2022. Dimensions are not entirely accurate but the relative proportions are.

The structure and layout within the S&M trucks as defined above is already considerably advanced in the sense that each S&M mechanic has identical racks, cabinets and water hose installations. Only the open area and upper rack are open to the respective S&M mechanic's insights and perceptions. Therefore, almost all inventory items have a fixed location within an S&M truck. However, one may question whether the current allocation of the inventory items to the six storage units is the most efficient and effective regarding the inventory requirements for the SOs to be performed and the mechanic's overview of the actual inventory levels in their S&M truck, as presented in Sections 2.2.1 and 2.3.1, respectively. Also, the current inventory replenishment process for the S&M trucks as a whole in Section 2.1 should be considered in this case.

2.4 CURRENT KEY PERFORMANCE INDICATORS

This section identifies the KPIs that RSI currently applies to measure the efficiency and effectiveness of its inventory replenishment process for the S&M trucks for the purpose of defining the potential KPIs from which RSI and its truck inventory replenishment process could benefit in case they would be measured. It intends to do so by answering the following sub-question.

1.4. What key performance indicators (KPIs) are currently used to measure the efficiency and effectiveness of the truck inventory replenishment process?

According to the discussion with the financial manager and functional manager, RSI effectively uses a singular KPI for this purpose, as has already been briefly introduced in the research motivation outlined in Section 1.2, called productivity.

- **Productivity**: the total amount of time that mechanics spend on direct orders that are related to service contracts in a predefined time horizon, which is usually defined as a workweek. These measurements are based on data registration on SOs and booked working hours in the software system. In short, productivity can be expressed by the following equation.

$$Productivity_{m,t} = \sum_j \sum_i Time\ on\ SO_{i,j,m,t}$$

Where,

$$i = SO \in \{1, 2, 3, \dots\}\ on\ service\ contract\ j$$
$$j = service\ contract\ \in \{1, 2, 3, \dots\}$$
$$m = S\&M\ mechanic\ \in \{1, 2, 3, \dots, 46\}$$
$$t = time\ horizon\ (day, week, month\ or\ year)\ \in \{1, 2, 3, \dots\}$$

Within the internal operations of RSI, weekly meetings are organized to discuss the productivity of the S&M mechanics. As indicated by the equation of productivity, they can delve into the productivity of each S&M mechanic per day, per week or per month. During the financial month-end closing, the aim is to obtain detailed insight into the productivity of the S&M mechanics over the four eldest establishments of RSI. Then, it is determined whether RSI's overall norm regarding the productivity of these mechanics has been achieved and explanations for the reasons why the mechanics' productivity meets or does not meet RSI's norm are searched for.

On the other hand, the relative unproductivity of these mechanics is also addressed during all of these meetings. This KPI is strongly related to the productivity, as the relative unproductivity depends to a great extent on the total amount of time that mechanics spent on direct orders that are related to service contracts in a predefined time horizon.

- **Relative unproductivity**: the percentage of time spent on indirect orders by the respective mechanics, where an indirect order entails an order or action that the S&M mechanic performs, which is never directly related to any SO or service contract and so it does not directly provide value to the client. In this case, replenishing the inventory of the S&M trucks is considered an indirect order by RSI even though certain inventory items need to be replenished in order for a specific SO to be completed. Subsequently, the percentage of time spent doing this would be considered unproductive.
  In turn, the client cannot be charged for an indirect order and the related costs are to be paid by RSI itself. The equation that defines the relative unproductivity of the S&M mechanics is stated below.

$$Relative\ Unproductivity_{m,t} = \frac{\sum_k Time\ on\ indirect\ orders_{k,m,t}}{(\sum_j \sum_i Time\ on\ SO_{i,j,m,t} + \sum_k Time\ on\ indirect\ orders_{k,m,t})}$$

Where,

$$i = SO \in \{1, 2, 3, \dots\}\ on\ service\ contract\ j$$
$$j = service\ contract\ \in \{1, 2, 3, \dots\}$$
$$k = \ indirect\ order\ \in \{1, 2, 3, \dots\}$$
$$m = S\&M\ mechanic\ \in \{1, 2, 3, \dots, 46\}$$
$$t = time\ horizon\ (day, week, month\ or\ year)\ \in \{1, 2, 3, \dots\}$$

Altogether, RSI compares and evaluates the proportion of time spent on the direct SOs versus indirect orders performed to determine whether the S&M mechanics meet its norm, which is spending a total amount of 8 hours per workday or 40 hours per workweek on high-yield SOs related to service contracts per S&M mechanic. When this norm has been met, it is acceptable for the S&M mechanics to be unproductive and spend time on indirect orders, so they are allowed to effectively work more than 8 hours per day and 40 hours per week. However, RSI does not currently assess the truck inventory replenishment process and its corresponding efficiency and effectiveness specifically according to KPIs. An example of which entails the return frequency of the S&M mechanics to the warehouse for truck inventory replenishment or the time or distance that these visits cost. Also, the causes of these visits are not currently considered at all, such as whether the returns occurred for emergency or precautionary truck inventory replenishments. These suggestions could form potential KPIs to be applied in evaluating the optimized truck inventory replenishment process for RSI as well as the productivity of the S&M mechanics in general.

2.5 CONCLUSION

This chapter has derived a clear and detailed overview of the current situation as well as the problem context at RSI regarding its inventory replenishment process for its S&M trucks, which has been achieved by structurally presenting and explaining the data relevant for answering the four sub-questions. By outlining the current truck inventory replenishment process, defining the current replenishment technique, identifying the current way of truck inventory management as well as the current KPIs applied to this process, the research question of this chapter can be answered.

1. *How is the current inventory replenishment process for service and maintenance trucks organized?*

From this chapter can be concluded that RSI has an established step-wise truck inventory replenishment process. However, a missing replenishment technique and inaccurate truck inventory data limit RSI from being in control of the entire process including the productivity of the S&M mechanics, the frequency of inventory replenishments and which inventory items to be replenished in which quantities. Furthermore, the KPIs used by RSI to measure this process limit themselves to the productivity of the S&M mechanics, so disregarding any other components from the truck inventory replenishment process, such as the return frequency or distance and truck inventory levels.

Figure 2-9 displays a schematic summarized input to output figure, in which the inputs gathered during this context analysis and the expected outputs of this research, as pointed out in the context analysis, are stated. Here, the prospect entails that with these inputs and the right literature model, an optimal replenishment system and process can be designed and RSI can register as well as evaluate the related data structurally and correctly. In turn, the productivity of the S&M mechanics increases and RSI has more monetary control over the truck inventory while having the potential to obtain savings in this regard.

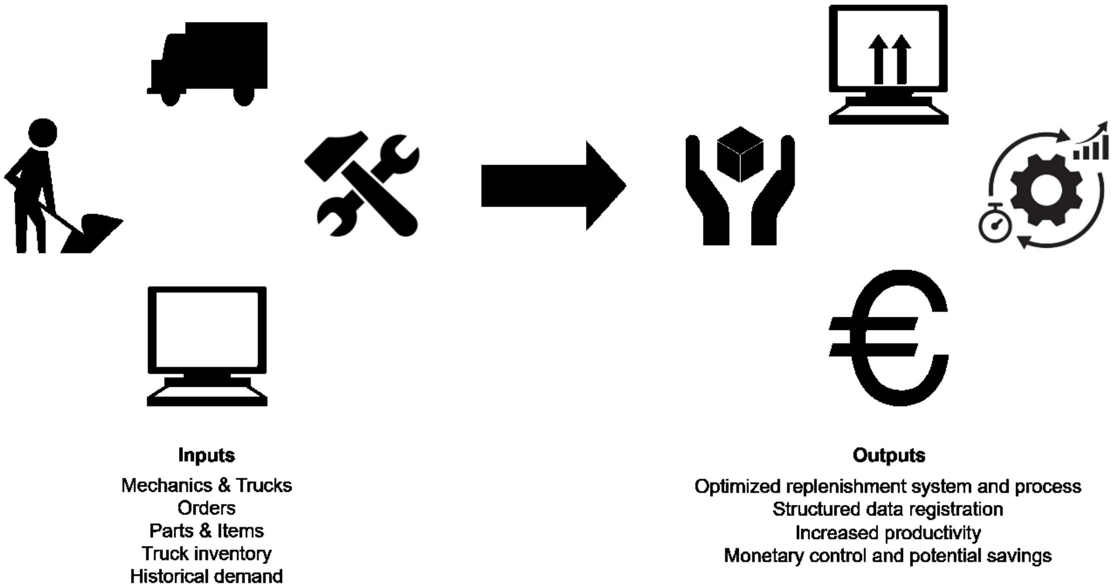

Figure 2-9 Research inputs and expected outputs, which hint towards the development of a replenishment system.

Now, the key questions to be answered in developing the optimized truck inventory replenishment process for RSI are formulated as follows.

- When should truck inventory be replenished?
- What is the optimal time between replenishments?
- What and how much truck inventory should be replenished?

In the subsequent literature study, the key elements from this context analysis will shape its assumptions in order to identify a suitable literature model to adapt in such a way that the aforementioned questions can be answered and RSI's truck inventory replenishment process can be optimized.

3. LITERATURE STUDY

This chapter performs the literature study to seek literature models and scientific contributions that can optimize RSI's inventory replenishment process for the S&M trucks. Based on the zero-measurements as presented in Chapter 2, additional information is needed regarding various replenishment systems and models applicable to truck inventory replenishment processes, replenishment techniques and truck inventory management. Especially, potential optimization techniques for the entire truck inventory replenishment process should be investigated. Therefore, this chapter aims to provide an answer to the following research question.

2. *What information is available in literature regarding truck inventory replenishment processes, replenishment techniques and truck inventory management?*

Initially, the theoretical framework instigates the possible directions for solution models and systems in terms of background literature, requirements and assumptions that these solution approaches should comply with. In the subsequent sections, the resulting models and systems found in the literature are explained, evaluated and adapted, respectively, to develop the ultimate literature model that meets RSI's problem context.

3.1 THEORETICAL FRAMEWORK

The purpose of the theoretical framework is to organize the composition of literature models that can be applied to RSI's problem context and used to optimize the inventory replenishment process for the S&M trucks. First, the foundations of the literature study are explained and the literature models resulting from this literature study are discussed. Then, the requirements and assumptions for the ultimate literature model to comply with are formulated.

3.1.1 Background

When attentively analysing RSI's problem context, the available relevant data regarding the truck inventory replenishment process and the key questions to be answered, the corresponding core characteristics of these three components from Chapter 2 greatly resemble one specific spare parts management issue known in literature as the repair kit problem. As defined in all related literature, the repair kit problem determines which inventory items and how many parts of these items should be stored in inventory or "repair kit" of the S&M trucks.

Certain key elements for the repair kit problem have been established in the context analysis for which specific scientific literature is required in order to define how to optimize RSI's truck inventory replenishment process. The three most important features entail independent demand between inventory items differentiated by the three kinds of SOs performed, replenishment costs that depend on the return distance and advance demand information (ADI). Further requirements and assumptions that the formulation of the repair kit problem should meet, will explicitly be outlined in Section 3.1.2. In case some of these elements are not addressed by repair kit literature, literature on other inventory management models should be looked into.

However, other inventory management approaches such as general multi-item inventory models and can- or must-order policies mainly focus on warehouse inventory levels instead of service truck inventory levels used by field service mechanics for on-site jobs (Saccani et al., 2017) and do not consider the same complexity and uncertainty involved in the customer demand, inventory replenishments and backorders. Specifically, the repair kit problem is a type of inventory model tailored to support organizations that provide field repair services to their customers, such as RSI, by determining which inventory items and corresponding levels to attain in the trucks used to complete these services accordingly (Rippe & Kiesmüller, 2023).

Therefore, this literature study focuses completely on collecting and evaluating potential variations on the repair kit problem. If certain features, as previously-touched upon, are not included in any of the existing repair kit literature, these features will be treated for the first time in this research. So, the repair kit problem to be formulated is going to be framed based on scientific literature and will present model innovations concerning the specific problem that RSI faces regarding its inefficient and ineffective truck inventory replenishment process, as outlined in detail in Chapters 1 and 2. Now, the following sub-questions of this research can be answered.

2.1. *What truck inventory replenishment processes exist in literature, and which fit with service and maintenance trucks?*
2.2. *What replenishment techniques exist in literature, and which are applicable to service and maintenance trucks?*
2.3. *What are suitable methods to manage the inventory in service and maintenance trucks?*
2.4. *What optimization techniques for inventory replenishment processes for service and maintenance trucks are available in the literature?*

In order to select the most applicable repair kit problem to optimize the current state of RSI's truck inventory replenishment process, the different variations of the repair kit problem as found during the literature study should be elaborated on. Therefore, the history of relevant literature papers and their characteristics with respect to the repair kit problem are mapped as follows.

The repair kit problem, as is fitting to this research, was firstly addressed by Smith et al. (1980) as the problem of determining the cost-minimizing set of inventory items to be carried by a mechanic who performs jobs or SOs, which is basically another term for jobs used in this research, in the field. After every job, the mechanic's repair kit is replenished making this a single-job problem. To derive the optimal repair kit, Smith et al. (1980) employ an unconstrained cost model that weighs inventory holding costs for the inventory items held in the repair kit against penalty costs incurred for failing to complete jobs at once. In general, cost models, including the one developed by Smith et al. (1980), aim to minimize the total costs due to inventory holding costs for carrying inventory items and costs for uncompleted jobs. The latter may include travel and labour costs plus the opportunity costs for the customer and/or loss of goodwill (Saccani et al., 2017).

While several inventory items might be needed to complete a job, only one part per item may be needed and demands for different inventory items are independent. Adopting these assumptions, Graves (1982) and Hausman (1982) consider a service model with a job fill rate constraint that ensures that the chance to complete a job is above a given threshold. In service models, generally speaking, the objective is to minimize the holding costs with a constraint over the service level. Most models, such as the models of Graves (1982) and Hausman (1982), measure the service level through the job fill rate, the fraction of jobs that can be completed from the repair kit (Saccani et al., 2017).

Further extensions to the single-job repair kit problem incorporate dependent demands and demands for multiple parts per inventory item by one job (Mamer & Smith, 1982; March & Scudder, 1984), spare machines (Mamer & Smith, 1985) and budget constraints (Mamer & Shogan, 1987). Brumelle & Granot (1993) derive a monotone sequence of optimal repair kits for different parametrizations of their cost model's objective function.

Thereafter, Heeremans & Gelders (1995) are the first ones to study a multiple-job repair kit problem, where the mechanic performs several jobs before replenishing the inventory of the repair kit. In contrast to the single-job papers, however, they consider a tour fill rate instead of a job fill rate meaning that they regard the probability that all jobs in a tour can be completed rather than the chance that an arbitrary job is completed. Teunter (2006) is the first one to derive a job fill rate equation for the multiple-job repair kit problem. He develops a general formulation for a cost as well as a service model. Nevertheless, for the calculation of the job fill rate, he requires independent demands for different inventory items and at most one part of each item may be needed for each job. He also assumes that inventory items are left with the first job who needs them regardless of whether this job can be completed in its entirety. To determine the repair kit, two greedy heuristics are proposed, which concern a job heuristic that makes use of the job fill rate and a simpler part heuristic that is based on a part fill rate. Following Teunter (2006), three further extensions to the multiple-job repair kit problem have been presented (Bijvank et al., 2010; Saccani et al., 2017; Prak et al., 2017). Bijvank et al. (2010) assume a job-completion process in which available spare parts are not left with customers for a second visit if their jobs cannot be completed at the first try. Saccani et al. (2017) solve an integer linear model to determine the repair kit that would have performed best given past demand data and assess its future performance based on simulation. Prak et al. (2017) consider a non-zero replenishment lead time for inventory items and manage the contents of the repair kit using individual (s, S)-policies for the different inventory items.

All repair kit papers previously-discussed assume that the condition of the job is unknown to the mechanic before their first visit to the job. All jobs are taken to be homogeneous and historical demand data aggregated across all past jobs are used to decide which inventory items to put into the repair kit. In contrast to this, Rippe & Kiesmüller (2023) (2) include information about the source of the demand in their model. So, not only historical data are used to estimate spare part requirements, but also real-time information about the condition of the job. They extend the model described in the seminal multiple-job repair kit paper by Teunter (2006), adjusting it to incorporate imperfect advance demand information (ADI). Furthermore, they allow spare parts to be returned to the warehouse, which is completely new to the repair kit problem. The only other previous contribution so far that considers ADI for the repair kit problem is also from Rippe & Kiesmüller (2023) (1), where the ADI obtained is considered to be perfect. The difference between imperfect and perfect ADI entails the degree of uncertainty incorporated in the information about customer demand. In perfect ADI, the mechanic has complete and reliable information about the demands for different inventory items in advance, so the orders and jobs cannot and do not change over time once the information is known. In other words, perfect ADI can also be called certain advance demand. In imperfect ADI, the demand information for orders and jobs is also known beforehand but this information is uncertain and can change at any moment (Boudrika, 2015).

3.1.2 Requirements and assumptions

From the relevant data presented in the context analysis in Chapter 2 together with the introduced literature in the previous section can be determined with which requirements and assumptions the ultimate literature model for RSI's truck inventory replenishment process has to comply. In turn, the literature models as outlined in Section 3.1.1 can be assessed based on their degree of applicability to these requirements and assumptions. The repair kit problem to be applied should meet the following requirements and assumptions.

- Multiple inventory items can be demanded by an SO, also called complex jobs (Rippe & Kiesmüller, 2023).
- Multiple parts of the same inventory item can be demanded by an SO.
- A multiple-period/multiple-jobs perspective is applied.
- The number of SOs per tour are random variables within in a predefined interval with certain probabilities.
- Multiple kinds of (heterogeneous) SOs are performed according to certain probabilities.
- Replenishment lead time for truck inventory is non-existent or equal to 0, as the inventory items are always available in the warehouse for replenishment (Saccani et al., 2017).
- No inventory items are returned to the warehouse from truck inventory once they are stored in the S&M trucks (Rippe & Kiesmüller, 2023).
- Inventory items are immediately used on the first SO that demands them even if the SO cannot be entirely completed.
- If an SO cannot be entirely completed, penalty costs are incurred, the S&M mechanic orders the missing item(s) and the truck inventory replenishment process is initialized.
- Uncompleted SOs in a tour are added to the start of the next tour. Subsequently, the uncompleted SOs will be immediately completed.
- Truck inventory replenishments will take place at the end of a tour.
- Truck inventory replenishments are included to prevent penalty costs but require replenishment costs (Saccani et al., 2017).
- Return frequencies and distances should be determined, monitored and/or optimized.
- Penalty and replenishment costs should be based on return frequency and/or distance.
- Developing a periodic replenishment policy can be assumed, such as daily, weekly or more specified. Though, the S&M mechanics currently issue replenishment orders daily (Saccani et al., 2017). This depends on the trade-off between total holding costs of the inventory items to be included in the repair kit and the return frequency and/or distance.

- For the items included in the repair kit, the order-up-to levels are equal to their repair kit quantities (Saccani et al., 2017; Prak et al., 2017). This means that, for the inventory items included in the repair kit, their maximum stock levels in truck inventory are defined by their inventory levels in the repair kit.
- For the inventory items not included in the repair kit, the ordered quantity corresponds to the quantity demanded by the uncompleted SOs between two subsequent replenishments (Saccani et al., 2017).
- Demand between the inventory items is assumed to be independent for the formulation of the repair kit problem, as has been thoroughly argued and justified in Section 2.2.1. Though, the ultimate repair kit problem is intended to be tested using the demand between the different inventory items.
- Perfect or no ADI is known about what inventory items and how many parts of these items are exactly required depending on the kind of SO to be performed (Rippe & Kiesmüller, 2023).
- An SO's demand for a certain quantity of an inventory item does not exceed the maximum quantity of that inventory item used on historical SOs (Teunter, 2006).
- The repair kit problem should focus on either the part-fill rate in combination with the approximate job-fill rate instead of the exact job-fill rate or the cost model instead of the service model, as RSI's truck inventory replenishment process deals with multiple parts of each inventory item that can be used on a single SO (Teunter, 2006).
- No explicit financial or size constraint in the form of an inventory budget or a truck inventory space capacity for the repair kit is going to be inflicted (Saccani et al., 2017; Heeremans & Gelders, 1995; Bijvank et al., 2010).

