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Preface

Dear reader,

The thesis you are about to read is the final step before obtaining a Master of Science degree in Mechanical Engineering. The specialization of Transport Engineering and Logistics has been the perfect opportunity to broaden my mechanical engineering knowledge. It has led, amongst many other things, to the personal discovery of a whole new and exciting research area called Operations Research. Originally being developed for the military and currently used in applications all over the world in different industries it has been exciting to study and apply this method to a problem it was originally created for: military logistics. It has been an honour and pleasure to be able to work with the Royal Netherlands Army, an organization that I have always been fascinated with.

I would have never been able to do this research on my own. Many thanks go out to Mark Duinkerken and Rudy Negenborn for your supervision, advice and patience. I would also sincerely like to thank Major Niek van Schip for the opportunity of doing my graduate internship at the Royal Netherlands Army, being available as supervisor for any question at any time and for showing me around at the RNLA sites. It has been a great pleasure.

At last I would like to thank God, my family and my friends for their valuable advice and support during the course of my graduation project.

Rutger Koffeman,
Delft, July 2018

List of Acronyms

RNLA - Royal Netherlands Army

NATO - North Atlantic Treaty Organization

KPI - Key Perfomance Indicator

ER - Emergency Response

NRF - Nato Response Force

VJTF - Very High Readiness Joint Task Force

IFFG - Initial Follow-on Forces Group

FFG - Follow-on Forces Group

SAP - System Applications Products

VED - Vital, Essential, Desirable

LP - Linear Programming

Abstract

Background: Currently the Royal Netherlands Army (RNLA) has a traditional three-echelon supply chain consisting of suppliers that deliver to a warehouse and the warehouse that delivers to customers. However, the RNLA is interested in having its stock geographically spread for safety reasons. A solution for this would be to re-design the supply chain into a decentralized stock distribution design. This means that instead of keeping the majority of the stock at a RNLA controlled storage facility, the stock will be stored at the suppliers location and delivered when required. Updating the current RNLA supply chain network towards a decentralized product storage network might lead to a better performing network, but the downsides in case of an emergency response situation are still unclear. This lack of knowledge could severely jeopardize the safety of the Netherlands, it's citizens and also the employees of the RNLA. This research aims to answer the following question:
What RNLA supply chain design, with a focus on decentralized stock distribution, is the most effective in case of an RNLA emergency response situation?
Methods: Based on a literature research, interviews and a flow chart analysis the RNLA specific situation has been studied and translated into an extended supply chain design. Using the method of mathematical programming a multi-period, multi-commodity, multi-objective model has been created that describes the flow between multiple sources and sinks. Penalties are used as cost function to differentiate between desirable and less desirable product flows. By turning on and off different new supply chain functionalities such as cross-docking, direct supplier deliveries and pop-up cross-docks different supply chain designs can be experimented with. User service level and decentralized stock distribution are used as key performance indicators. Fuzzy numbers have been used to account for uncertainty of demand. By utilizing both single and multi-objective objectives a complete picture of a specific situation can be created.
Results: Experimenting with different scenarios, which are combinations of supply chain setups and parameter settings, led to the classification of different supply chain designs based on the resulting objective values. Insight is created in decentralized product storage, early and late product flows and the maximum number of late days, based on the resulting product flows. It was noticed that the weighted-sum multi-objective method took less time to find the optimal solution, compared to the other methods.
Conclusions and Recommendations: Using the supply chain classification, the best supply chain design can be chosen. Using the weighted-sum method, this can be done in an efficient manner. It is recommended to study additional key performance indicators such as the effect of costs. The effect of more advanced objective methods could lead to better results, especially the effect of penalty factors should be studied. Also, internal logistics and vehicle routing should be studied to improve the solutions. On top of that it is very important for the RNLA to accumulate the right kind and amount of data in order to be able to optimize their supply chain now and in the future.