3.2 LITERATURE MODEL

Now that the theoretical framework has been established in terms of which repair kit problems have been developed in literature so far and the demands to which the ultimate repair kit problem should comply, the different variations of the repair kit problem can be evaluated on their applicability. Subsequently, the most suitable literature model(s) can be selected and outlined in such a way that the ultimate formulation of the repair kit problem can be used to optimize RSI's inventory replenishment process for the S&M trucks.

3.2.1 Selection of literature model

In order to select the paper(s) that will shape the repair kit problem to be solved, the different characteristics of the 15 repair kit problems formulated in the papers identified during the literature study have been assessed and compared on their applicability to this research. Table 3-1 presents an overview of the repair kit problems introduced by different authors as initially discussed in Section 3.1.1 and the 18 characteristics in which these problems may differ. In particular, the last row of this table represents this research and its corresponding requirements and assumptions, as defined in Section 3.1.2, to enable the assessment of and comparison between the papers to these requirements and assumptions.

For this table, inspiration has been drawn from the literature overview table from Rippe & Kiesmüller (2023) (2) to which some alternative characteristics have been added to encompass the entirety of this research and to illustrate all characteristics on which the various papers might differ. A plus sign indicates that the respective literature paper includes and addresses the corresponding characteristic in its repair kit problem. For instance, all papers have developed a repair kit problem, which considers multiple inventory items to be included in the repair kit, which is also required by this research. Therefore, no unique distinction can be made between the papers on this particular characteristic.

Furthermore, what stands out is that certain requirements and assumptions have not been included in this table because of one of the following reasons. Firstly, either no repair kit problem or all repair kit problems developed in existing literature include(s) that particular requirement or assumption. Secondly, that requirement or assumption is not a hard constraint in selecting or eliminating the respective repair kit problem in the sense that all repair kit problems can be adapted to meet that particular requirement or assumption. However, the currently left-out requirements and assumptions in the table below will still be considered and discussed in the selection of the final paper(s).

Table 3-1 Literature overview: repair kit problem.

	Multiple item	*Single part*	*Multiple parts*	*Single job*	*Multiple jobs*	*Immediate use*	*Complete use*	*Zero lead time*	*Positive lead time*	*With returns*	*Without returns*	*With replenishment frequency*	*Without replenishment frequency*	*Independent demand*	*Dependent demand*	*Imperfect ADI*[1]	*Perfect ADI*[1]	*No ADI*[1]
Smith et al. (1980)	+	+		+			+	+			+		+	+				+
Graves (1982)	+	+		+			+	+			+		+	+				+
Hausman (1982)	+	+		+			+	+			+		+	+				+
Mamer & Smith (1982)	+		+	+			+	+			+		+		+			+
March & Scudder (1984)	+		+	+			+	+			+		+		+			+
Mamer & Smith (1985)	+		+	+			+	+			+		+		+			+
Mamer & Shogan (1987)	+		+	+			+	+			+		+		+			+
Brumelle & Granot (1993)	+		+	+			+	+			+		+		+			+
Heeremans & Gelders (1995)	+	+			+		+	+			+		+	+				+
Teunter (2006)	+	+	+		+	+		+			+		+	+	+			+
Bijvank et al. (2010)	+		+		+		+	+			+		+	+				+
Saccani et al. (2017)	+		+		+	+		+			+	+		+				+
Prak et al. (2017)	+		+		+	+			+		+		+	+				+
Rippe & Kiesmüller (2023) (1)	+		+		+	+			+		+		+	+			+	
Rippe & Kiesmüller (2023) (2)	+		+		+	+		+		+			+	+		+		
This research	+		+		+	+		+			+	+		+			+	+

[1] Advance Demand Information

Other than the multiple item characteristic listed in Table 3-1, significant differences in the characteristics exist between the different repair kit problems, especially between the more recent papers. The key differences between the papers will subsequently be highlighted in comparison to the required characteristics of this research.

When assessing the various repair kit problems against the requirements and assumptions as depicted in the table, no repair kit problem exactly matches these requirements and assumptions. The most applicable paper meets 9 out of 10 characteristics that this research defines, which concerns the respective repair kit problem from Saccani et al. (2017). Remarkably, this paper includes the replenishment frequency but does not consider any form of ADI, which is of significant importance to the optimization of RSI's truck inventory replenishment process. The only repair kit problems to consider any form of (perfect or imperfect) ADI are the ones developed by Rippe and Kiesmüller (2023) (1) and (2). In comparison to Saccani et al. (2017), these papers consider the replenishment frequency as a given input. However, their repair kit problems can be adjusted and tested in such a way that these papers meet 10 out of 10 research characteristics and that the optimal replenishment policy can subsequently be defined.

Other papers, whose repair kit problems might qualify for the optimization of RSI's truck inventory replenishment process, also do not consider any form of ADI or the replenishment frequency. Furthermore, some of these papers also lose out on the immediate use/reservation of inventory items on uncompleted SOs, zero lead time for inventory replenishments and independent demand between different inventory items. Potentially adapting the repair kit problems in these papers in such a way that they will meet all of these characteristics would be a vain attempt, as the papers from Rippe and Kiesmüller (2023) (1) and (2) already possess all of these characteristics except for the replenishment frequency, which is a much simpler characteristic to incorporate into the repair kit problem than any form of ADI. As a result of this perception, these papers and the papers that comply with even less characteristics of this research are deemed not suitable to be applied and will therefore not be selected. In turn, due to the significance of ADI to this research, both papers from Rippe and Kiesmüller (2023) (1) and (2) have the potential to complement each other in order to create a repair kit problem that complies with all necessary requirements and assumptions stated in Table 3-1 so far, especially regarding the ADI, no returns and zero lead time.

Delving into the requirements and assumptions that were not included in Table 3-1 as well as exclusively focussing on the papers of Rippe and Kiesmüller (2023) (1) and (2), both of these papers do not consider the possibility that multiple kinds of (heterogeneous) SOs can be performed and that each kind of SO can have different inventory requirements or demands for certain inventory items. Moreover, Rippe and Kiesmüller (2) are the only one to consider a minimum and maximum number of SOs with corresponding probabilities for the number of SOs that can be performed in a tour. Furthermore, both papers do not include replenishment costs for a regular repair kit replenishment. With inspiration from the paper of Saccani et al. (2017), these costs can be included in the formulation of the ultimate repair kit problem. Subsequently, neither of these papers consider the distance that the S&M mechanics have to travel to the warehouse for the replenishment of their repair kit – the return distance – in their penalty or replenishment costs. Next, Rippe and Kiesmüller (2023) (2) adopt an undesirable capacity constraint in their repair kit problem while Rippe and Kiesmüller (2023) (1) do not inflict any constraint finance- or size-related. Moreover, Rippe and Kiesmüller (2023) (1) are the only one to consider a maximum quantity of each inventory item that can be demanded by a single SO. Also, neither of these papers develop a periodic replenishment policy in terms of the replenishment frequency or distance. Instead, Rippe & Kiesmüller (2023) (2) derive an optimal inventory policy. Thereafter, both papers assume that the order-up-to levels are equal to the repair kit quantities determined for the inventory items. Besides that, only Saccani et al. (2017) have explicitly included the policy that for the inventory items not included in the repair kit, the ordered quantity corresponds to the quantity demanded by the uncompleted SOs, which should be added to the ultimate repair kit problem. Finally, Rippe and Kiesmüller (2023) (2) recommend the repair kit problem in this research to be solved by the part-fill rate in combination with the cost model while Rippe and Kiesmüller (2023) (1) apply the exact job-fill rate together with the cost model. All other remaining requirements and assumptions are met by either of these repair kit problems.

Although the papers from Rippe and Kiesmüller (2023) (1) and (2) nicely complement each other on most requirements and assumptions of this research, they do not include – as well as all other existing scientific literature on the repair kit problem – crucial characteristics that the repair kit problem of this research requires. Two of these missing characteristics entail the multiple kinds of SOs that can be performed and the consideration of the replenishment policy including the return frequency and/or distance. Furthermore, the way in which these papers implement ADI in their formulations of the repair kit problem is completely different from the ADI that is required by this repair kit problem, as Rippe and Kiesmüller (2023) (2) bases their ADI on failure codes only and not the actual demand for the different inventory items while Rippe and Kiesmüller (2023) (1) assumes to know all demand information perfectly in advance. The repair kit problem to be solved in this research concerns a specific combination of perfect or no ADI based on the kinds of SOs to be performed, which neither of these papers address. The main contribution of this research to scientific literature is to address these characteristics and include them in the formulation of the repair kit problem to be solved, which has never been done in any literature before to the best of my knowledge. So, this research aims to formulate and solve a repair kit problem according to the requirements and assumptions formulated in Section 3.1.2 that includes multiple kinds of SOs, an optimal replenishment policy based on the return frequency and/or distance, and a novel implementation of ADI based on maintenance and incidental SOs on the one hand and malfunction SOs on the other hand.

Conclusively, the repair kit problems from Rippe and Kiesmüller (2023) are selected to be the most applicable to the objective that this research intends to achieve, which is to optimize the current state of RSI's truck inventory replenishment process. In turn, these repair kit problems will be combined and adapted to accurately depict RSI's inventory replenishment process for the S&M trucks according to the total of 22 requirements and assumptions.

3.2.2 Model notations

Now, the first step entails defining notations that provide the basis for the formulation of the actual model of the repair kit problem. The notations that will be used in the remainder of this research are listed in Table 3-2. These model notations are inspired by those of Rippe and Kiesmüller (2023) (1) and (2). However, particular attention has been devoted in these notations to the inclusion of the multiple kinds of SOs that can be performed, the replenishment policy including the return frequency and/or distance, and either perfect or no ADI.

Table 3-2 Model notations.

Terminology	
Tour	Sequence of SOs before a repair kit is replenished
Job fill rate	Fraction of a single SO not broken
Tour fill rate	Fraction of an entire sequence of SOs not broken
Input parameters	
C_{min}	Minimum number of SOs in a tour
C_{max}	Maximum number of SOs in a tour
J	Number of different kinds of SOs
N	Number of different inventory items
M	Number of different S&M mechanics
$h_n, n = 1, \dots, N$	Holding cost per inventory item n per tour
$r_m, m = 1, \dots, M$	Replenishment cost for mechanic m
$P_i, i = 1, \dots, C$	Penalty cost for broken/uncompleted SO i in the tour
$P(C = c)$	Probability that the number of SOs in a tour is c
$P(C_{i,j} = c_j), i = 1, \dots, C, j = 1, \dots, J$	Probability that SO i is of kind j
$P(D_{i,j,n} = d_{j,n}), i = 1, \dots, C, j = 1, \dots, J, n = 1, \dots, N$	Probability that $d_{j,n}$ parts of inventory item n are demanded by SO i of kind j
$P(D_{i,n} = d_n), i = 1, \dots, C, n = 1, \dots, N$	Probability that d_n parts of inventory item n are demanded by SO i of any kind
$d_n^{max}, n = 1, \dots, N$	Maximum number of parts of inventory item n required by a single SO of any kind
Stochastic variables	
C	Number of SOs in a tour
$C_{i,j}, i = 1, \dots, C, j = 1, \dots, J$	SO i is of kind j

$D_{i,j,n}, i = 1, \dots, C, j = 1, \dots, J, n = 1, \dots, N$	Demand of SO i of kind j for inventory item n
$D_{i,n}, i = 1, \dots, C, n = 1, \dots N$	Demand of SO i of any kind for inventory item n
$D_i = (D_{i,1}, \dots, D_{i,N})$	Demand of SO i of any kind for all different inventory items
$D_n, n = 1, \dots, N$	Total demand for inventory item n in one tour
$D = (D_1, \dots, D_N)$	Total demand vector in one tour
$X_n, n = 1, \dots, N$	Net inventory level of inventory item n in the repair kit at the end of the previous tour
$X = (X_1, \dots, X_N)$	Net inventory levels of the inventory items in the repair kit at the end of the previous tour
Other notations	
$Y_n, n = 1, \dots, N$	Net inventory level of inventory item n in the repair kit after replenishment before the start of the tour
$Y = (Y_1, \dots, Y_N)$	Net inventory levels of the inventory items in the repair kit after replenishment before the start of the tour
$NJFR(i, y)$	Job fill rate for SO i in the next tour given information y
$NTFR(c, y)$	Tour fill rate for the entire upcoming tour given information c and y
$V_t(x, c, \pi)$	Total expected (holding, replenishment and penalty) costs in t tours starting in state (x), given information c and applying policy π
$R_m, m = 1, \dots, M$	Replenishment of the repair kit for mechanic m per tour
R	Total replenishments over all mechanics per tour

The repair kit problem formulation using the model notations as presented in the table above will be outlined in the following section, which is a combination and adaptation of the repair kit problems from Rippe and Kiesmüller (2023). Especially, the multiple kinds of SOs, the extensive replenishment policy, and the (perfect or no) ADI have been clarified in this formulation.

3.2.3 Formulation of the repair kit problem

For each tour, which concerns a sequence of SOs to be performed over one or multiple workdays between two subsequent visits to the warehouse for the replenishment of the repair kit, the following order of events will occur. First, SOs are allocated to tours based on their geographical locations in relation to each other and the S&M mechanics' residences, as explained in Section 2.2.1. The information available on the SOs' demand regarding the different kinds of SOs J is passed on to S&M mechanic m, who adjusts the content of the repair kit to the SOs' inventory item requirements. Note that only demand information on maintenance ($j = 1$) and incidental ($j = 3$) SOs can be known perfectly in advance, not malfunction ($j = 2$) SOs. So, the mechanic is not able to exactly adapt their repair kit for the inventory item requirements of malfunction SOs. Next, the S&M mechanic visits the SOs in their tour one by one, attempting to complete them with the inventory items carried in the repair kit. Costs attributed to the repair tour are charged after the last SO in the tour.

The number of SOs in a tour is modelled with a random variable C. The minimum and the maximum number of SOs in a tour are denoted by C_{min} and C_{max}. The probability that $c \in \{C_{min}, \dots, C_{max}\}$ SOs need to be visited in one repair tour is given by $P(C = c)$. Each of the C SOs demands at least one out of N different inventory items. Furthermore, each SO in the tour can be a maintenance, malfunction or incidental SO, which is modelled by random variable C_{ij}, according to the probability that SO $i \in \{1, \dots, C\}$ in the tour is of kind $j \in \{1, \dots, J\}$ given by $P(C_{i,j} = c_j)$. In case of a maintenance or incidental SO and if its demand is known to the S&M mechanic when they replenish their repair kit before starting the next tour in which that particular SO is to be performed, these inventory item requirements are essentially perfect ADI. As inventory item requirements for malfunction SOs cannot be known, no ADI can be assumed.

Each S&M mechanic can carry N different inventory items on their truck, which might be required to perform an SO. Multiple parts of each inventory item may be required by each SO no matter whether an SO has ADI. However, the inventory item requirements depend on the kind of SO in consideration. Let $D_{i,j,n} \in \{0, \dots, d_n^{max}\}$ ($i \in \{1, \dots, C\}, j \in \{1, \dots, J\}, n \in \{1, \dots, N\}$) denote the ith SO's demand for inventory item n, where the SO is of kind j. The demands of different SOs for the same inventory item as well as the requirements of one SO for different inventory items are considered to be independent.

In turn, given the kind of SO j, the demand for any inventory item $n \in \{1, \ldots, N\}$ of SO $i \in \{1, \ldots, C\}$ follows an established empirical distribution (Larsen & Marx, 2011) that generates the demand probabilities $P(D_{i,j,n} = d_{j,n})$, which means that $d_{j,n}$ can attain any integer value between 0 and d_n^{max} according to some empirical probability. Conditioning these demand probabilities by the probability that SO $i \in \{1, \ldots, C\}$ in the tour is of kind $j \in \{1, \ldots, J\}$, let the probability that $d_n \in \{0, \ldots, d_n^{max}\}$ parts of inventory item $n \in \{1, \ldots, N\}$ are demanded by any (kind of) SO i be given by $P(D_{i,n} = d_n) = \sum_{j=1}^{J} \big(P(C_{i,j} = c_j) \cdot P(D_{i,j,n} = d_{j,n})\big)$, which retains an empirical distribution. Subsequently, the aggregated demand for inventory item $n \in \{1, \ldots, N\}$ by the SOs to be performed in the upcoming tour is a convolution of the empirical distribution for $P(D_{i,n} = d_n)$ conditioned by the probability that $c \in \{C_{min}, \ldots, C_{max}\}$ SOs need to be visited in one repair tour, as the number of SOs to be performed in a tour C is stochastic. So, under these conditions, let $D_n = \sum_{i=1}^{C_{max}} P\big(C > (i-1)\big) \cdot D_{i,n}$ denote the aggregated demand for inventory item $n \in \{1, \ldots, N\}$ in one tour. Then, $D = (D_1, \ldots, D_N)$ denotes the vector of total demand across all inventory items per tour.

Given the potential number of SOs in the upcoming tour and the probabilistic demands for inventory items, the S&M mechanic decides whether to modify the content of their repair kit to meet the presumed needs of the SOs. All modifications come into effect immediately, so no lead time for replenishment is incurred. We denote the content of the repair kit at the end of the previous tour with $X = (X_1, \ldots, X_N)$, and after replenishment but before the start of the next tour by $Y = (Y_1, \ldots, Y_N)$. For each inventory item $n \in \{1, \ldots, N\}$, the mechanic can update the inventory level to any value $Y_n \geq X_n$, where $Y_n \geq 0$. In case any $Y_n > X_n$, this corresponds to a replenishment. In this way, the mechanic can react to anticipated stockouts for all (kinds of) SOs. In case, $Y_n = X_n$, the inventory level of inventory item n is not altered at all. The replenishments for one tour are counted per mechanic $m \in \{1, \ldots, M\}$ per tour by $R_m \in \{0, 1\}$, where a replenishment is defined as any modification to the inventory levels in the repair kit before the start of the next tour. In this case, it does not matter if the mechanic only replenishes inventory item n or all inventory items simultaneously. Let $R = \sum_{m=1}^{M} R_m$ denote the total amount of replenishments performed over all mechanics each tour.

Next, the S&M mechanic visits the SOs one by one to perform on-site jobs. To complete the SO, the mechanic identifies broken, missing or generally needed components and replaces them with the inventory items from the repair kit. If all required inventory items are available, the SO is deemed complete and broken otherwise. Following, it is assumed that all inventory items are left with the first SO who needs them regardless of whether that SO can be completed.

Once the S&M mechanic completes the tour, costs incurred in or attributed to that tour are determined. Three different types of costs are considered. Firstly, part-specific holding costs h_n are incurred for each part of any item n stored in the repair kit, as an average of the repair kit's inventory level right after replenishment Y_n and its inventory level after the last SO in the tour has been visited $E[(Y_n - D_n)^+]$ for all inventory items $n \in \{1, \ldots, N\}$. Secondly, mechanic-specific replenishment costs r_m are incurred in case of any modification to the content of the repair kit that S&M mechanic $m \in \{1, \ldots, M\}$ makes before the start of the tour. The reason that the replenishment costs differ per mechanic is due to the difference in return distance from their residence to the warehouse, as some mechanics live further away from their nearest warehouse than others. The greater the return distance of a mechanic, the greater the replenishment costs for that mechanic. Finally, the S&M mechanic incurs penalty costs P_i for each broken SO $i \in \{1, \ldots, C\}$ in the tour. These penalty costs include the actual costs for a second visit to the SO and a penalty for the loss of goodwill. Furthermore, the exact penalty costs incurred depend on the location of the broken SO in the sequence of the tour, because the earlier an SO is broken in a tour, the longer that SO has to wait for a second visit. In fact, the rest of the tour has to be finished first before the broken SO can be completed at the start of the next tour. Leaving an SO uncompleted for longer periods of time results in serious consequences for the immediate environment. So, the earlier an SO is broken in a tour, the higher the penalty costs will be, and vice versa. So, the penalty costs downscale uniformly relative to the number of SOs that remain to be performed in the tour including the current uncompleted SO $i \in \{1, \ldots, C\}$ according to $P_i = (C - i + 1)/C$, which still need to be scaled to the number of workdays between replenishments. The penalty costs should also be conditioned by the probability that $c \in \{C_{min}, \ldots, C_{max}\}$ SOs need to be visited in a tour to account for these SOs actually being performed and to which penalty costs can be assigned due to having the potential to be broken.

The repair kit problem with ADI as formulated above can be modelled as a Markov decision process (MDP) with state spaces (X) defined by the repair kit X at the end of the previous tour before replenishment, and with the probability distributions for the number of SOs in a tour and the demand for the inventory items. It makes sense to assume that the minimum for inventory level X_n as well as Y_n of any item $n \in \{1, \dots, N\}$ is 0, which means either no parts of an inventory item were stored in the repair kit at all or that all parts of an inventory item stored in the repair kit were required by the SOs. Some SOs might even have required a certain inventory item quantity that was not available in the repair kit anymore resulting in broken SOs. In turn, the maximum for inventory level X_n of any item $n \in \{1, \dots, N\}$ in the repair kit is inventory level Y_n meaning that the expectation was that the SOs combined would require the total quantity of an inventory item stored in the repair kit but none of them actually required that item at all. If there is a maximum of C_{max} SOs and the maximum number of parts of inventory item $n \in \{1, \dots, N\}$ that can be demanded by one SO is d_n^{max}, the corresponding maximum for inventory level Y_n of any item n equals $C_{max} \cdot d_n^{max}$. That means that $X \in \{0, \dots, Y_n\}^N$ as well as $Y \in \{0, \dots, C_{max} \cdot d_n^{max}\}^N$. As defined before, the number of SOs to be performed ranges from C_{min} to C_{max} and each SO may require multiple parts of more than one item out of N inventory items. Thus, for a given number of SOs, $D_i \in \{D_{i,1}, \dots, D_{i,N}\}^C$.

The overall objective is to find a stationary replenishment policy π^* that minimizes the long-run average costs per tour over an infinite time horizon. The existence of such an optimal policy is guaranteed for average-costs MDPs with finite state and action spaces, which holds in this case.

To derive the long-run average costs, let us first consider a single tour. Given a state (x) and new inventory levels y, the calculation of the replenishment and expected holding costs for the upcoming tour is straightforward. To compute the expected penalty costs, we need to determine the probability that a randomly selected SO in the tour can be completed, which is determined by the job fill rate (JFR). However, since repair kits differ from tour to tour in this formulation, an JFR is not derived across all tours but only for the next tour ahead. This next JFR or $NJFR$ can be calculated as follows, where perfect ADI is excluded. In turn, the SOs with perfect ADI are handled separately, as their inventory item requirements are known at the moment of replenishment before the start of the next tour, which means that the S&M mechanic can store the required inventory item quantities in truck inventory next to the repair kit. The $NJFR$s of these SOs would automatically be equal to 100%, as the S&M mechanic will be able to immediately complete these SOs with the required items. So, the following equation for the $NJFR$ holds for the SOs in the tour without ADI.

$$NJFR(i, y) = \prod_{n=1}^{N} \left(\sum_{d_n=0}^{d_n^{max}} \left(P(D_{i,n} = d_n) \cdot P\left(\sum_{l=1}^{i-1} D_{l,n} < (y_n - d_n) \right) \right) \right)$$

Equation 3-1 Next job fill rate (NJFR)

For any SO $i \in \{1, \dots, C\}$, Equation 3-1 describes the probability for all N inventory items that $d_n \in \{0, \dots, d_n^{max}\}$ parts of inventory item $n \in \{1, \dots, N\}$ are required and still available for the ith SO of any kind in the tour. Subsequently, the average expected fill rate over all potential number of SOs C to be performed in the entire next tour ahead, which is called the next tour fill rate or $NTFR$, can be calculated as follows by summing all $NJFR$s times the probability that the tour consists of at least $i \in \{1, \dots, C\}$ SOs with $c \in \{C_{min}, \dots, C_{max}\}$ and dividing the resulting value by the expected number of SOs in the upcoming tour.

$$NTFR(c, y) = \frac{1}{E[C]} \cdot \left(\sum_{i=1}^{C_{max}} \left(P(C > (i-1)) \cdot NJFR(i, y) \right) \right)$$

Equation 3-2 Next tour fill rate ($NTFR$).

Let $V_1(x, c, y)$ denote the expected single-tour costs given a state (x) and post-modification inventory levels y. Using the $NJFR$-formula, the following equation for the objective function is obtained.

$$V_1(x,c,y) = \sum_{n=1}^{N}\left(h_n \cdot \left(\frac{(y_n + E[(y_n - D_n)^+])}{2} \cdot \pi\right)\right) + \sum_{m=1}^{M}(r_m \cdot R_m) + \sum_{i=1}^{C_{max}}\left(P\left(C > (i-1)\right) \cdot P_i \cdot [1 - NJFR(i,y)]\right)$$

Equation 3-3 Expected single-tour costs.

Let π be a stationary policy that maps each state (x) to a new repair kit y. Then, $V_1(x,c,\pi)$ denotes the expected single-tour costs if the action in state (x) is determined by policy π. In a similar way, we define $V_t(x,c,\pi)$ as the total expected costs in t consecutive tours when the initial state is (x) and the action at the beginning of each tour is determined by policy π. For any $t > 1$, the expected costs in t tours are calculated recursively. Let $\mathfrak{D}(d) = \{d|P(D = d) > 0\}$ define the set of possible demand events given the corresponding ADI; then, $V_t(x,c,\pi)$ can be derived as follows.

$$V_t(x,c,\pi) = V_1(x,c,\pi) + \sum_{d\in\mathfrak{D}(d)}\sum_{c'=C_{min}}^{C_{max}}(V_{t-1}(x + \pi(x) - d, c', \pi) \cdot P(C = c) \cdot P(D = d)), \qquad \forall t > 1$$

Equation 3-4 Total expected cost in t consecutive tours.

The long-run average costs per tour when the system is controlled by policy π and the initial state is (x) is then given by the limit.

$$\lim_{t\to\infty}\frac{V_t(x,c,\pi)}{t}$$

Equation 3-5 Long-run average cost per tour.

Since the Markov chain that describes the content of the repair kit and the available ADI at the beginning of a tour for any given policy π is unichain, which means that all states can be reached from each other, the long-run average costs do not depend on the initial state. Thus, the optimization problem can be expressed as follows.

$$\min_{\pi}\lim_{t\to\infty}\frac{V_t(\pi)}{t}$$

Equation 3-6 Optimization problem.

3.3 CONCLUSION

This chapter has formulated the literature model that is going to be applied in such a way that the inventory replenishment process for the S&M trucks of RSI can be optimized. The formulation of the literature model has been achieved by performing a systematic literature review on the repair kit problem. By identifying the key elements in the current situation as well as the problem context at RSI, which determine the requirements and assumptions for the ultimate literature model, gathering and elaborating on the relevant existing scientific literature on the repair kit problem, selecting the most applicable repair kit problem to shape this research's repair kit problem and formulating the ultimate repair kit problem including model notations, the research question of this chapter can be answered.

2. *What information is available in literature regarding truck inventory replenishment processes, replenishment techniques and truck inventory management?*

From this chapter can be concluded that the three aspects to be researched in literature all come together in one specific spare parts management issue known in literature as the repair kit problem. After evaluating all relevant existing literature on the repair kit problem against the requirements and assumptions defined based on the key elements from the context analysis, a combination of both papers from Rippe and Kiesmüller (2023) was deemed to be the most applicable version of the repair kit problem. However, even the combination of these papers could not meet all requirements and assumptions for the ultimate repair kit problem, such as the multiple kinds of (heterogeneous) SOs and their respective inventory item requirements as well as a periodic replenishment policy including the return frequency and/or distance and a combination of perfect or no ADI depending on the kind of SO.

In the formulation of the ultimate repair kit problem including the model notations, the necessary adaptations have been made to define a repair kit problem that encompasses all requirements and assumptions of RSI’s truck inventory replenishment process and that can derive the corresponding optimal solutions highly sought-after.

With the literature study performed and the repair kit problem formulated, this research is closer to achieving the prospective outcomes of this research, which are outlined in Figure 2-9, as the right literature model has now been defined next to the inputs in Chapter 2. This enables the next step to be taken in this research, which entails the development of a standard solution procedure to complete this research’s solution model for optimizing RSI’s truck inventory replenishment process, requiring the following key questions to be answered.

- What are the values for the defined model parameters in the ultimate repair kit problem?
- How should the formulated repair kit problem be optimally solved?
- What numerical results can be derived for the simplest problem instance of the repair kit problem?

In the subsequent solution design, the solution procedure to the formulation of the repair kit problem derived in this literature study will be developed in order to finalise the entire solution model and obtain the numerical results to the repair kit problem. This way the aforementioned questions can be answered and ultimately, RSI’s truck inventory replenishment process can be presented in terms of the optimal repair kit and corresponding replenishment interval, also called the optimal replenishment system.

4. SOLUTION DESIGN

In this chapter, the solution design for this research is constructed, which aims to optimize the inventory replenishment process for RSI's S&M trucks according to developed literature model in Chapter 3 based on RSI's requirements and assumptions for the optimal replenishment system. To develop the optimized truck inventory replenishment process, additional data is required to estimate the defined model parameters and the composition of repair kit literature has to be assessed once more in order to formulate the solution procedure required to derive this replenishment system. Subsequently, this chapter will be able to answer the following research question.

3. *How should the optimized inventory replenishment process for service and maintenance trucks be designed?*

Firstly, the values for the model parameters, as formulated in Section 3.2.2, have to be estimated, so that they can be applied to the solution procedure to ultimately derive the optimal repair kit for RSI's truck inventory replenishment process. Secondly and finally, the solution procedure is developed, as part of the solution model in combination with the literature model in Chapter 3, which can solve the formulation of the repair kit problem in Section 3.2.3 to optimality.

4.1 MODEL PARAMETERS

In order to solve the repair kit problem, as formulated in Chapter 3, the values for the defined model parameters should be estimated. Based on relevant data presented in the context analysis performed in Chapter 2, the values for most model parameters have already been determined. However, some model parameters remained unknown and therefore required an additional data analysis, which allows for the subsequent sub-question to be answered.

3.1. Which data is required to design the optimized truck inventory replenishment process?

Table 4-1 depicts a summarized overview of the model parameters and their corresponding values and value sets, which will be applied in the upcoming solution procedure to derive the results to this research. First, the number of SOs that can be performed in a single tour is defined as a function of the number of SOs that are performed on a single workday, and the predefined number of workdays between two subsequent replenishments, which in other words concerns the replenishment interval π. From Section 2.2.1, the number of SOs that can be performed in a single day is equal to 5, 6, 7, 8, 9 or 10, correspondingly. Subsequently, the probability for the number of SOs that will be performed in a tour has been derived based on the historical data presented in the context analysis. Depending on the value for π, the number of SOs to be performed in an entire tour is a convolution of the number of SOs that can be performed in a single workday and their corresponding probabilities. In case the replenishment interval $\pi = 3$, it can occur that 6 SOs have to be performed on the first day, 8 SOs on the second day and 5 SOs on the third and last day of the tour according to the simulation that draws these values based on their probabilities. Thus, 19 SOs will be performed in this specific tour in total.

The three different kinds of SOs that can be performed have also been derived from Section 2.2.1, where $j = 1$ corresponds to maintenance SOs, $j = 2$ concerns malfunction SOs and $j = 3$ relates to the incidental SOs. The probability that an SO is one of these kinds is given by $P(C_{i,j} = c_j)$ and is equal to 0.4613, 0.5283 and 0.0105, respectively. Each kind of SO has a threshold for when their demand information is perfectly known or completely unknown in advance. According to the context analysis in Chapter 2, perfect ADI is only known when $\pi \leq \theta_j \in \{5, \frac{1}{4}, 3\}$ for the maintenance, malfunction and incidental SOs, respectively. When a truck inventory replenishment takes place, these threshold values for π imply that the demand information for the maintenance SOs in the upcoming 5 workdays, for the malfunction SOs in the upcoming 2 hours and for the incidental SOs in the upcoming 3 workdays are perfectly known in advance. In turn, the demand information is completely unknown for the SOs that are performed outside of these threshold values. In case of no ADI, the historical demand probabilities $P(D_{i,j,n} = d_{j,n})$ are leading in which inventory items to include in the repair kit. As replenishment intervals π are defined per workday, the assumption is made that no ADI exists for malfunction SOs at all times.

Besides that, the total number of inventory items has been established at 537, where the demand for each inventory item is assumed to be independent according to the statistical hypothesis test performed in Section 2.2.1. However, to increase the processability and time efficiency of the solution procedure to be developed, only the top 10% of most frequently used inventory items on the 2,582 SOs performed over 2022 are considered, which comes down to a total number of 53 inventory items. Examples of these items are depicted in Table 2-1 in which the top ten most frequently used inventory items are depicted to be precise. Furthermore, the probability that an SO demands a certain quantity of these inventory items ($P(D_{i,n} = d_n)$) depends on the kind of SO ($P(C_{i,j} = c_j)$ and $P(D_{i,j,n} = d_{j,n})$) and the maximum demand for each item on any SO (d_n^{max}), which, in turn, rely on the number of SOs of each kind performed in 2022 and the number of parts of each inventory item used per SO of each kind in 2022. Note that the values for these demand probabilities are not included in Table 4-1, as these concern empirical probabilities derived from a dataset in RSI's software system. Furthermore, the demand probabilities cannot be accurately depicted in terms of a general range, because that range would differ for each of the 53 inventory items. As stated in the context analysis as well, RSI has 46 S&M mechanics across their four eldest establishments and each of them has their own truck. Therefore, each mechanic has their own repair kit to complete SOs with.

Now, the costs that will be applied in the solution procedure are the holding, replenishment and penalty costs. Each inventory item has its own holding cost. The holdings costs are defined as 5% of each inventory item's cost-price, as derived in Section 2.3.1. The replenishment costs for an S&M mechanic to replenish their truck inventory are newly-defined based on the return distance of each mechanic to the warehouse, which are assigned to a certain cost-distance interval with a width of 5 kilometres. As each mechanic usually performs their tour around their residence according to Sections 2.2.1 and 3.2.3, the return distance is derived from the distance from each mechanic's residence to the nearest warehouse. For instance, one mechanic lives 2.8 kilometres from the warehouse, so this mechanic has to pay a replenishment cost of €0.50. Another mechanic lives 26.1 kilometres from the warehouse, so this mechanic has to pay a replenishment cost of €3.00, and so on. Finally, the penalty costs for not being able to complete an SO on the first visit are based on the location of the broken SO in the sequence of the tour, as introduced in Section 3.2.3. These penalty costs have a perfect negative linear relationship with the number of SOs to be performed in a tour, where they downscale uniformly relative to the number of SOs still to be performed in the tour including the current uncompleted SO. As the number of SOs that will be performed in a tour depends on the predefined number of workdays between replenishments (π) and the corresponding time left until replenishment has a significant impact on the value of the penalty, the penalty costs are also scaled to the replenishment interval π. So, when a maximum of 20 (C) SOs are to be performed in a tour with replenishment interval $\pi = 2$ and the first SO cannot be completed, a penalty cost of $\frac{2}{20} * 20 = €2$ will be incurred for that SO. In case the twentieth SO in this tour remains uncompleted, a penalty cost of $\frac{2}{20} * 1 = €0.10$ will be incurred.

Table 4-1 Value estimations and sets for model parameters.

Parameter	Definition	Range
C	Number of SOs for a replenishment interval of $\pi = 1$	$5, 6, 7, 8, 9, 10$
J	Number of SO kinds	$1, 2, 3$
N	Number of inventory items	$1, 2, 3, 4, 5, 6, 7, 8, 9, 10, \dots, 49, 50, 51, 52, 53$
M	Number of S&M mechanics	$1, 2, 3, 4, 5, 6, 7, 8, 9, 10, \dots, 41, 42, 43, 44, 45, 46$
h_n	Holding cost per inventory item (€)	$0.05 * \{0.01, 0.02, 0.03, \dots, 472.00, 567.26, 588.00\}$
r_m	Replenishment cost per S&M mechanic (€)	$0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5$
P_i	Penalty cost per SO for a replenishment interval of π (€)	$(\pi/C) \cdot \{C, C-1, C-2, \dots, 4, 3, 2, 1\}$
$P(C = c)$	Probability for number of SOs for a replenishment interval of $\pi = 1$	$0.25, 0.19, 0.17, 0.12, 0.14, 0.13$
$P(C_{i,j} = c_j)$	Probability for kind of SO	$0.4613, 0.5283, 0.0105$
θ_j	Threshold for ADI per kind of SO	$5, 1/4, 3$
d_n^{max}	Maximum demand per inventory item per SO	$1, 2, 3, 4, 5, \dots, 16, 20, 24, 32, 64$

Following, these model parameters and their values are going to be applied to the solution procedure, which is going to be developed in the upcoming section, for the optimization of the truck inventory replenishment process of RSI.

4.2 SOLUTION PROCEDURE

A repair kit problem can be solved in various ways using different methods and procedures. Therefore, a solution procedure is developed that is suitable to the characteristics of the ultimate repair kit problem formulated in this research, as outlined in Section 3.2.3, in order to complete the solution model. In turn, this section is dedicated to answering the following sub-questions.

3.2. How can the found literature be applied to the development of the solution design for the optimized truck inventory replenishment process?

3.3. What should the solution design for optimizing the truck inventory replenishment process look like?

One particular and potential solution method is dynamic programming. The term dynamic programming (DP) refers to a collection of algorithms that can be used to compute optimal solutions given a perfect model of the environment as an MDP, as the repair kit problem in this research has been formulated in Section 3.2.3. Classical DP algorithms are of limited utility in reinforcement learning because of their assumption of a perfect model, where the entire environment is known, and because of their great computational expense when the number of states increase to a large number (Sutton & Barto, 2005). Potential procedures included in DP are policy iteration, which consists of policy evaluation and policy improvement, and value iteration (Choudhary, 2018).

To demonstrate the need for heuristic solution methods to solve the MDP formulated in Section 3.2.3 instead of DP procedures, the size of its state space should first be determined. As discussed in that section, each item's inventory level at the end of each tour can take any value between 0 and $C_{max} \cdot d_n^{max}$. With N different inventory items, there are $\sum_{n=1}^{N}(d_n^{max}) \cdot (C_{max}+1)^N$ states that the repair kit can be in at the end of each tour. Even for a moderate size example with a fixed number of 6 SOs per tour, 20 inventory items with a maximum demand of 2 each, the size of the state space is already equal to $3.2 \cdot 10^{18}$. Never mind that the actual values for these parameters are significantly larger than the ones used in this example resulting in an even larger complete state space. Because of this already enormous number of possible states, the repair kit problem can only be solved with a DP procedure to optimality for very small unrealistic problem instances. The methods that can be employed to determine the optimal policy for an MDP, such as value or policy iteration, require the iterative update of value function estimates for all states. Even a single update, however, can be computationally intractable for a large state space, especially when the $NJFR(i,y)$, $NTFR(c,y)$ and objective cost functions are non-linear. Performing an exhaustive DP procedure will quickly become impossible. To overcome these difficulties and derive near-optimal solutions, a greedy heuristic has been developed, which is a common approach in the repair kit literature as depicted in Section 3.1.1.

Algorithm 4-1 presents the algorithm derived to perform the greedy heuristic, which intends to create the optimal repair kit given the preferred replenishment interval π and the defined model parameters in Section 4.1. The greedy algorithm is myopic, in so far that it does not look beyond the upcoming tour, where the principle of decision time planning is applied, which means that certain actions are only determined once a particular state is actually encountered. Immediately before the start of each tour, the content of the repair kit can be optimized regarding the immediate replenishment costs as well as the expected penalty and holding costs incurred for the upcoming tour. Thus, the focus solely lies on the expected single-tour cost equation $V_1(x,c,y)$. This greedy heuristic iteratively adds different inventory items to the repair kit. In each step of this algorithm, the inventory level of exactly one item is raised by one part, which is limited by the maximum number of parts per inventory item that can be demanded by all SOs in the tour. This increase of one item's inventory level has an impact on the $NJFR(i,y)$ of certain SOs as well as the $NTFR(c,y)$ and total costs assigned to the performed tour. The inventory item of which a single part should be added to the optimal repair kit is the item with the greatest single-tour cost decrease. After each addition of an item's part to the optimal repair kit, the corresponding interim solutions will be stored to identify, analyse and map the progression of the $NTFR(c,y)$ and expected single-tour costs.