Summary (Dutch)

Achtergrond De huidige bevoorradingsketen van de Koninklijke Landmacht is een traditionele bevoorradingsketen bestaande uit leveranciers, een magazijn en klanten. Echter, de Koninklijke Landmacht heeft de voorkeur om zijn producten geografisch verspreid op te slaan om veiligheidsredenen. Een oplossing hiervoor kan zijn om de bevoorradingsketen te re-organiseren in een decentraal opgeslagen voorraad ontwerp. Dit betekent dat een deel van de voorraad bij leverenaciers ligt, in plaats van het in eigen beheer houden. Op het moment dat het dan benodigd is komt het vanuit die locaties, via de bevoorradingsketen van de Koninklijke Landmacht bij de klanten terecht. Dit zou kunnen leiden tot een verbeterde bevoorradingsketen, maar de keerzijdes zijn nog niet bekend. Dit gebrek aan kennis kan de veiligheid van Nederland, haar inwoners en de werknemers van de Koninklijke Landmacht ernstig in gevaar brengen. Het doel van dit onderzoek is om de volgende vraag te beantwoorden:
Welk Koninklijke Landmacht bevoorradingsketen ontwerp, met een focus op decentraal opgeslagen voorraad, is het meest effective in het geval van een noodsituatie?
Methode: De situatie van de Koninklijke Landmacht is bestudeerd, gebaseerd op een literatuur onderzoek, interviews en een stroomdiagram analyse. Het is daarna omgezet in gereorganiseerde bevoorradingsketen. Gebruik makende van mathematisch programeeren is een multi-periode, multi-artikel, multi-doelstelling model gecreeerd dat de stroom van verschillende origines naar verschillende eindpunten beschrijft. Strafpunten zijn gebruikt om te differentieren tussen gewenste en ongewenste product stromen. Door bevoorradingsketen functionaliteiten zoals cross-docking, directe belevering vanuit de leverancier, pop-up cross-docks te combineren kan er geÃńxperimenteerd worden met verschillende bevoorradingsketen ontwerpen. Gebruikers service level en decentralizatie van product opslag worden gebruikt als prestatie indicatoren. Fuzzy nummers zijn gebruikt om de onzekerheid van vraag te bescrhijven. Door gebruik te maken van singl-objectives en multi-objectives wordt een duidelijk overzicht van elke situatie gegenereerd.
Resultaten: Door te experimenteren met verschillende scenarios, bestaande uit combinaties van bevoorradingsketen ontwerpen en parameters, is er, gebaseerd op de objective waarden, een classificatie ontstaan van bevoorradingsketen ontwerpen. Gebaseerd op de resulterende artikel stromen is inzicht gecreerd in het aantal gedecentraliseerde, te vroege en te late producten. Ook kan het maximumaal aantal dagen te late levering bijgehouden worden. Door parameters zoals artikel belangrijkheid aan te passen komen er andere resultaten naarboven. Het werd opgemerkt dat de gewogen-som multi-objective methode minder tijd nodig had om de optimale oplossing te vinden dan de andere methoden.
Conclusies en aanbevelingen: Door het best scorende ontwerp van de bevoorradingsketen classificatie te kiezen wordt het beste ontwerp gevonden. Door gebruik te maken van gewogen-som multi-objective methode kan dit op een efficientie manier gedaan worden. Het wordt aanbevolen om additionele prestatie indicatoren te onderzoeken, zoals het effect van kosten. Verder kunnen interne logistiek en route planning in het geval van de Koninklijke Landmacht verder onderzocht worden. Daarnaast is het erg belangrijk dat de juiste data bijgehouden wordt, zodat de bevoorradingsketen nu en in de toekomst geoptimaliseerd kan worden.