When a single-part addition of any item to the repair kit does not lead to a decrease of the expected single-tour costs anymore, the algorithm is finished. Note that each repair kit derived by this algorithm is a repair kit for a single S&M mechanic, where all 46 S&M mechanics receive an identical repair kit.

Algorithm 4-1 Greedy heuristic algorithm.

Algorithm 1. Repair kit creation heuristic

Input: repair kit at the end of the previous tour x,
repair kit after replenishment y,
replenishment interval π,
inventory items $n \in \{1, \dots, N\}$,
maximum demand d_n^{max} $\forall n \in \{1, \dots, N\}$,
number of SOs in a tour $c \in \{C_{min}, \dots, C_{max}\}$ of kind $j \in \{1, \dots, J\}$,
next job fill rate equation $NJFR(i, y)$,
next tour fill rate equation $NTFR(c, y)$,
expected single-tour cost equation $V_1(x, c, y)$.

Output: repair kit with optimal inventory levels y^{opt} with corresponding $NTFR(c, y^{opt})$ and expected single-tour costs $V_1(x, c, y^{opt})$.

// Initialization
$y \leftarrow x$
$y^{opt} \leftarrow y$
$\Delta \leftarrow -M$
// Perform procedure until terminal condition
while $\min_{n: y_n < d_n^{max} \cdot c} \Delta_n < 0$ **do**
// Derive single-tour cost improvement per inventory item limited to the maximum parts that can be demanded by all SOs
for $n \in \{1, \dots, N\}$ with $y_n < d_n^{max} \cdot c$ **do**
$y^{temp} \leftarrow y$
$y_n^{temp} \leftarrow y_n + 1$
$\Delta_n \leftarrow V_1(x, c, y^{temp}) - V_1(x, c, y)$
end for
// Add the inventory item with greatest single-tour cost improvement to the repair kit
$n^* \leftarrow \arg \min_{n: y_n < d_n^{max} \cdot c} \Delta_n$
$y_{n^*} \leftarrow y_{n^*} + 1$
// Terminal condition: Does the greatest single-tour cost improvement actually decrease single-tour costs?
if $\min_{n: y_n < d_n^{max} \cdot c} \Delta_n < 0$ **then**
// Store optimal inventory item in the optimal repair kit and store the corresponding interim solutions
$y^{opt} \leftarrow y$
$NTFR(c, y^{opt}) \leftarrow NTFR(c, y)$
$V_1(x, c, y^{opt}) \leftarrow V_1(x, c, y)$
store these and other interim solutions
end if
end while

Before the greedy heuristic can be executed in its entirety, it requires support algorithms and functions to be performed, as input to its procedure. They concern Equation 3-1, Equation 3-2 and Equation 3-3, which calculate the $NJFR(i, y)$, $NTFR(c, y)$ and expected single-tour costs – also called the objective function, respectively. The $NJFR(i, y)$ function calculates the job fill rate for each individual SO to be performed in the tour with the repair kit. In turn, every time one part of any inventory item is added to the optimal repair kit, the $NTFR(c, y)$ function determines the tour fill rate that corresponds to that optimal repair kit. Besides that, the expected single-tour costs for any repair kit including the expected holding, replenishment and penalty costs can be calculated using the objective function $V_1(x, c, y)$. Next to these functions, an input algorithm has been constructed to load the necessary data for the model parameters into the procedure, such as the replenishment interval π, the demand and SO-related probabilities as well as the inventory items and all of the costs involved. This algorithm also allows for the values of these model parameters to be adjusted, so that the entire solution procedure – including its optimal repair kit – remains flexible and accurate in the face of any future changes in RSI's inventory replenishment process for the S&M trucks.

In this solution procedure, perfect or no ADI has been implemented to determine the optimal repair kit depending on the kinds of SOs and the replenishment interval π that is applied. In case the replenishment interval is being set to a value equal to or smaller than $\pi = 5$ workdays, maintenance SOs are entirely disregarded in the derivation of the optimal repair kit, because the demand of these SOs will be completely known in advance, as the ADI-threshold for these kinds of SOs equals $\theta_1 \leq 5$ workdays. This means that every time the S&M mechanics replenish their repair kits, they know exactly what inventory items and the corresponding number of parts per item the upcoming maintenance SOs demand. So, the mechanics can add these inventory items in the right quantities to the optimal repair kit themselves. The same reasoning would hold for incidental SOs when the replenishment interval would be equal to or smaller than $\pi = 3$ workdays, as the ADI-threshold for these kinds of SOs equals $\theta_3 \leq 3$ workdays. However, no ADI for the incidental SOs has been implemented in the solution procedure for the derivation of any optimal repair kit, due to the limited impact of incidental SOs and their ADI on the repair kit, as approximately only 1% of SOs in a tour is an incidental SO. As previously explained in Section 4.1, no ADI will be considered for the malfunction SOs in this solution procedure under any circumstances, because the demand for these SOs is only known less than one workday ($\theta_2 \leq 1/4$) in advance. So, for a replenishment interval equal to or smaller than $\pi = 5$, the optimal repair kit is defined based on the demand probabilities for the malfunction and incidental SOs only. Once the replenishment interval π exceeds the ADI-threshold for the maintenance SOs, perfect ADI remains to be considered for the maintenance SOs performed in the first 5 workdays of the tour. However, no ADI exists for the remaining maintenance SOs in the rest of the tour. Therefore, the demand probabilities for the maintenance SOs that will be performed in the workdays beyond their ADI-threshold will also be considered in the derivation of the optimal repair kit next to the demand probabilities for the malfunction and incidental SOs.

Due to excluding the maintenance SOs to be performed in the first 5 workdays of a tour from the derivation of the optimal repair kit because of their perfect ADI, the $NTFR(c, y)$ calculated for the optimal repair kit is always a worst-case value. This means that the job fill rates of 100% for the maintenance SOs to be performed in the first 5 workdays of a tour are not considered in the calculation of the $NTFR(c, y)$, which has a negative impact on the resulting value for the $NTFR(c, y)$. Simply-put, the $NTFR(c, y)$ calculated for the optimal repair kit is always the minimal $NTFR(c, y)$ that can be achieved with this repair kit.

4.3 CONCLUSION

This chapter has presented the solution procedure to derive the optimal repair kit for RSI's truck inventory replenishment process. The solution procedure has been designed by determining the most suitable solution method for the repair kit problem formulated in Section 3.2.3 and the corresponding requirements and characteristics that this procedure should meet. By having designed this solution procedure, the following research question can be answered.

3. *How should the optimized inventory replenishment process for service and maintenance trucks be designed?*

From this chapter can be concluded that the solution method most suited to solve the formulation of the repair kit problem in this research to optimality is a greedy heuristic. Once the need for a heuristic algorithm was clear, the solution procedure was derived. Its main goal is to iteratively add a single part of the different inventory items to the repair kit until the expected single-tour costs are minimized, which requires the consideration of the expected holding, replenishment and penalty costs of that repair kit. Next to the expected single-tour costs, which includes its underlying costs, as well as the optimal repair kit, this solution procedure also yields the $NTFR(c, y)$ that can be achieved with the respective optimal repair kit generated as output.

By designing the solution procedure to solve the formulated repair kit problem in this research, a standard solution method has now been developed, which can create an optimal repair kit for any values assigned to the model parameters. Hereby, the entire solution model has been completed in combination with the repair kit problem formulation. Now, the optimal repair kit, which is based on the replenishment interval π as well as other model parameters, has to be determined for specifically RSI's truck inventory replenishment process. So, the following key questions have to be answered next.

- What experimental settings should be applied to the model parameters in the solution procedure?
- What is the performance of RSI's truck inventory replenishment process when the experimental settings are applied to the model parameters in the solution procedure?
- What is the optimal repair kit and corresponding replenishment interval for RSI's truck inventory replenishment process?

The experimental evaluation to be performed in the subsequent chapter aims to find the replenishment interval π as well as the values for other model parameters that derive the optimal repair kit, which suits RSI's truck inventory replenishment process the best. In other words, the next chapter intends to define RSI's optimal replenishment system in terms of the optimal repair kit and corresponding replenishment interval π. This way answers will be provided to the aforementioned questions and the optimized truck inventory replenishment process can finally be defined in terms of RSI's optimal repair kit and corresponding replenishment interval π.

5. EXPERIMENTAL EVALUATION

This chapter performs the experimental evaluation of the solution procedure to derive RSI's optimal replenishment system, which consists of the optimal repair kit based on its corresponding replenishment interval π and other model parameters, that is best suited for RSI's truck inventory replenishment process, as extensively described in Section 2.1. Well-founded experimental settings for relevant model parameters are required to obtain this optimal replenishment system. In turn, the purpose of this chapter is to answer the following research question.

4. *How does the optimized inventory replenishment process for service and maintenance trucks perform under experimental settings?*

The solution procedure developed in Chapter 4 is first performed with the estimated model parameters from Section 4.1, which represents the simplest problem instance, to obtain the initial numerical results to the repair kit problem as formulated in this research. These results subsequently allow for the initial optimal repair kit for the S&M trucks to be defined. From analysing the initial numerical results, the relevant model parameters are selected and subsequently the experimental values for these parameters are determined, which defines the experimental settings. In turn, by applying the solution procedure in combination with these experimental settings, the performance of RSI's truck inventory replenishment process for all possible combinations of the experimental settings can be acquired. Consequently, RSI's optimal replenishment system, which is established to be the best suited replenishment system resulting from the performed experiments, will be specified in terms of its optimal repair kit and corresponding replenishment interval π. In turn, the KPIs recommended to evaluate RSI's optimized truck inventory replenishment process in terms of efficiency and effectiveness are defined.

5.1 NUMERICAL RESULTS

In this section, the initial performance of the heuristic solution procedure, as formulated in the previous section, is examined. Initially, we evaluate the solutions found for the simplest problem instance, where the ratio between the penalty costs and holding costs ($P{:}\,h$), for which the values have been defined in Section 4.1, is defined as $200{:}\,1$ and the replenishment interval is set to $\pi = 1$ meaning that the S&M mechanics can replenish their repair kits at the end of each workday. This value for the $P{:}\,h$ ratio has been derived after some initial experimenting with the solution procedure for a replenishment interval of $\pi = 1$. An $NTFR(c, y)$ of 80% can be achieved with a $P{:}\,h$ ratio of at least $200{:}\,1$. As an $NTFR(c, y)$ of at least 80% is preferred and most organizations aim for an $NTFR(c, y)$ of 95% (Flora, 2022), the minimum $P{:}\,h$ ratio is correspondingly set to $200{:}\,1$ for the simplest problem instance. Also, the terminal condition implemented in the procedure is defined as the new minimal expected single-tour costs not being strictly an improvement upon the current expected single-tour costs, so the increment between these two values is no longer negative. A negative value for this increment is therefore required for the solution procedure to continue. In this instance, the expected total costs per tour can exactly be determined for the initial optimal repair kit and the following sub-question can be answered.

4.1. Which initial numerical results can be derived from the solution design?

After a running time of 0.073 hours – almost 5 minutes, the solution procedure derives the following initial optimal repair kit. The content of this repair kit can be observed in Figure 5-1. In this figure, the exact corresponding inventory levels of the initial optimal repair kit are also depicted.

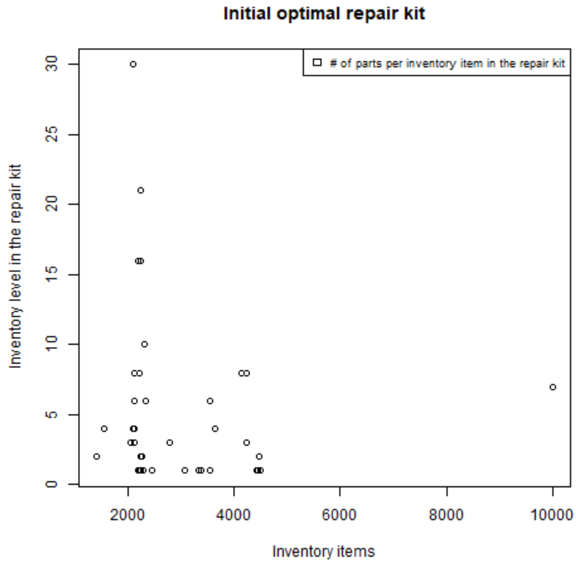

Figure 5-1 Initial optimal repair kit per S&M mechanic.

Applying this initial optimal repair kit yields certain expected results, such as the $NTFR(c, y)$ and expected single-tour costs – also called the expected total costs (ETC). The initial optimal repair kit achieves an $NTFR(c, y)$ of 80.71% and ETC of €160.94. The ETC can be divided into the expected holding costs (EHC), expected penalty costs (EPC) and expected replenishment costs (ERC), which refer to the three different components in Equation 3-3, with the respective rounded values of €15.88, €27.07 and €118.00. The $NTFR(c, y)$ achieved is similar to the minimal job fill rates that organizations usually aim for and other literature papers, such as Prak et al. (2017), Saccani et al. (2017), Rippe & Kiesmüller (2023) (1), manage to achieve, which is an $NJFR(c, y)$ of at least 80%. However, an $NTFR(c, y)$ of at least 95% is actually preferred (Flora, 2022), which this initial optimal repair kit cannot attain. This statement can be explained by the fact that the solution procedure cannot find another part of any inventory item to include in the initial optimal repair kit anymore that results in an improvement of the ETC. This means that the solution procedure in its simplest state cannot on the one hand reduce the EPC more than the EHC would increase on the other hand when adding a single part of any inventory item to the initial optimal repair kit. Basically, the penalty costs are too low in comparison to the holding costs, as they have been defined in Section 4.1. Therefore, the penalty costs per SO for a given replenishment interval should be increased with respect to the holding costs, which can be done by applying higher values to the $P: h$ ratio, in order to achieve a target $NTFR(c, y)$ of at least 95% and to obtain a more accurate repair kit with corresponding expected single-tour costs (ETC) in general.

Furthermore, the replenishment interval is currently set to $\pi = 1$ day meaning that the S&M mechanics replenish their repair kits every workday. In order to increase the efficiency and effectiveness of RSI's truck inventory replenishment process and minimize the downtime of the S&M mechanics caused by this process, the mechanics should return to the warehouse for replenishment of their truck inventory as little as realistically possible. The replenishment interval would ideally be at least equal to or larger than $\pi = 2$ resulting in a return frequency of at most 2 or 3 times per workweek, which is approximately equivalent to the current return frequency as stated in Section 2.2.2, so that the downtime of the S&M mechanics decreases compared to the current truck inventory replenishment process of RSI. This means that a large replenishment interval would be preferred. However, a larger replenishment interval implies that the optimal repair kit should include more inventory items in greater quantities to meet the target $NTFR(c, y)$ of 95%. Consequently, the monetary investment value of each mechanic's truck inventory would increase, which would require RSI to commit a larger amount of cash outlay to truck inventory reducing the amount of cash available for other investment purposes. Moreover, storing (more) high-value inventory items in trucks leads to a higher risk of theft and damages. So, an appropriate balance between the replenishment interval π and the total investment value of the optimal repair kit is required.

Besides that, for this repair kit or any repair kit, for that matter, the total ERC remains constant over all possible replenishment intervals π, as each S&M mechanic only has to replenish their repair kit once before the start of the tour to obtain the required inventory levels. However, the average ERC per day decreases when increasing the replenishment interval π. For instance, for a replenishment interval of $\pi = 1$, the average ERC per day is €118.00 while for a replenishment interval of $\pi = 5$, the average ERC per day becomes €23.60. Consequently, the greater the value for the replenishment interval π, the smaller the average ETC per day will be as well. Nonetheless, the decline in average ETC per day will stagnate once the replenishment interval π is set to such a value, which results in the sum of the average EHC and EPC per day in combination with the average ERC per day being minimized. As the overall objective defined in the formulation of the repair kit problem in Section 3.2.3 is to find the optimal replenishment interval π for RSI's truck inventory replenishment process that minimizes the average expected single-tour costs, the primary aim is to minimize the average ETC per workday, which is not yet achieved by these initial numerical results.

Based on the previously-discussed results, Figure 5-2, Figure 5-3 and Figure 5-4 present the progress of the EHC, EPC and ETC, correspondingly, with respect to the progress of the $NTFR(c, y)$ during the execution of the solution procedure. Each line graph represents the progress of adding a single part of an inventory item to the initial optimal repair kit. The inventory item that has improved the ETC the most in comparison to any other inventory item in that specific iteration is added to the repair kit. As expected in the incremental derivation of the repair kit, the EHC experience a positive trend, which is due to the fact that adding a certain inventory item to the repair kit increases the holding costs of that repair kit. Similarly, a negative trend for EPC has been expected, because adding one part of an inventory item to the repair kit results in being able to (partially) complete more SOs. Due to the objective of deriving the repair kit with the smallest expected single-tour costs, a negative trend should be and is observed in the progress of the ETC, as the decrease in EPC should outweigh the increase in EHC in each iteration until the terminal condition is met. Additionally, when the EPC decrease as a result of adding one part of an inventory item to the repair kit, the $NTFR(c, y)$ has correspondingly increased meaning that the $NTFR(c, y)$ experiences a positive trend during the execution of the solution procedure. At an $NTFR(c, y)$ of 80.71%, the EHC, EPC and ETC reach their previously-stated final values.

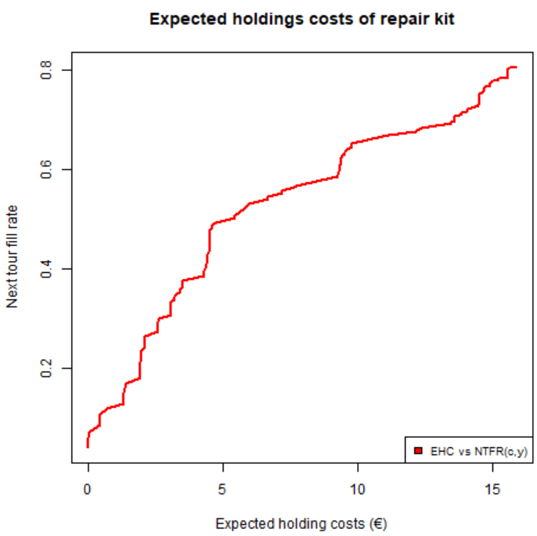

Figure 5-2 EHC (€) of initial optimal repair kit.

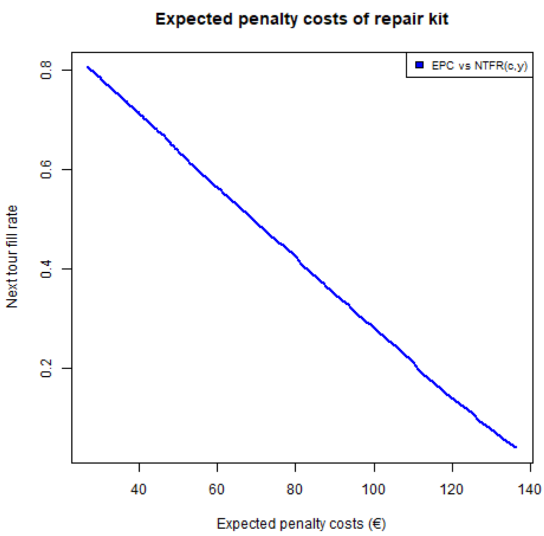

Figure 5-3 EPC (€) of initial optimal repair kit.

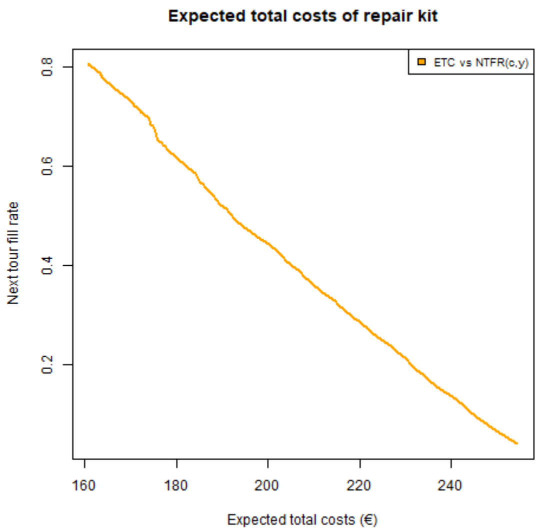

Figure 5-4 ETC (€) of initial optimal repair kit.

Every time a part of an inventory item is added to the initial optimal repair kit or another iteration is performed, a unique repair kit is generated with its corresponding $NTFR(c,y)$. However, the initial optimal repair kit is the only one of those considered optimal, which is depicted by the right limit in Figure 5-2 and the left limit in Figure 5-3 as well as Figure 5-4. Any other repair kit found below this optimum is not optimal in any sense, because the solution procedure aims to derive the optimal repair kit and corresponding results given the $P:h$ ratio and replenishment interval π, so such a repair kit is deemed just an interim step in the derivation of the optimal repair kit with these model parameters. To derive an optimal repair kit that attains an $NTFR(c,y)$ of, for instance, 40%, the values for the $P:h$ ratio and replenishment interval π should be set in such a way that an $NTFR(c,y)$ of 40% is achieved by the final repair kit that results from the solution procedure. So, every time a new target $NTFR(c,y)$ is defined, the optimal repair kit needs to be re-optimized by performing the solution procedure in its entirety.

Furthermore, Figure 5-5 and Figure 5-6 indicate the values of the inventory items added to the initial optimal repair kit in terms of the cost-price of each unique inventory item included and the total investment value of the entire initial optimal repair kit, respectively. Figure 5-5 shows the actual monetary value of a single part of the inventory item in the iteration when it is first added to the initial optimal repair kit. Remarkably, the solution procedure mainly adds low value items to the initial optimal repair kit, which all have a value smaller than €25. This can be explained by the main objective of this procedure, which entails for each iteration to include the inventory item in the repair kit that results in the largest single-tour costs (ETC) decrease, in other words the greatest decrease in EPC compared to the increase in EHC. During the execution of the solution procedure, more inventory items with slightly higher cost-prices are added to this repair kit for the first time. When the $P:h$ ratio and replenishment interval π will be increased, inventory items with higher cost-prices can and will be included even more in the optimal repair kit, so a positive trend is to be expected here.

In Figure 5-6, the relationship between the required stock investment to obtain the initial optimal repair kit and its inventory items with corresponding inventory levels, and the achieved $NTFR(c,y)$ is graphically depicted. This figure presents the progress of the actual total monetary value of the initial optimal repair kit and what $NTFR(c,y)$ can be achieved using the different iterations of the repair kit. For the initial optimal repair kit, the total investment value equals €363.97. Also, higher values for the ratio between the penalty costs and holding costs will affect the total investment value of the optimal repair kit next to the values for the replenishment interval π, as previously explained. More and increasingly expensive inventory items will then be added to the optimal repair kit in order to minimize the ETC, which would lead to an increase in the $NTFR(c,y)$ as well as the total investment value of this repair kit.

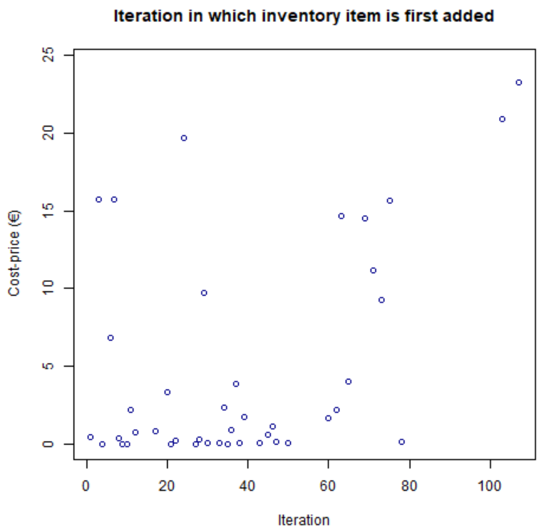

Figure 5-5 Cost-price (€) of an inventory item when added for the first time to the initial optimal repair kit.

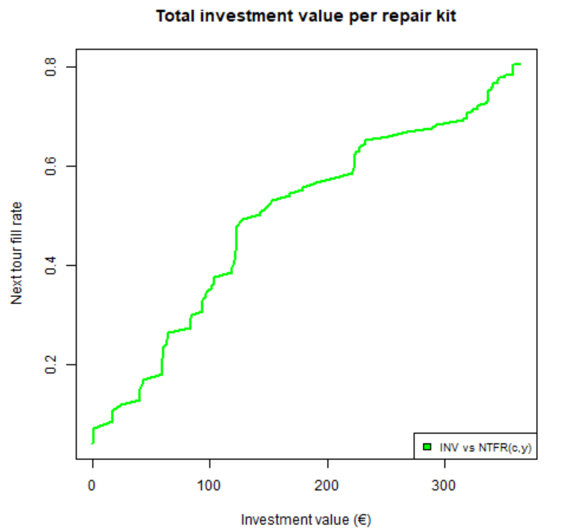

Figure 5-6 Total investment value (€) of the complete initial optimal repair kit.

5.2 EXPERIMENTAL SETTINGS

In order to find the best-performing optimal repair kit for RSI's truck inventory replenishment process, the experimental settings should be defined consisting of relevant model parameters and their experimental values. This section intends to answer the subsequent sub-question.

4.2. Which experimental settings should be considered?

According to the statements made on the $NTFR(c,y)$ and total investment value as well as the replenishment interval π and the ratio between the penalty costs and holding costs in the previous section, the experimental evaluation should focus on two model parameters in particular. Table 5-1 presents the experimental settings to be applied in the experimental evaluation for the model parameters: cost ratio $P\!:h$ and replenishment interval π. To optimize the return frequency of the S&M mechanics to the warehouse for the replenishment of their truck inventory while also considering the appropriateness of certain replenishment intervals in order to minimize the average ETC per workday, the minimum replenishment interval has been set to $\pi = 1$ workday, which means that the S&M mechanics can replenish their truck inventory at the end of each day for the SOs to be performed on the next day. Moreover, the maximum replenishment interval has been set to $\pi = 5$ workdays or one workweek, which means that the S&M mechanics can only replenish their truck inventory at the end of every week when they should replenish their repair kits for the SOs to be performed in the upcoming workweek. Based on the initial numerical results, an $NTFR(c,y)$ of 80% can be achieved with a $P\!:h$ ratio of at least $200\!:1$. As an $NTFR(c,y)$ of at least 80% is preferred and most organizations aim for an $NTFR(c,y)$ of 95% (Flora, 2022), the minimum $P\!:h$ ratio is correspondingly set to $200\!:1$. Increasing the $P\!:h$ ratio results in more penalty costs to be accounted for relatively to the holding costs. Subsequently, an increase in the $NTFR(c,y)$ is expected because higher penalty costs should be compensated by adding more parts of certain inventory items to the optimal repair kit that minimize the ETC. These additional inventory item quantities can be used to (partially) complete more SOs in the tour. Therefore, the maximum $P\!:h$ ratio has been increased compared to the minimum and set to $3{,}200\!:1$ in order to enable an $NTFR(c,y)$ of at least 95% for any replenishment interval π.

Table 5-1 Experimental settings.

Parameters	Cost ratio $P\!:h$	Replenishment interval π	
Experimental values	$200\!:1$ $1{,}200\!:1$ $2{,}200\!:1$ $3{,}200\!:1$	1 2 3	4 5

The experimental settings outlined in the table above will be applied to the solution procedure. This way the experiments will be performed and the performance of RSI's inventory replenishment process for its S&M trucks on the different settings can be derived and assessed.

5.3 PERFORMANCE TRUCK INVENTORY REPLENISHMENT PROCESS

By running the solution procedure several times using the experimental settings, as defined in the previous section, the performance of RSI's truck inventory replenishment process on these settings can be determined. Each experiment run considers one combination of the cost ratio $P\!:h$ and replenishment interval π. As 4 values for the $P\!:h$ ratio and 5 values for the replenishment interval π have been defined, a total of 20 experiments have been performed. In turn, the following sub-question can be answered.

> *4.3. How does the solution design for optimizing the truck inventory replenishment process perform under experimental settings?*

The results for all experiments performed are presented in detail in Table 5-2. Each experiment generates an optimal repair kit for that particular combination of experimental settings. Then, the performance of RSI's truck inventory replenishment process is assessed based on the expected single-tour costs (ETC) and $NTFR(c, y)$ obtained for each optimal repair kit across all experiments. Furthermore, the total monetary investment value corresponding to that optimal repair kit and runtime of the solution procedure for each experiment are considered in this assessment as well.

Table 5-2 Experimental results for RSI's truck inventory replenishment process.

Experiment Nr.	Cost ratio $P\!:h$	Replenishment interval π	ETC (€)	Average ETC (€)	$NTFR(c, y)$ (%)	Investment value (€)	Runtime (hrs)
1	$200\!:1$	1	160.94	160.94	80.71	363.97	0.06
2		2	202.13	101.06	79.96	401.81	0.66
3		3	243.44	81.15	80.54	472.69	2.51
4		4	291.45	72.86	77.93	480.16	7.10
5		5	335.79	67.16	79.06	542.11	17.33
6	$1{,}200\!:1$	1	241.41	241.41	89.67	776.74	0.09
7		2	356.21	178.11	89.37	815.98	0.75
8		3	470.48	156.83	91.99	1,386.89	2.62
9		4	579.50	144.88	91.88	1,447.54	7.57
10		5	690.75	138.15	91.65	1,510.93	22.09
11	$2{,}200\!:1$	1	287.74	287.74	94.94	1,963.16	0.08
12		2	441.44	220.72	94.80	2,000.83	0.96
13		3	589.61	196.54	94.73	2,064.11	2.69
14		4	728.35	182.09	96.34	2,708.54	9.81
15		5	857.59	171.52	96.39	2,793.88	18.24
16	$3{,}200\!:1$	1	314.15	314.15	96.54	2,530.55	0.09
17		2	492.22	246.11	96.40	2,568.09	1.05
18		3	661.22	220.41	96.54	2,669.65	3.29
19		4	819.77	204.94	96.47	2,728.28	10.28
20		5	971.64	194.32	96.39	2,794.64	18.70

Figure 5-7, Figure 5-8, Figure 5-9, Figure 5-10 and Figure 5-11 display the summarized results of the experimental evaluation. These figures present the progress of the resulting experimental values for the (average) ETC, $NTFR(c,y)$, investment value and runtime when increasing the $P{:}h$ ratio and replenishment interval π, which are differentiated in terms of line graphs. From these figures can be observed that a larger $P{:}h$ ratio automatically implies larger (average) ETC, a higher $NTFR(c,y)$, a larger total investment value as well as a larger runtime of the solution procedure. Also, the majority of figures, aside from Figure 5-8 and Figure 5-9 for the average ETC per workday and $NTFR(c,y)$, show an overall positive trend in their line graphs meaning that increasing the replenishment interval π results in overall higher values for these experimental results as well. In particular, the ETC in Figure 5-7 increase as a result of the underlying higher values for the EHC and EPC due to the increasing replenishment intervals π and $P{:}h$ ratios.

The values for the average ETC per workday in Figure 5-8 will decrease the larger the replenishment interval π becomes until the sum of the average EHC, EPC and ERC per workday is minimized, as explained in Section 5.1, which has unfortunately not been achieved by these experiments thus far. To attain the minimal average ETC per workday, experiments with even larger replenishment intervals π should be performed for each $P{:}h$ ratio. Then, the replenishment interval π for which the average ETC per workday are minimized, is the optimal and would generate the optimal repair kit for RSI's truck inventory replenishment process. So, for other smaller and larger replenishment intervals, their resulting average ETC per workday will be larger compared to the minimal average ETC per workday for the optimal replenishment interval. However, aiming for the optimal replenishment interval with the minimal average ETC per workday will be at the expense of the runtime of the solution procedure, which exponentially increases when increasing the replenishment interval π, as can be observed from Figure 5-11. This is due to the increasing number of SOs to be performed in the tour as well as to be considered in the derivation of the optimal repair kit and corresponding experiment results, such as the $NTFR(c,y)$ and ETC. For instance, the runtime for the replenishment interval $\pi = 5$ already amounts to 17.33 hours, which would make it basically intractable to implement the solution procedure within RSI's operations. The $P{:}h$ ratio, on the other hand, only slightly affects the runtime for each replenishment interval π.

Besides that, the values for the $NTFR(c,y)$ slightly increase or decrease between the replenishment intervals depending on the $P{:}h$ ratio considered, which can be explained by the relation between the EHC and EPC. For one experiment, a further decrease in expected single-tour costs can be realised by including another part of an inventory item in the repair kit, which leads to a relative increase in $NTFR(c,y)$, while another experiment results in a relative decrease in $NTFR(c,y)$, because the expected single-tour costs cannot be decreased any further by adding a single part of any inventory item to the repair kit. Still, the $NTFR(c,y)$ remains fairly stabilised across the replenishment intervals. In turn, 7 combinations of the $P{:}h$ ratio and replenishment interval π manage to achieve an $NTFR(c,y)$ of at least 95%, which is a value that most organizations aim for and consider an adequate and attainable service rate (Flora, 2022). In order to attain an $NTFR(c,y)$ of 95%, a monetary investment of at least €2,500.00 is required, which more than triples the monetary investment required to attain an $NTFR(c,y)$ of 80% depending the replenishment interval π considered. Also, the monetary investment required to obtain an $NTFR(c,y)$ of 95% almost doubles the monetary investment required for an $NTFR(c,y)$ of 90%.

Thus, even though the minimal average ETC and the corresponding optimal replenishment interval have not been reached yet, as was intended by the main objective of the repair kit problem formulated in this research, a recommendation will be provided in the upcoming sections for the best suited replenishment system to optimize RSI's truck inventory replenishment process.

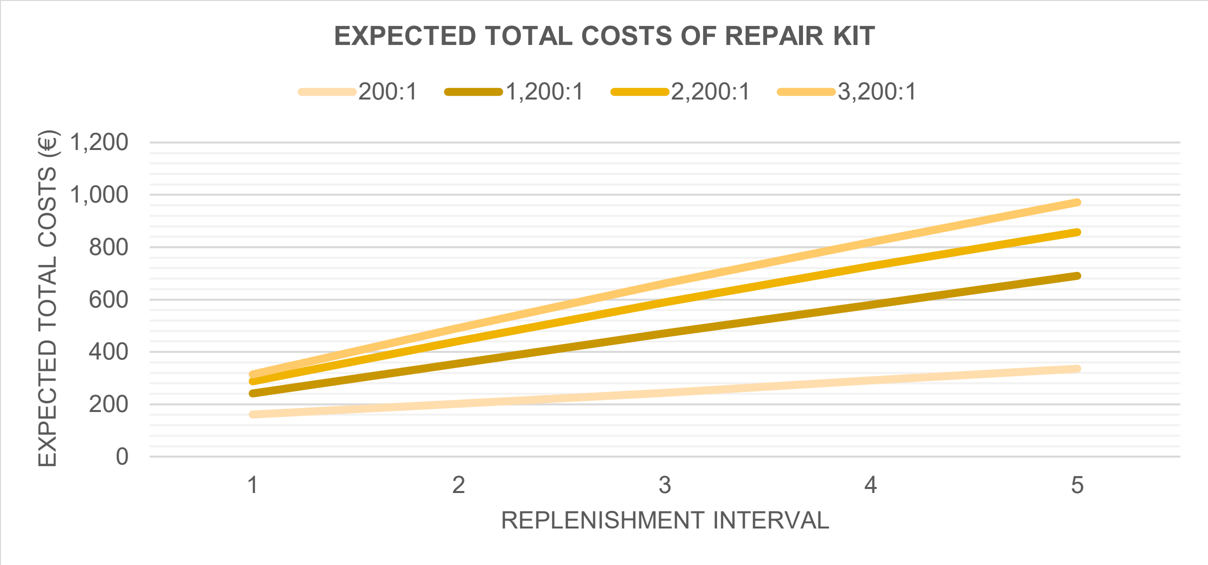

Figure 5-7 ETC (€) of all 20 experimental optimal repair kits.

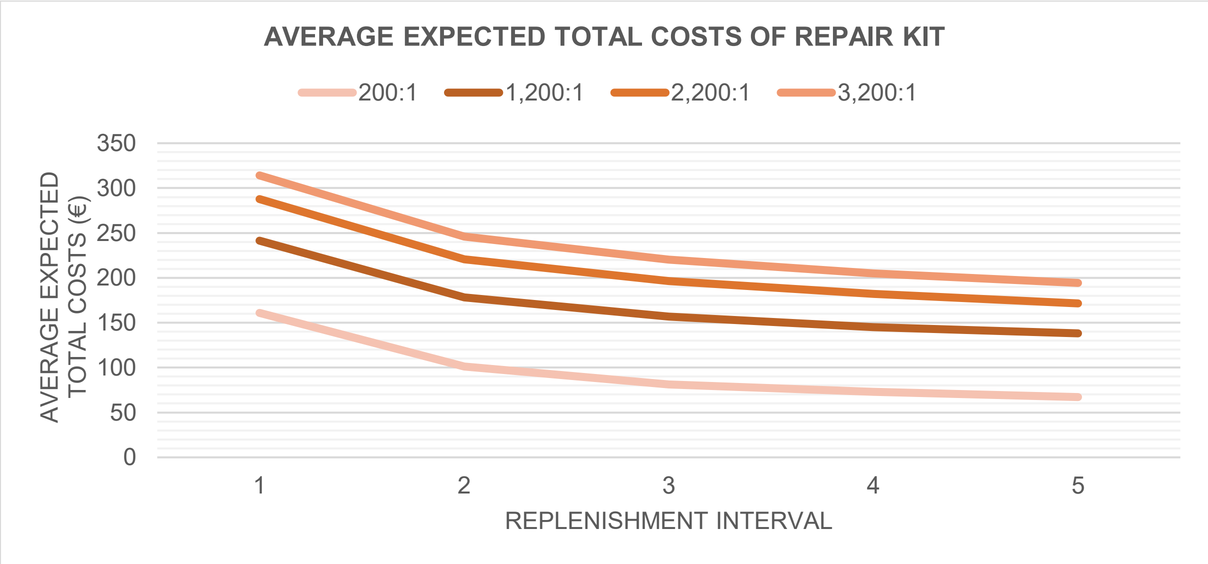

Figure 5-8 Average ETC (€) of all 20 experimental optimal repair kits.

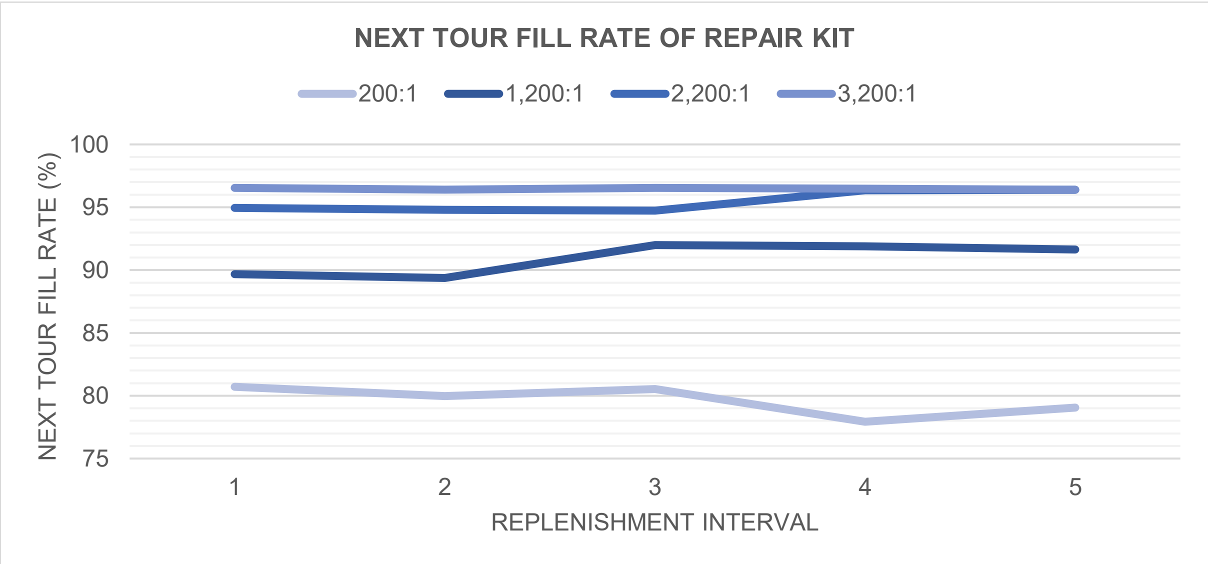

Figure 5-9 $NTFR(c, y)$ (%) of all 20 experimental optimal repair kits.