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1 Introduction

1.1 Research context

This research is conducted at the Royal Netherlands Army (RNLA). The RNLA is part of the Dutch ministry of Defence and is responsible for defending the Netherlands, its (economical) interest and allies abroad. It does so by protecting against attacks from countries or groups on territory of the Netherlands including power stations, water companies or computer systems for example. Besides that, it provides assistance when military materiel or expertise is required by the government authorities in case of disaster. The RNLA also offers support to social organizations when needed. Outside the territory of the Netherlands the RNLA cooperates frequently with other Services of the Netherlands armed forces (Royal Netherlands Air Force, Royal Netherlands Navy, Royal Gendarmerie) and foreign army units from European or North Atlantic Treaty Organization (NATO) allies for example. During these cooperations the tasks are to defend NATO Allied territory, peacekeeping missions, providing humanitarian aid and supporting local population or civil organizations. By standing up for others and providing support during disasters, the Royal Netherlands Army works on peace, freedom and safety in the Netherlands and abroad [1].
A driving force behind the RNLA's activities is the supply chain, which ensures the timely availability of required products. As part of a general supply chain update the RNLA is researching new ways of improving the supply chain. One of these ways is a closer cooperation with the companies that deliver products (later referred to as "the industry") to the RNLA, as it is not the core business of the RNLA to run a logistics company. By studying the effect of decentralized product allocation, options are explored to store products not only in the new logistical centre, but also at the physical warehouses of the suppliers themselves. The advantage is that stocks are geographically dispersed, which is considered more safe than locating all the stocks at the same place. However, the negative effects on the effectiveness of the supply chain are not known yet. For example, will the products still arrive in time? Or, what are the required preparations if a specific supplier does not deliver when called upon?

1.2 Research scope

Within the RNLA, no previous research has been conducted on the possible effects of decentralized product storage for the RNLA so this thesis will consider the highest aggregation level of the supply chain. It is tempting to study all the separate aspects of the supply chain, such as internal processes of individual facilities, but this would be to extensive for the six months that are available for this project. It is expected that the supply chain will be most strained in case of emergency response situations, as opposed to regular business, because emergency response situations are characterized by large and beforehand uncertain demands. Since the renewed supply chain allows for different configurations of the storage location of products, the research aims to provide a tool that can give more insight in the effects of different configurations, so that decision makers can make well founded choices.

1.3 Research problem

As mentioned in paragraph 1.2 a lot of questions go unanswered. Not only are the lives of the RNLA employees depended of it's supply chain, a failure in the RNLA supply chain during an emergency requirement could affect the entire Netherlands and it's citizens. Altering the supply chain needs to be thoroughly studied and thus the following problem definition can be defined:
Updating the current RNLA supply chain network towards a decentralized product storage network might lead to a more effective supply chain, but the downsides in case of an emergency response situation are still unclear. This lack of knowledge could severely jeopardize the safety of the Netherlands, it's citizens and also the employees of the RNLA. By analyzing the system and designing a model, a tool can be created that evaluates the possible outcomes for different supply chain configurations. This tool can be utilized in the RNLA decision making process of allocation products.

1.4 Research objectives & approach

1.4.1 Objectives

The objectives of this research thesis are the following:

- Create insight in the emergency response effects on the RNLA supply chain, to obtain a solid basis for building a decision making tool.
- Determine the relevant KPI's, to ensure that the tool abides performance indicators that have value in real life.
- Develop a tool to evaluate different supply chain parameter settings, to generate usable advice that can be used for decision making on decentralized product storage.

1.4.2 Approach

This graduation project aims at developing a tool, which can be used as source of advice on the effects of decentralized product distribution in case of an emergency situation. The approach is split in 3 steps [2]:

1. Analyze the problem, related factors and boundaries by performing a study consisting of a literature research and system analysis. This is done to be able to create a synthesis between the academic research and the current real-life situation, and in this way determine an academic knowledge gap and a practical requirements for a model.
2. Create a model based on the synthesis from literature research and the system analysis to find the optimal solution for the problem. A model can provide insight without requiring the real-life situation to be altered or experimented with.
3. Use the tool to perform experiments, in order to find the optimal supply chain design and study the performance of the tool.