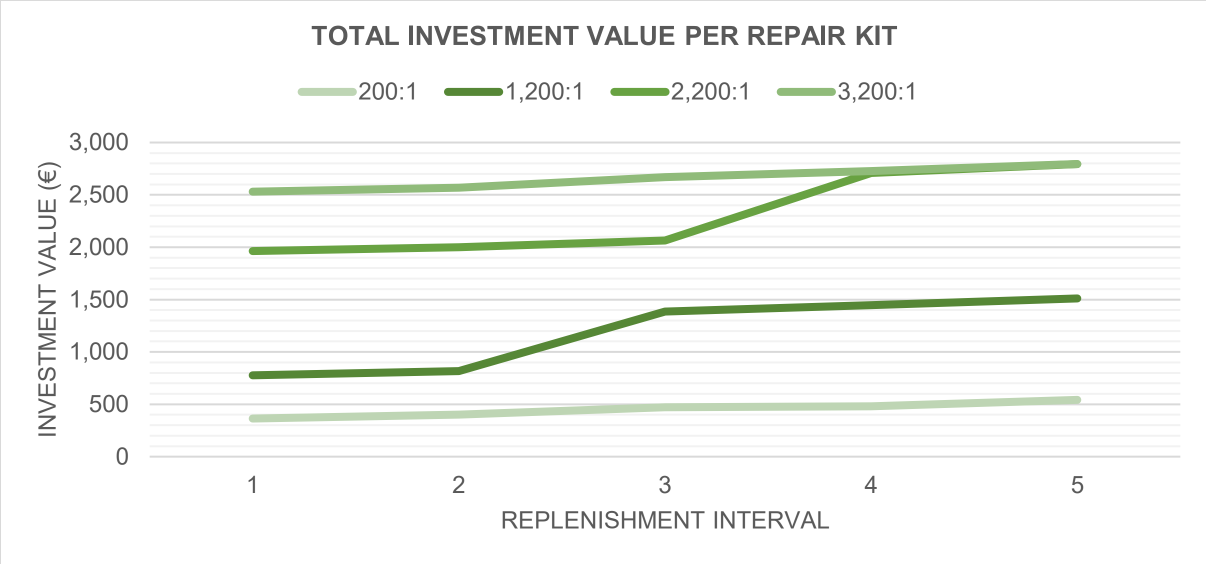

Figure 5-10 Total investment value (€) of all 20 experimental optimal repair kits.

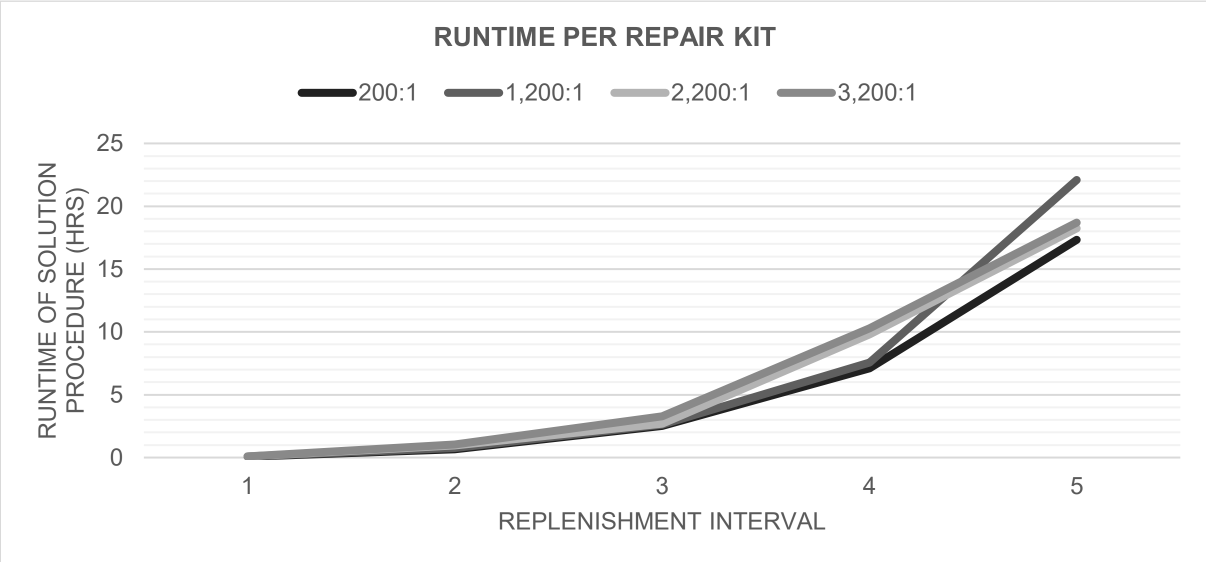

Figure 5-11 Runtime (s) of the solution procedure for deriving all 20 experimental optimal repair kits.

5.4 OPTIMAL REPLENISHMENT SYSTEM

Analysing and evaluating the performance of RSI's inventory replenishment process for the S&M trucks allows for the selection of the optimal replenishment system, which consists of the optimal repair kit and its corresponding replenishment interval. So, the answer to the following sub-question can be provided.

4.4. What should the optimized inventory replenishment process for service and maintenance trucks look like?

The upcoming sections discuss the optimal replenishment interval and optimal repair kit for RSI's truck inventory replenishment process, respectively, and explain the practical implications that this replenishment system will have. Moreover, the KPIs recommended to measure the efficiency and effectiveness of this replenishment process using the optimal replenishment system are outlined.

5.4.1 Optimal replenishment interval

In order to derive the optimal repair kit specifically for RSI's truck inventory replenishment process from the solution procedure, the solution procedure is required to be performed in combination with the optimal replenishment interval. So, before the optimal repair kit can be derived and defined, the optimal replenishment interval needs to be defined and argued, which is done by answering this sub-question.

4.4.1. What should the return frequency of the service and maintenance trucks to the warehouse be?

The highly sought-after optimal replenishment interval for RSI's truck inventory replenishment process or, in other words, the optimal return frequency of the S&M mechanics to the warehouse for the replenishment of their truck inventory should minimize the average expected single-tour costs per workday per S&M mechanic. Alas, after assessing the performance of RSI's truck inventory replenishment process on the different replenishment intervals π, the minimal average expected single-tour costs cannot be determined, as the corresponding minimal average ETC per workday have not been reached yet. Therefore, the optimal replenishment interval cannot be defined based on the 20 combinations of experimental settings and their corresponding results. However, a recommendation can still be provided on which replenishment interval π would be best suited to specifically optimize RSI's truck inventory replenishment process.

As the main objective is to minimize the average expected single-tour costs per workday, the recommended 'optimal' replenishment interval π – when applied to the solution procedure – generates optimal repair kits that result in the smallest average ETC per workday across all $P{:}\,h$ ratios. Evaluating the performance of RSI's truck inventory replenishment process across the potential replenishment intervals from Figure 5-8 in Section 5.3, the recommended 'optimal' replenishment interval specifically for RSI's truck inventory replenishment process is $\pi = 5$ workdays between two subsequent replenishments of truck inventory for each $P{:}\,h$ ratio.

The practical implication of this replenishment interval for RSI's truck inventory replenishment process and general operations would be that the S&M mechanics would make fewer returns to the warehouse for the replenishment of their truck inventory or "repair kits". In fact, this replenishment interval implies that these mechanics should only visit the warehouse once per workweek, which directly corresponds to a return frequency of once per workweek for the S&M trucks to replenish their truck inventory at the warehouse, with an interval of $\pi = 5$ workdays. This leads to a total time of 11.50 hours per workweek spent on truck inventory replenishment over all 46 S&M mechanics across RSI's four eldest establishments. In comparison to the current situation, as outlined in Section 1.2, the implementation of this replenishment interval would already save RSI 23.14 hours per workweek over all S&M mechanics on the actual duration of truck inventory replenishment only. The travel time in which the S&M mechanics' return to and from the warehouse for the replenishment of their truck inventory and its potential savings have not been considered yet.

When the travel time to and from the warehouse is included in the calculation, assuming that the return distance of each S&M mechanic equals the distance between their residence and the nearest warehouse just like in the formulation of the repair kit problem in Section 3.2.3, the S&M mechanics require a total of 32.70 hours combined every time they travel to and from to the warehouse. Reducing the average return frequency from 3 to 1 time(s) per workweek for all S&M mechanics, RSI will save an additional 65.40 hours per workweek on travel time. In total, the potential time savings amount to 88.54 hours per workweek, which can be spent on significantly increasing the amount of valuable services provided to RSI's clients and subsequently as well as equivalently increasing the mechanics' productivity.

The next section provides a profound analysis and explanation on the optimal repair kit derived as a result of applying the recommended 'optimal' replenishment interval of $\pi = 5$ workdays to the solution procedure to obtain the optimal replenishment system for RSI's truck inventory replenishment process.

5.4.2 Optimal repair kit

When the solution procedure is performed in combination with the recommended 'optimal' replenishment interval, as defined in the previous section, the optimal repair kit that each S&M mechanic should store in their truck inventory to perform the SOs related to service contracts can be defined by answering the following sub-questions.

4.4.2. In what way should inventory be stored in the service and maintenance trucks?
- *4.4.2.1. What kind of inventory should be stored in the trucks?*
- *4.4.2.2. In which quantities should the inventory be in stock in the trucks?*

Applying the recommended 'optimal' replenishment interval of $\pi = 5$ to the solution procedure generates four optimal repair kits depending on the $P{:}h$ ratio. Aside from the main objective intended to be achieved, which concerns minimizing the average expected single-tour costs, the S&M mechanics should have a repair kit that enables them to achieve an $NTFR(c, y)$ of at least 95%, as most organizations as well as scientific literature usually aim for an $NTFR(c, y)$ of 95% (Flora, 2022). Figure 5-9 in Section 5.3 shows that two $P{:}h$ ratios manage to achieve such an $NTFR(c, y)$ of at least 95%. Therefore, the best suited $P{:}h$ ratio, when applied to the solution procedure together with the replenishment interval of $\pi = 5$, should generate the repair kit with the minimal total investment value required to acquire the inventory items and their corresponding inventory levels as well as with the minimal runtime required to execute the solution procedure. This way the amount of cash outlay on truck inventory required to implement this repair kit is minimized, which will enable RSI to have the maximum amount of cash available for other investment purposes, and the practicality of implementing the solution procedure within RSI's operations will be maximized. Based on this order of objectives, the optimal repair kit for RSI's truck inventory replenishment process specifically is derived by applying the replenishment interval of $\pi = 5$ and the $P{:}h$ ratio of $2{,}200{:}\,1$ to the solution procedure.

Subsequently, the optimal repair kit generated for RSI's truck inventory replenishment process including the kind of inventory items and corresponding inventory levels is presented in Figure 5-12. The optimal repair kit represents the repair kit to be used by each individual S&M mechanic. This repair kit is associated with the following results for the progress of the EHC, EPC, ETC and total investment value with respect to the progress of the $NTFR(c, y)$, as depicted in Figure 5-14, Figure 5-15, Figure 5-16 and Figure 5-18, respectively. Besides that, Figure 5-17 shows the monetary value of the inventory items when added for the first time to RSI's optimal repair kit in terms of the cost-price of each unique inventory item included. The progress in these figures represents all iterations performed in the solution procedure, where in each iteration one part of an inventory item is added to the optimal repair kit that results in the greatest decrease in the expected single-tour costs, as defined in Section 4.2. The solution procedure manages to derive this optimal repair kit in a runtime of 18.24 hours, when the expected single-tour costs no longer decrease by adding another part of any inventory item to the repair kit.

RSI's optimal repair kit in Figure 5-12 shows high diversity in the kind of inventory included, as 52 out of the 53 potential inventory items, that are in the top 10% of most frequently used inventory items on the 2,582 SOs performed in 2022, are included with various inventory levels ranging from 1 until 43. However, the majority of these inventory items, specifically 65.38% of inventory items, have an inventory level between 1 and 5, which means that many unique inventory items are required in each tour but not always in great quantities. So, large differences exist between the SOs to be performed regarding their inventory requirements.

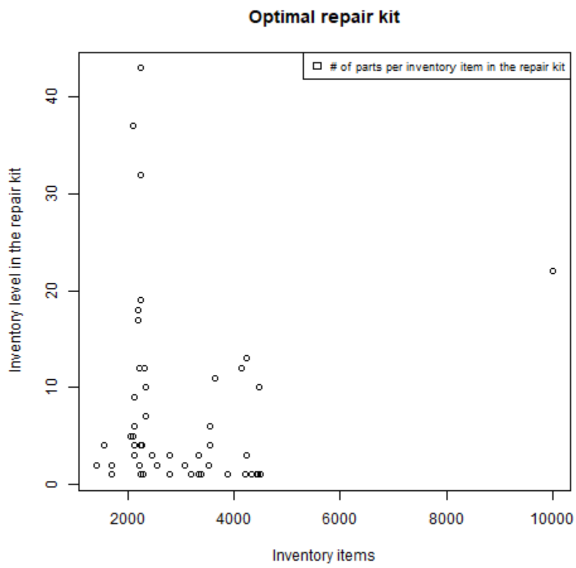

Figure 5-12 Optimal repair kit per S&M mechanic for RSI's truck inventory replenishment process including 52 out of 53 inventory items (from a total of 537 inventory items) with various inventory levels.

To give an indication of the reality of this repair kit, the kinds of inventory items that should be stored in truck inventory according to the optimal repair kit can be described as follows. The optimal repair kit indicates that 23 distinctive kinds of inventory items are required in truck inventory to complete the SOs to be performed, including, amongst others, lamps, fuses, bolts, nuts, air hoses, cable ties, magnetic switches, sensors, hoisting chains and floats. Figure 5-13 presents the classification of the content of the optimal repair kit based on the different kinds included. This figure shows the number of inventory items per kind as well as the total inventory stored per kind, which stands for the total number of parts of the inventory items included per kind, in this repair kit.

The content of this repair kit as well as its classification, as depicted in Figure 5-12 and Figure 5-13, respectively, have been confirmed by a prominent manager within RSI's S&M division. Most inventory items and their inventory levels in the optimal repair kit have been approved by the S&M manager and match with the reality of current truck inventory to a significant degree when accounting for the decrease in return frequency for truck inventory replenishment from 3 to 1 time(s) per workweek. Only, regularly storing a pump in truck inventory is currently not done in practice. The main reason why pumps are typically not stored in truck inventory is due to their size and/or weight but also because of their cost-price. No size, weight or financial constraint has been inflicted in the derivation of the optimal repair kit, according to the assumptions in Section 3.1.2. This assumption and/or RSI's view on including pumps in truck inventory should be reconsidered before the implementation of the optimal repair kit in practice. Also, other inventory items, as identified in the inventory requirements in Section 2.2.1, that should not normally be stored in truck inventory for the same reason are, for instance, control cabinets and concrete blocks. These other items were not considered while deriving the optimal repair kit at all, as they were not included in the top 10% of most frequently used inventory items on the 2,582 SOs performed in 2022.

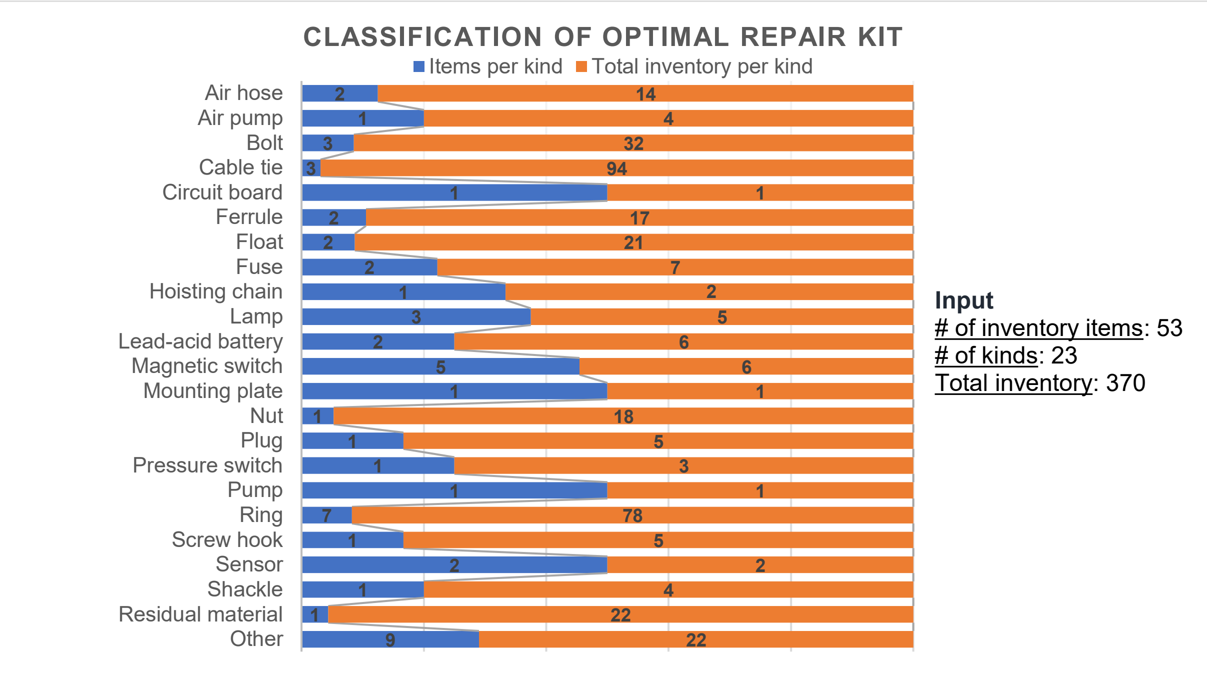

Figure 5-13 Classification of the inventory items included in the optimal repair kit in terms of their kind and total inventory level.

Ultimately, the solution procedure derives the final values that correspond to implementation of the optimal repair kit in RSI's truck inventory replenishment process. A final $NTFR(c, y)$ of 96.39% and ETC of €857.59 are achieved. Then, the EHC, EPC and ERC attain final values of €488.59, €251.00 and €118.00, respectively. Again, as expected, a positive trend for the EHC and a negative trend for the EPC as well as ETC are identified, which has previously been explained in Section 5.1, where the final values for the EHC, EPC and ETC corresponding to RSI's optimal repair kit can be observed at the level of the final $NTFR(c, y)$ in the figures below. In addition, due to the replenishment interval of $\pi = 5$ workdays, the average ETC of this optimal repair kit come down to €171.52 per workday.

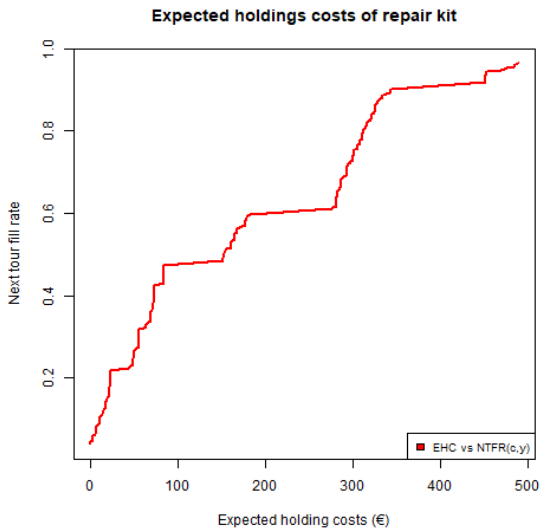

Figure 5-14 EHC (€) of the optimal repair kit for RSI's truck inventory replenishment process.

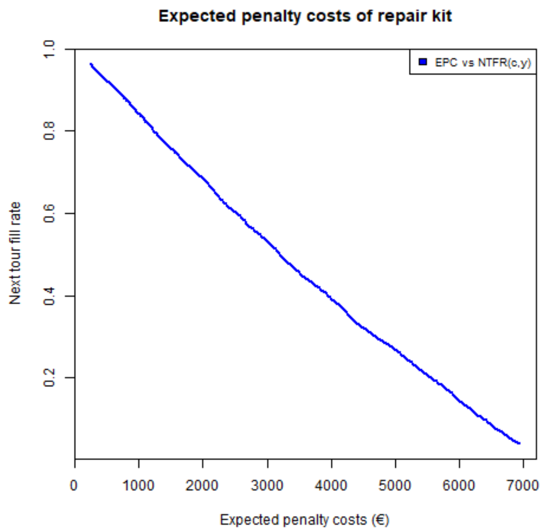

Figure 5-15 EPC (€) of the optimal repair kit for RSI's truck inventory replenishment process.

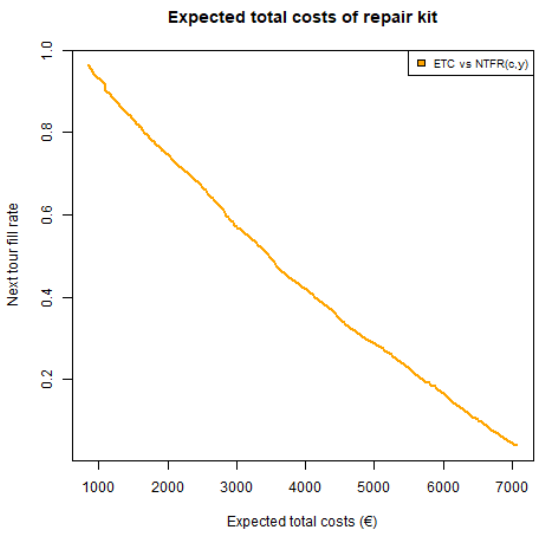

Figure 5-16 ETC (€) of the optimal repair kit for RSI's truck inventory replenishment process.

In turn, the final value for the total investment value to acquire the optimal repair kit for RSI's truck inventory replenishment process is €2,793.88 for each individual repair kit per S&M mechanic. Also, a positive trend between the required stock investment to obtain the optimal repair kit and its inventory items with corresponding inventory levels, and the achieved $NTFR(c, y)$ is once again observed, as indicated and outlined in Section 5.1, where this final value is located at the level of the final $NTFR(c, y)$ of 96.39% as well.

When comparing the cost-price of the inventory items when added for the first time to the optimal repair kit for RSI's truck inventory replenishment process to the initial optimal repair kit, more inventory items with a higher cost-price are included, especially in later iterations when certain items cost more than €400. As predicted, a positive trend can be identified in the actual monetary value of a single part of the inventory item in the iteration when it is first added to the optimal repair kit. Still, the vast majority of inventory items added to the optimal repair kit are of relatively low value, such as a cost-price smaller than €25, due to the main objective of the solution procedure.

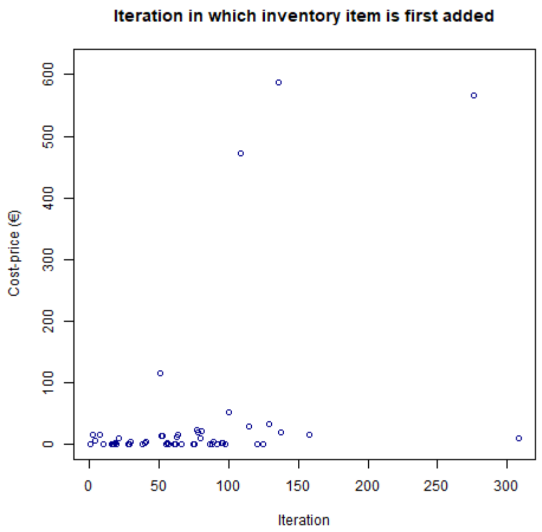

Figure 5-17 Cost-price (€) of an inventory item when added for the first time to the optimal repair kit for RSI's truck inventory replenishment process.

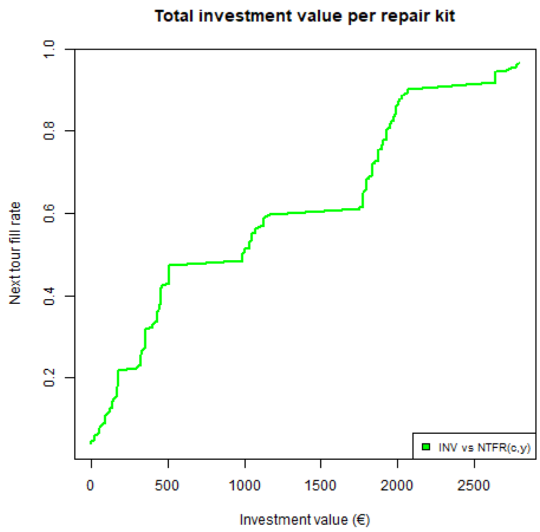

Figure 5-18 Total investment value (€) of the complete optimal repair kit for RSI's truck inventory replenishment process.

The actual meaning behind RSI's optimal repair kit and its practical implication for RSI's truck inventory replenishment process can be expressed as follows. In a tour between subsequent truck inventory replenishments, an S&M mechanic should be capable of performing 25 up to 50 SOs with this optimal repair kit, as determined by the recommended 'optimal' replenishment interval of $\pi = 5$, depending on the kinds of SOs encountered, where only maintenance, malfunction and incidental SOs are considered. At most 4% of the SOs in the tour are expected to not be completed at once due to the $NTFR(c, y)$ of just over 96%. Especially since the calculated $NTFR(c, y)$ is a worst-case value, as explained in Section 4.2, this translates to a maximum of 1 to 2 SOs that cannot be directly completed in a tour. The S&M mechanic will have to visit these SOs a second time at the start of the next tour with the remainder of the demanded inventory items next to a completely replenished repair kit, as assumed in Section 3.1.2. Furthermore, RSI's optimal repair kit quantities for the included inventory items indicate the order-up-to levels that the S&M trucks should maintain. So, every time the S&M mechanic is due for a replenishment of their repair kit according to the recommended 'optimal' replenishment interval, the S&M mechanic can determine which inventory items in which quantities to replenish in their truck inventory to reach the maximum inventory levels defined by RSI's optimal repair kit. In case, some SOs in the tour could not be completed, the inventory levels of the optimal repair kit may be exceeded in truck inventory by the inventory item quantities still demanded by these uncompleted SOs. This way truck inventory contains the appropriate inventory items and corresponding inventory levels to complete the uncompleted SOs and perform the next tour.

In short, the optimal replenishment system to optimize RSI's truck inventory replenishment process consists of the recommended 'optimal' replenishment interval of $\pi = 5$ workdays and the optimal repair kit for each S&M mechanic, as depicted in Figure 5-12. Furthermore, the definition of the optimal repair kit for RSI's truck inventory replenishment process supports the structured data registration of truck inventory in RSI's software system and allows for closely and precisely monitoring and evaluating the corresponding data by serving as a benchmark. In turn, RSI has more monetary control over the inventory item quantities stored in truck inventory while having the potential to obtain savings in this regard.

5.4.3 Recommended key performance indicators

Now that the optimal replenishment system has clearly been defined and thoroughly explained, the KPIs to monitor and evaluate the efficiency and effectiveness of RSI's truck inventory replenishment process should be outlined. The subsequent sub-question will define the KPIs most suitable for implementation within RSI's operations.

4.4.3. What KPIs should be used to measure the efficiency and effectiveness of the truck inventory replenishment process?

In Section 2.4, the current KPIs used by RSI to measure and assess the efficiency and effectiveness of its inventory replenishment process for its S&M trucks are defined and explained. The purpose of these KPIs is to measure the productivity of the S&M mechanics over the four eldest establishments of RSI and to determine whether these mechanics meet RSI's norm of working 8 hours per workday or 40 hours per workweek on direct SOs. In this section, the limitations of these KPIs are also addressed, which concern the actual assessment of RSI's truck inventory replenishment process and its corresponding efficiency and effectiveness – or actually the lack thereof.

Based on results obtained from the experimental evaluation and the performance assessment of RSI's truck inventory replenishment process, this research recommends the implementation of the following KPIs in RSI's operations to measure and assess the performance of RSI's truck inventory replenishment process in terms of efficiency and effectiveness.

- **Return frequency**: the number of times per workday or -week (or other time horizon) each S&M mechanic returns to the nearest warehouse for the replenishment of their truck inventory, whether its necessity originated out of emergency or routine according to the replenishment interval π. This KPI sums over all S&M mechanics to obtain the return frequency given the time horizon. Then, the return frequency can be expressed by the subsequent equation.

$$Return\ frequency_t = \sum_m \sum_t Number\ of\ truck\ inventory\ replenishments_{m,t}$$

  Where,

$$m = S\&M\ mechanic \in \{1, 2, 3, \dots, 46\}$$
$$t = time\ horizon\ (day, week, month\ or\ year) \in \{1, 2, 3, \dots\}$$

- **Investment value**: the total monetary value of the entire truck inventory – or all inventory items in the repair kit – stored in each S&M mechanic's truck. Summing the individual investment values per S&M mechanic results in the total investment value for RSI. In turn, the investment value over all S&M mechanics across the four eldest establishments of RSI can be calculated using the following equation.

$$Investment\ value = \sum_m \sum_n Cost\ price_{m,n} * Quantity\ in\ truck\ inventory_{m,n}$$

  Where,

$$m = S\&M\ mechanic \in \{1, 2, 3, \dots, 46\}$$
$$n = inventory\ item \in \{1, \dots, 537\}$$

  One major restriction to the applicability of this KPI concerns the shortcomings that exist in RSI's registration of truck inventory data. As this data is currently inaccurate and unreliable, this KPI cannot be calculated and it cannot evaluate the performance of RSI's truck inventory replenishment process. However, once RSI's data on truck inventory in the software system is and remains accurate, implementing this KPI will be invaluable to the assessment of the performance of RSI's truck inventory replenishment process as well as RSI's monetary control over the inventory item quantities stored in the S&M trucks.

This does not mean that the current KPIs, as defined in Section 2.4, do not serve an important and valuable purpose. These KPIs evaluate whether the S&M mechanics spent a sufficient proportion of their workday on performing high-yield SOs related to service contracts and ensure that these mechanics work their contractual hours per day and per week. Therefore, this research proposes to monitor and evaluate RSI's truck inventory replenishment process according to the recommended KPIs: "Return frequency" and "Investment value", alongside the current KPIs: "Productivity" and "Relative unproductivity".

5.5 CONCLUSION

This chapter has performed the experimental evaluation of the solution procedure and its corresponding model parameters to obtain the optimal replenishment system for RSI's truck inventory replenishment system consisting of the optimal repair kit and corresponding replenishment interval. Together with the values for the model parameters, as estimated in the first section of Chapter 4, the solution procedure was first performed to derive the numerical results to the simplest problem instance resulting in the definition of the initial optimal repair kit and its corresponding $NTFR(c, y)$, ETC including EHC, EPC and ERC as well as the monetary investment value of this repair kit. In order to enable the experimental evaluation to be performed, 20 experimental settings were defined based on these initial numerical results. By performing the experimental evaluation of the performance of RSI's truck inventory replenishment process, where the experimental settings were being applied to the solution procedure, 20 optimal repair kits and their respective experimental results for the $NTFR(c, y)$, (average) ETC, investment value and runtime of the solution procedure were obtained. Subsequently, the following research question can be answered.

4. *How does the optimized inventory replenishment process for service and maintenance trucks perform under experimental settings?*

From this chapter can be concluded that the optimal replenishment system to optimize the inventory replenishment process for the S&M trucks of RSI consists of the optimal repair kit presented in Figure 5-12 and its corresponding replenishment interval of $\pi = 5$ workdays. Implementing this optimal replenishment system into RSI's operations would result in a total investment value per S&M mechanic of €2,793.88, which would add up to a total investment of €128,518.48 for the repair kits of all 46 S&M mechanics, and an $NTFR(c, y)$ of 96.39% for each tour performed. This optimal repair kit includes 23 distinctive kinds of inventory items that mainly consist of magnetic switches, cable ties, bolts, rings and many more, which matches the reality of RSI's current truck inventory to a significant degree considering the recommended 'optimal' replenishment interval.

In combination with the $P{:}h$ ratio of $2{,}200{:}1$, the optimal replenishment system is deemed the best performing among all experimental settings specifically for RSI's truck inventory replenishment process when aiming primarily for minimal average expected single-tour costs as well as secondarily for a target $NTFR(c, y)$ of at least 95%. In addition, this chapter has derived the KPIs recommended to be implemented in RSI's operations to monitor and evaluate the efficiency and effectiveness of RSI's truck inventory replenishment process once the optimal replenishment system is implemented.

In general, RSI's truck inventory replenishment process performs well and as expected under all experimental settings defined based on the initial numerical results. This is concluded from five figures depicted and analysed in Section 5.3 that illustrate the minimization of the average ETC, the relative stability of the $NTFR(c, y)$ and the gradual increase in investment value of the optimal repair kit as well as the exponential increase of the runtime of the solution procedure. The $NTFR(c, y)$ attains promising values between the 75% and 97% while the monetary investment value per optimal repair kit remains smaller than €2,800.00 under all experimental settings. However, the practicality of the solution procedure to RSI's truck inventory replenishment process greatly decreases once the replenishment interval exceeds $\pi = 5$ workdays, because the runtime becomes larger than 24 hours.

As the optimal replenishment system has now been derived to optimize RSI's truck inventory replenishment process in terms of efficiency and effectiveness, no key questions remain to be answered by this research. Therefore, the next chapter intends to discuss the interim conclusions to this research and to provide the answer to the main research question including the final outputs to this research. Moreover, the recommendations for the implementation of the optimal replenishment system as well as the propositions for future research are also outlined in the next chapter.

6. CONCLUSIONS AND RECOMMENDATIONS

In the closing chapter of this research, the conclusions and recommendations as well as future research propositions are outlined. As the optimal replenishment system for RSI's truck inventory replenishment process as well as its corresponding experimental results and practical implications have been defined and explained in Chapter 5, the subsequent research question can be answered.

5. *Which conclusions can be drawn, and recommendations can be made from the optimized inventory replenishment process for service and maintenance trucks and the corresponding experimental results?*

The first upcoming section draws the various conclusions to this research resulting in the answer to the main research question. In the section thereafter, several distinctive recommendations for RSI are described while in the final section, propositions for potential future research are presented.

6.1 CONCLUSIONS

To properly conclude this research, the answer to the main research question, as formulated in Section 1.3.2, should be provided. In order to ensure a complete and detailed answer, the subsequent sub-question is answered by considering the interim conclusions formulated in the previous chapters in their respective sequence.

5.1. *What can be concluded from the performance of the optimized truck inventory replenishment process?*

In this research, the following conclusions from the previous chapters can be drawn to support the answer to the main research question. These interim conclusions are depicted in order in which the chapters were discussed.

1. To solve RSI's core problem concerning the *"inefficient and ineffective truck inventory replenishment process for service and maintenance trucks"*, RSI's inventory replenishment process for its S&M trucks should be designed in such a way that the downtime of the corresponding mechanics caused by this process is minimized.
2. RSI has an already established step-wise truck inventory replenishment process, which lacks a replenishment technique and accurate truck inventory data. Therefore, RSI refrains itself from being in control of the productivity of the S&M mechanics, the frequency of truck inventory replenishments and which inventory items to be replenished in which quantities.
3. The characteristics of optimizing RSI's truck inventory replenishment process resemble one specific spare parts management issue known in literature as the repair kit problem. In the formulation of the repair kit problem for this research, necessary adaptations have been made to existing scientific literature and new theoretical additions have been included to define the ultimate repair kit problem that encompasses all requirements and assumptions of RSI's truck inventory replenishment process and that can derive the corresponding optimal solutions.
4. A greedy heuristic is the most suitable solution method to solve the formulation of the repair kit problem in this research to optimality. Subsequently, the solution procedure was developed that minimizes the expected single-tour costs – holding, replenishment and penalty costs – associated with the repair kit. This solution procedure can create an optimal repair kit for any values assigned to its model parameters, such as the replenishment interval π and the ratio between the penalty costs and holding costs $P{:}h$.
5. The optimal replenishment system to optimize the inventory replenishment process for the S&M trucks of RSI in terms of efficiency and effectiveness consists of the optimal repair kit presented in Figure 5-12 and it corresponding replenishment interval of $\pi = 5$ workdays, which is deemed the best performing replenishment system for RSI's truck inventory replenishment process when aiming for minimal average expected single-tour costs and a target $NTFR(c, y)$ of at least 95%.

Now that the interim conclusions are clearly outlined, the answer to the main research question can correspondingly be provided.

"How can the truck inventory replenishment process for the service and maintenance trucks of REMONDIS Smart Infra be optimized in terms of efficiency and effectiveness?"

By implementing the optimal replenishment system consisting of the optimal repair kit presented in Figure 5-12 and its corresponding replenishment interval of $\pi = 5$ workdays for each of the 46 S&M mechanics, as derived in this research, the truck inventory replenishment process for the S&M trucks of RSI can be optimized in terms of efficiency and effectiveness by minimizing the downtime of the S&M mechanics caused by this process. The downtime minimized concerns the travel time to and from the warehouse as well as the time spent on the actual replenishment of truck inventory, or the repair kit in this case, where a total of 88.54 hours per workweek can be saved over all S&M mechanics while obtaining an $NTFR(c, y)$ of more than 95% per tour.

The optimal replenishment system can be derived using the standard solution procedure developed in this research that suits RSI's truck inventory replenishment process and complies with its corresponding requirements and assumptions. The final outputs of this research are summarized and displayed in Figure 6-1. Comparing these final research outputs to the prospective outputs introduced and depicted in Figure 2-9, the optimal replenishment system in terms of the optimal repair kit and corresponding replenishment interval enables RSI's truck inventory replenishment system to be optimized by means of implementation within RSI's operations. Furthermore, the optimal repair kit for RSI's truck inventory replenishment process supports the structured data registration of truck inventory in RSI's software system and allows for closely and precisely monitoring and evaluating the corresponding data by serving as a benchmark. Especially, the inventory levels for the different inventory items included in the optimal repair kit indicate the order-up-to levels to be maintained in truck inventory. With the previously-stated potential savings on downtime, as a result of implementing the recommended 'optimal' replenishment interval, RSI and its S&M mechanics can provide a significant increase in valuable services to their current clients but also to potential clients. When providing more valuable services to clients, the S&M mechanics will spend more time on direct orders related to service contracts, so the mechanics' productivity will increase. Besides that, the minimized downtime for RSI's truck inventory replenishment process contributes to RSI's ambition of becoming the eventual market leader in such a way that it allows RSI to serve an increasing number of clients. Finally, the optimal repair kit provides RSI with increased monetary control over the inventory item quantities stored in actual truck inventory while having the potential to obtain savings in this regard.

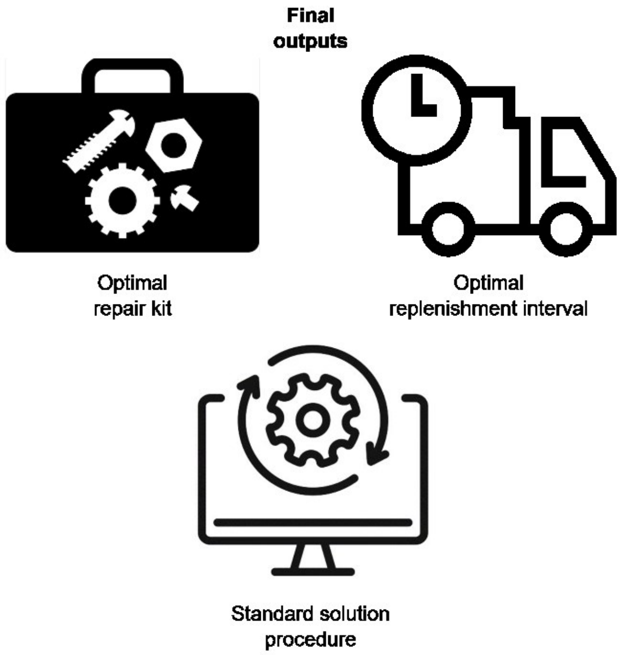

Figure 6-1 Final research outputs for RSI's truck inventory replenishment process.

6.1.1 Key outcomes for REMONDIS Smart Infra

One of the most important outcomes that RSI should take away from this research concerns on the one hand the standard solution procedure, which can create an optimal repair kit for any values assigned to the model parameters, such as the replenishment interval π and $P{:}h$ ratio. RSI should tune these parameters according to the objectives of the repair kit problem. First and foremost, the definite value for replenishment interval π should be determined by the interval π that minimizes the average expected single-tour costs per workday, as this concerns the main objective that the repair kit problem formulation intends to achieve. Then, the value for the $P{:}h$ ratio should be tuned to the intended target $NTFR(c, y)$ with that ratio, which this research recommends to be at least 95%. As an $NTFR(c, y)$ of 95% is not the main objective, RSI has the liberty to set another target $NTFR(c, y)$ according to its own practical insights. In conclusion, this standard solution procedure allows RSI to derive future optimal repair kits when more new clients are served as well as to validate and verify the resulting values for the $NTFR(c, y)$ and total investment values.