1.5 Research questions

1.5.1 Main question

What RNLA supply chain design, with a focus on decentralized stock distribution, is the most effective in case of an RNLA emergency response situation?

1.5.2 Sub questions

1. What are the characteristics, specific problems and methods related to emergency response models as described in literature?
2. How is the RNLA supply chain currently arranged and performing?
3. What additional supply chain design options could improve the current supply chain?
4. How can the resulting supply chain design options be modelled?
5. How do different supply chain designs affect the supply chain performance?

1.6 Research ethics

According to Royakkers et al. [3] the main goal of engineers is to design, and thus shape society. Because of this expertise and influence, engineers are required to be responsible and make thoughtful decisions. In order to guarantee the ethical boundaries, this paragraph deals with some ethical factors of this research.

1.6.1 Research goal

Studying concepts in the military field should always be considered very carefully. This field involves life and death scenarios, strong economical and political powers, large operations and possibly an unjust sense that the goal justifies the means. Besides that, a sense of nationalism might urge an engineer to design the best tool for their country, without taking into consideration the lives on the opposite side or country. Therefore the goal of this research and the general function of the RNLA should be ethically justified. The goal of this research is to study decentralized stock, which will contribute to a better defensive allocation of stock due to its decentralized nature. The main goal and responsibilities of the RNLA are of an aiding and defending nature. Therefore the goals contribute to policy making that tries to avoid aggressive behaviour at all costs, an thus no ethical problems have been found for studying the supply chain in the manner it is studied in this research.

1.6.2 Project ethics

In order to perform an ethically unobstructed research project it is important to be aware of the responsibility the researcher is carrying. Therefore care was taken that the researcher did not merely study and decided on his own. Regular meetings were held with RNLA as well as Delft University of Technology staff. Care was taken to discuss matters to ensure both a correct view of the information retrieved and written about the RNLA as well as correct implemented technical concepts. In order to deal with issues as unbiased as possible, personal preference was tried to be kept at a minimum by comparing pros and cons as well as basing decisions on accepted scientific literature. To the writers knowledge the research performed has not been studied before.

1.7 Research structure

The structure of the research aims at creating better readability and understanding of the research and is thus structured in the following way: Chapter 2 creates insight in the emergency response effects as well as discusses a newly designed emergency response analysis method. Chapter 3 holds a system analysis of the RNLA supply chain in it's current state. Chapter 4 Analyzes the emergency situation based on insights from the literature research. New supply chain design options are discussed that might improve the current supply chain. Chapter 5 holds the model of the current supply chain supplemented with the new supply chain design options from chapter 4. Chapter 6 holds the verification and validation of the model. Chapter 7 evaluates several supply chain designs by activating or de-activating the new supply chain design options. Based on the resulting objective values the best design can be found. Chapter 8 concludes the work with a recap of the answers on the research questions and recommendations for future work.

1.7.1 Overview

Chapter	Sub questions
2. Literature study	1
3. Current state analyses	2
4. Future state design	3
5. Model	4
6. Verification & Validation	4
7. Experiments & Results	5
8. Conclusion	Main and sub questions

Table 1.1: Research structure

2 Literature analysis

This chapter gives an overview of the current state of research on Emergency Response modelling (ER). To offer both the inexperienced reader and the experienced reader a solid introduction and literature overview of the ER modelling research area, basis concepts are discussed which are supplemented with the academical developments so far. Widely accepted sources such as Google Scholar [4], ScienceDirect [5], Researchgate [6] and Scopus [7] have been used to gather information. The following sections deal with next the sub-question:

- *What are the characteristics, specific problems and methods related to emergency response models as described in literature?*