To make this solution procedure applicable to RSI's operations now, RSI should implement the recommendations, as to be defined in Section 6.2. Crucially, RSI should actualise its data on the current inventory levels stored in the S&M trucks as well as incorporate the recommended KPIs within its operations, among other recommendations. In turn, RSI should consider performing future research based on the propositions to be formulated in Section 6.3 in order to enhance the applicability of the entire solution model, which consists of the formulation of the repair kit problem as well as the solution procedure, to RSI's operations in the future. Examples of which are specifying the optimal replenishment system per establishment or even per individual S&M mechanic, reconsidering the assumptions applied to the solution model, such as the no financial or size constraint on the optimal repair kit, and improving the efficiency of the solution procedure itself.

Subsequently, RSI is advised to thoroughly consider the practical implications of implementing the optimal replenishment system for RSI's truck inventory replenishment process into its operations, which has been explained in detail in Section 5.4, where the optimal repair kit and corresponding replenishment interval π as well as the recommended KPIs for monitoring and evaluating RSI's truck inventory replenishment process have been defined.

6.1.2 Striking insights

Some additional striking and unforeseen insights can be gathered from results of this research. For instance, in order to attain an $NTFR(c, y)$ of 90% or 95%, the required stock investment of the corresponding repair kit approximately doubles and more than triples, respectively, compared to the investment value to achieve an $NTFR(c, y)$ of 80%, which can be concluded from Figure 5-9 and Figure 5-10 in Section 5.3. Also, almost double the stock investment is required for a repair kit that manages to achieve an $NTFR(c, y)$ of 95% instead of 90%. These observations indicate that RSI has to commit an exponentially increasing amount of cash outlay to truck inventory to increase the minimum $NTFR(c, y)$ of 80% by 5%, 10% or 15%, which RSI will not be able to dedicate to other investment purposes.

Furthermore, an indirect relation between the $NTFR(c, y)$ and the investment value of the optimal repair kit is identified, as these experimental results are linked to the EPC and EHC, respectively, which initially went unnoticed before the experimental results were derived. So, the EHC increase and EPC decrease as a result of adding a single part of the inventory item with the greatest single-tour cost decrease to the optimal repair kit, which increases the investment value of this repair kit as well as its $NTFR(c, y)$ within a replenishment interval π. However, between subsequent replenishment intervals, a significant increase in investment value is required to attain the same $NTFR(c, y)$ and an even greater increase in investment value is required to lead to an increase in $NTFR(c, y)$ compared to the previous interval π, which can be explained by the increasing number of SOs to be performed that have the potential to be broken in the tour due to the larger replenishment interval π. In case the investment value does not adequately increase in order to meet the inventory item requirements of the additional SOs, the $NTFR(c, y)$ may even decrease in comparison to the previous replenishment interval π.

What was also unsuspected before executing the solution procedure, is the effect that the number of SOs to be performed in a tour has on the runtime of the solution procedure, especially how extreme this effect seems to be. The increasing number of SOs in a tour, as a result of the increasing replenishment interval π, have to be constantly accounted for in each calculation of the $NJFR(i, y)$, $NTFR(c, y)$, and expected single-tour costs $V_1(x, c, y)$ in the solution procedure formulated in Section 4.2. That is why the runtime of the solution procedure exponentially increases irrespective of the $P: h$ ratio, which significantly impacts the efficiency and practicality of the developed solution procedure to RSI's operations.

Finally, according to the experimental settings defined, the optimal replenishment interval was expected to fall within one workweek. This seems likely to be incorrect, as concluded from experimental results in Section 5.3. The optimal replenishment interval can still be equal to $\pi = 5$ when the average expected single-tour costs per workday turn out to be greater for $\pi = 6$ than $\pi = 5$. However, this cannot be confirmed by experiments performed in this research. Instead, the optimal replenishment interval most probably lies beyond one workweek according to the progress of the average expected single-tour costs per workday across the five replenishment intervals depicted in Figure 5-8.

6.1.3 Reflection on solution model

Reflecting on the formulation of the repair kit problem, the developed solution procedure and the corresponding results derived, their fit to RSI's operations can determined. Looking back on the well-argued conclusion of independent demand between inventory items, the results of this research would change in case dependent demand between inventory items would be assumed instead, especially for combinations of inventory items with perfect positive correlation. As 1,814 significant correlations between the demand for the 537 inventory items have been identified of which 88 combinations have perfect positive correlations, the demand probabilities for the 447 inventory items involved in these significant correlations will be affected. When one inventory item is required by an SO with a certain probability, the probability that the other inventory item is also demanded should be appropriately adjusted and vice versa. Subsequently, the inventory items that are involved in perfect positive correlations should be considered as one item, which means that their demand probabilities as well as their cost-prices should be combined, effectively reducing the number of inventory items to be considered. All in all, this should not result in a completely different optimal replenishment system, as merely 0.6% of inventory item combinations experience some degree of dependence when it comes to their inventory requirements for an SO. However, the dependent demand between certain inventory items might impact the actual content of the optimal repair kit, which should be looked into.

When defining the values for the model parameters, only the top 10% of the most frequently used inventory items on the 2,582 SOs performed by the S&M mechanics in 2022 are considered in the derivation of the optimal replenishment system. When all 537 inventory items would be considered, the corresponding optimal repair kit would consist of a greater diversity of inventory items. Still, most of these top 10% items would remain in that repair kit, as these items have the greatest demand probabilities due to being used most frequently to perform the historical SOs according to the inventory item requirements in Section 2.2.1. Nevertheless, by considering all 537 inventory items, the (average) expected single-tour costs as well as the monetary investment value associated with the optimal repair kit are expected to significantly increase in order to attain an $NTFR(c, y)$ of 95% for each replenishment interval π, which also requires increasing the $P: h$ ratio. Although the optimal repair kit will most probably be severely impacted by considering all inventory items, the optimal replenishment interval is anticipated to be barely affected, as all replenishment intervals π and all SOs performed within these intervals are impacted in predominantly the same way. Albeit that the resulting increase in expected single-tour costs leads to an increase in the average expected single-tour costs per workday for each replenishment interval π, the optimal replenishment interval for which the average expected single-tour costs per workday are minimized most likely remains the same for each $P: h$ ratio. In turn, the runtime of the solution procedure is expected to significantly increase as well when considering all inventory items in its algorithm presented by Algorithm 4-1 reducing its efficiency and practicality to RSI's operations. In order to derive the optimal replenishment system that considers all 537 inventory items within reasonable runtime, the efficiency of the solution procedure should be improved.

Furthermore, the holding costs have been assumed to be 5% of each inventory item's cost price in mutual agreement with the warehouse, functional and S&M managers at RSI, which is a reasonable assumption based on similar percentages applied in scientific literature (Prak et al., 2017; Saccani et al., 2017). In turn, the penalty costs are costs currently not applied in RSI's operations, which have been based on the location of the broken SO in the sequence of the tour. These penalty costs initially have a low value, especially compared to the holding costs but also compared to what would be realistic for RSI's operations. With the introduction of the $P:h$ ratio, the penalty costs for each broken SO in the tour can be increased relative to the holding costs in such a way that the target $NTFR(c, y)$ can be achieved given the replenishment interval π. This significantly enhances the practicality of these penalty costs to RSI's operations.

In the optimal repair kit derived in Section 5.4, certain inventory items are included, such as a pump, which are not typically not stored in the inventory of RSI's S&M trucks due to their cost-price, weight or size. This is due to the fact that these items have been used so frequently on historical SOs that the solution procedure deems it worthwhile to store them in truck inventory. Also, no financial, size or weight constraint has been incorporated into the formulation of the repair kit problem to potentially prevent such items from being added to the repair kit. However, aside from the pump, the other inventory item quantities in the optimal repair kit match with the reality of RSI's current truck inventory to a significant degree when accounting for the recommended 'optimal' replenishment interval of $\pi = 5$ workdays. So, on the one hand, RSI should reconsider whether or not to allow such items, which in this case concerns a pump, to be stored in truck inventory. On the other hand, a financial, weight and/or size constraint should be incorporated within the formulation of the repair kit problem as well as the solution procedure, to match with the reality of RSI's operations. Additionally, other assumptions applied to the entire solution model should be reconsidered due to their impact on the derivation of the optimal replenishment system.

6.1.4 Concluding research results

In conclusion, the replenishment interval of $\pi = 5$ results in the S&M mechanics returning to the warehouse with a return frequency of once a week for the replenishment of their truck inventory. In between replenishments, 96.39% of the SOs performed in the tour are to be completed at once with the optimal repair kit. The other 3.61% of SOs are uncompleted, which corresponds to a maximum of 1 to 2 SOs per workweek, and will have to be visited a second time after the next truck inventory replenishment with the right inventory item quantities for completion. The optimal repair kit is an identical repair kit for each individual S&M mechanic that mainly consists of magnetic switches, cable ties, bolts and rings but also air hoses, ferrules, floats, fuses, lamps, lead-acid batteries, sensors and many more. The required stock investment to acquire the optimal repair kit is equal to €2,793.88 per repair kit, which would add up to a maximum total investment value of €6,682,960.96 over all 46 S&M mechanics per year for RSI. All in all, the downtime of all S&M mechanics caused by RSI's truck inventory replenishment process comes down to a total of 44.20 hours per workweek by implementing the optimal replenishment system in this process, which reduces the overall downtime caused by this process by 66.70% compared to its current state.

6.2 RECOMMENDATIONS

Furthermore, the next step for RSI would be to examine the possibility of implementing the optimal replenishment system, as outlined in Section 5.4, in its truck inventory replenishment process. The insights obtained while performing this research and by deriving the optimal replenishment system allow for an answer to be provided to the following sub-question.

5.2. *What are the recommendations for implementing the optimized truck inventory replenishment process?*

In order to implement the optimal replenishment system within RSI's truck inventory replenishment process, this research presents the following recommendations for an attainable and successful implementation. These recommendations are listed in order of the chapters in which they were first mentioned.

RSI's data on the (current) inventory levels stored in the S&M trucks should be actualised, so that the performance of the optimal replenishment system in terms of the $NTFR(c, y)$ and investment value as well as the inventory levels of the optimal repair kit can be compared to those of the current truck inventory. Then, it can be concluded whether the optimal replenishment system is an actual improvement upon RSI's current truck inventory replenishment process in terms of efficiency and effectiveness.

For RSI to be able to execute the solution procedure and generate optimal repair kits on its own, this research advises to acquire and install the software program in which the solution procedure has been implemented and coded. This way the company has the opportunity to validate and verify the results of this research before implementing the proposed optimal replenishment system, as defined in Section 5.4. Furthermore, it allows RSI to perform future research on the standard solution procedure to further optimize its truck inventory replenishment process in the future.

To verify the optimality of the optimal replenishment system, as defined in Section 5.4, this research recommends to implement the optimal repair kit and its corresponding replenishment interval π solely for S&M mechanics that perform maintenance, malfunction and incidental SOs on service contracts only, as the optimal repair kit has been constructed based on these kinds of SOs. Potentially expanding the optimal repair kit and its corresponding replenishment interval π to other S&M mechanics that also perform other kinds of SOs not included in this research, should be considered as future research.

The optimal repair kit should serve as a benchmark for the S&M mechanics to determine which inventory items in which quantities to replenish in their truck inventory while the optimal replenishment interval is a guideline for when to replenish their repair kits to ensure that the target $NTFR(c, y)$ can be attained. In other words, this research advises to implement the inventory levels of the items stored in the optimal repair kit as the order-up-to levels for each replenishment of truck inventory in the software system. In turn, once RSI has actualised its truck inventory data in the software system, the S&M managers can and are advised to monitor, evaluate and assess truck inventory according to these maximum inventory levels for the inventory items included in the optimal repair kit.

In order to successfully implement the optimal replenishment system in the practical setting of RSI's operations, it is recommended to develop a tailored policy and/or instruction manual on the practical way of working with the optimal replenishment system as well as to train the S&M mechanics according to this developed policy and/or manual beforehand. Also, the managers involved should be informed about and taught how the optimal replenishment system is going to work in practice.

To monitor and evaluate the actual performance of the implemented optimal replenishment system on its efficiency and effectiveness, this research suggests to implement the recommended KPIs, as they have been defined in Section 5.4.3, in RSI's operations to be and remain in control of the truck inventory replenishment process and its corresponding monetary position as well as to make timely adjustments to the process and replenishment system by being on top of the situation.

Finally, this research recommends RSI to develop an implementation roadmap, that most certainly includes the previously-formulated points of recommendation, and to plan each step to be performed in this roadmap accordingly in order to enable a successful implementation of the optimal replenishment system within RSI's operations. Furthermore, the propositions of future research meant for further optimization of RSI's truck inventory replenishment process somewhere in the future, which will be outlined in the following section, can also be incorporated within the long-term perspective of this roadmap.

6.3 FUTURE RESEARCH AND LIMITATIONS

Finally, limitations to this research but also certain areas for potential further research were identified while performing this research. These insightful perceptions gained enable the following sub-question to be answered, which entails that the propositions for future research can be outlined as follows.

> *5.3. What can be proposed as future research for RSI's truck inventory replenishment process?*

This research has formulated and solved the repair kit problem to optimality specifically for RSI's truck inventory replenishment process and its respective requirements and characteristics. However, this research has also been limited to certain boundaries set by the scope and assumptions defined. Future research can exploit these limitations and enhance the applicability and accuracy of the research results to RSI's truck inventory replenishment process. These propositions for future research are divided into three key directions, namely RSI's problem context, its truck inventory replenishment process and the entire solution model of this research.

6.3.1 Problem context

Aside from the core problem solved in this research, RSI faces more problems that impede it from achieving its ambition of becoming market leader in its sector, such as the inaccurate pricing of the tender due to inaccurate resource pricing. Therefore, RSI should further investigate and aim to resolve these problems by performing additional internal research. Furthermore, other causes also influence the core problem, as outlined in Section 1.3.1, regarding the productive time of the S&M mechanics next to the inefficiency and ineffectiveness of RSI's truck inventory replenishment process. These causes have been disregarded in this research but might indeed have an impact on the mechanics' productive time, such as the travel time between client locations. Future research is suggested to determine the exact impact of these causes and whether it would be valuable to derive an optimal solution for them.

6.3.2 Truck inventory replenishment process

In combination with the policy and/or instruction manual on how the optimal replenishment system works in practice, RSI should investigate whether the S&M mechanics correctly register the inventory items and their corresponding quantity used on the SOs performed, as this data serves as input to the solution procedure in terms of ADI and the respective demand probabilities applied to derive the optimal repair kit. If this is not the case, future research should determine how to optimize the data registration for the S&M mechanics resulting in an increasingly accurate optimal repair kit for RSI's truck inventory replenishment process.

Currently, the manual check and correction of a truck's picklist by the warehouse manager is not monitored on correctness. Also, with the implementation of the optimal replenishment system, the operations of the warehouse manager might be affected. In future research, the impact of the implementation of the optimal replenishment system on the operations of the warehouse manager should be depicted. Additionally, a policy and/or control system should be developed to ensure that the warehouse manager can correctly perform the checks and corrections of the various picklists. Once the warehouse manager has deposited the checked as well as collected inventory items in the internal crossdock, S&M mechanics should receive an indication when to return to the warehouse to collect their requested inventory items. Future research should develop such an indication in the software system, as such a guideline for the S&M mechanics does not currently exist leading to unnecessary returns to the warehouse or a lack of inventory in the trucks.

Now that the optimal repair kit has been derived in which the kind and quantity of inventory items included are known, it might be valuable to reconsider the structure and layout of the truck interior to optimize it in terms of the efficiency and effectiveness with which the required inventory items to complete the SOs can be acquired from truck inventory. Next to that, a policy for the S&M mechanics on how to optimally as well as efficiently store the inventory items included in the optimal repair kit in their truck inventory, also called a replenishment technique, should be derived.

Once RSI has actualised its data on the (current) inventory levels in the S&M trucks, as is recommended in the previous section, a policy should subsequently be constructed on how to maintain accurate truck inventory data in the software system. This way the performance of RSI's truck inventory replenishment process as well as the total investment value of the inventory stored in all S&M trucks can constantly and accurately be monitored and assessed.

6.3.3 Solution model

As concluded from the hypothesis test performed on the dependence of inventory item demand in Section 2.2.1, the demand between inventory items is considered to be independent for all inventory items in this research. However, 447 out of 537 inventory items, which comes down to 83.2% percent of items, experience some degree of dependence to another inventory item regarding their inventory requirements for an SO. Thus, the dependent demand between certain inventory items might impact the content of the optimal repair kit, especially for the inventory item combinations that have a perfect positive correlation. Although merely 0.6% of possible inventory item combinations experience dependency to a certain degree, future research is recommended to be performed in order to incorporate the dependent demand between certain inventory items and evaluate its impact on the optimal replenishment system for an increasingly accurate and practical optimal repair kit for RSI's truck inventory replenishment process.

In turn, the independent demand for the inventory items has only been differentiated on specific kinds of SOs in the formulation of the repair kit problem as well as in the solution procedure, which means that this research derives the optimal replenishment system for S&M mechanics that perform maintenance, malfunction and incidental SOs on service contracts only. So, in this research, the repair and project SOs as well as the incidental SOs that are not related to any service contract have been disregarded. Future research should investigate whether an optimal replenishment system should be derived for these kinds of SOs as well and whether they should get their own or whether they should be incorporated within the already-derived optimal replenishment system.

Subsequently, the optimal replenishment system derived, is identical for each S&M mechanic of the four eldest establishment of RSI. However, these four establishments differ quite significantly on the (kind of) clients that they serve and the exact agreements made with clients on how to perform the SOs. Also, the mechanics differ considerably on the composition of SOs that they are qualified to perform and that they actually perform in practice. For increasingly accurate repair kits to perform these SOs for RSI's current and potential clients, future research should look into specifying the demand for the inventory items, as input to the solution procedure, to derive distinctive optimal repair kits per establishment, per client or per S&M mechanic.

In this research, the current return distance that the S&M mechanics have to travel to the warehouse in order to replenish their truck inventory has been determined but it was technically not applied in the derivation of the optimal replenishment system in a way to minimize the total distance travelled by all mechanics. Future research can be performed to explicitly account for the return distance of each S&M mechanic individually in derivation of a mechanic-specific optimal repair kit to tailor this repair kit to each mechanic's unique work situation.

To enhance the practicality of the solution procedure as well as the optimal replenishment system to RSI's truck inventory replenishment process, it is advised to perform future research in order to eliminate the limiting assumptions made in this research. Instead, replenishment lead times for inventory items from the warehouse, returns of inventory items from truck inventory to the warehouse, uncompleted SOs are completed in the same tour by immediate replenishment from the warehouse, no maximum demand for inventory items defined per SO and a financial, weight and/or size constraint on the optimal repair kit should be incorporated into the formulation of the repair kit problem and the subsequent solution procedure.

The runtime of the solution procedure to generate an optimal repair kit increases exponentially when selecting larger replenishment intervals π and definitely becomes disproportionately large once the replenishment interval exceeds $\pi = 5$ workdays or one workweek, which makes the standard solution procedure basically intractable to implement within RSI's operations. This is due to the increasing number of SOs that the solution procedure has to account for in the derivation of the optimal repair kit and in the calculation of the corresponding results. Therefore, it is recommended to further improve the efficiency of the solution procedure in future research by a programming specialist to enable the derivation of optimal repair kits for larger replenishment intervals π including a larger number of SOs to be performed in a tour.

Once the efficiency of the solution procedure has been significantly improved or even optimized, future research is recommended to be performed in order to find the optimal replenishment interval, which could not be determined with the experimental settings in this research yet, as Section 5.3 explains. Subsequently, analyse the practicality of this optimal replenishment interval to RSI's truck inventory replenishment process as well as its potential for implementation with RSI's operations. With this optimal replenishment interval, RSI can generate the optimal repair kit that results in the minimal average expected single-tour costs per workday, which this research intended to achieve as its main objective.

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