2.1 Emergency response research area

The general definition of emergency response logistics is the process of planning, managing, and controlling the flow of resources to provide relief to affected people in times of disaster [8]. Caunhye, [9], Sheu [8] and Balcik and Beamon [10] describe the key challenges of ER as follows:

1. **Additional uncertainties** e.g. uncertainties such as unusable routes, safety issues, changing facility capacities, demand uncertainties.
2. **Complex communication and coordination** e.g. damage to communication lines, involvement of third parties, government, inaccessibility to accurate real-time demand information.
3. **Shortage of resources** e.g. due to the disastrous situations that emergency response logistics covers, it is not uncommon to have larger demands than available supplies.
4. **Harder-to-achieve efficient and timely delivery** e.g. when dealing with the aforementioned items, it is follows that it is harder to reach the set efficiency and time of delivery of the supply chain.

Emergency response is a broad research area that is influenced by many factors such as the emergency type, scale of emergency, emergency stage, time horizons, demand forecasting and more. After a brief history, this section will discuss these characteristics in order to create a clear overview of factors that influence an emergency response situation.

2.1.1 History

Emergency Response is a research area that emerges in the late 1970s as a reaction to a series of maritime disasters. In 1977 President Carter moved to have special ER done into responding to oil leaks. From there on many areas of emergency have been studied by ER researchers [9]. This is also confirmed by Simpson et al. [11] who have been looking at the last 50 years of emergency operations research. Whereas the first ER models basically optimized for maximum deterministic coverage of emergency facilities, later on also stochastic aspects were added [12]. In this way, for example, multiple scenarios could be incorporated [13].

2.1.2 Emergency response characteristics

From literature research five important characteristics have been selected. More may exist, but these five are considered to be the main characteristics.

Type

It is important to know what kind of disasters can happen and to know how they can affect the system or supply chain in order to create an efficient optimization model. According to the Red Cross: "A disaster is a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community's or society's ability to cope using its own resources. Though often caused by nature, disasters can have human origins" [14],[15]. Disasters with human origins can be war, terrorist attacks or chemical leaks for example [9]. It is obvious that different kinds of emergencies, have different effects on the system. Galindo et al. [16] have found that in general a shift can be noticed from purely man-made disasters towards an all-hazard approach, which can be applied to particular situations.

Scale

Once the emergency type is defined, the next step is to determine to what extend the geographical scale is influenced. For example, a single failing warehouse or a completely failing supply chain both have different effects on the system and its surroundings. The scale can be divided into multiple supply chains, single supply chain and single facility:

1. **Regional (multiple supply chains)**: In the case of a disaster such as earthquakes or war, entire regions will be affected. These crisis are not contained to one single supply chain or single facility. Villareal et al. [17] successfully applies the lean method on improving a regional logistics problem of a Mexican brewery instead of relying on the usual mathematics or simulation methods. Ramezanian et al. [18] study the effect of combining the blood donation supply chain design with the geological spread of their blood donators, solving the problem by using a mixed integer programming model and a robust optimization approach. Dinler et al [19] deal with a similar problem, but propose three other heuristics instead. Van den Berg [20] performed a phd research on different mathematical approaches to solve regional ambulance and firefighters facility location, routing, and shift scheduling. Tanksale et al. [21] study inventory allocation over multiple warehouses in a large supply chain network and geographical locations, using a mixed integer programming model with a custom heuristic.

2. **Single supply chain**: When multiple members from the supply chain are disturbed by the crisis, the scale of the emergency is considered to comprehend the entire supply chain. Bani-Asadi et al. [22] use the vendor managed inventory method to reduce the bullwhip effect in a supply chain with multiple layers (multi-echelon network). They did so by formulating a mixed integer programming model and dealt with the uncertainty using rectangular fuzzy numbers. Besides that they

tested two metaheuristics, namely genetic algorithm and particle swarm optimization. Chiadamrong et al. [23] propose a hybrid approach of both analytical and discrete-event simulation to solve a supply chain problem of 5 layers. Nurjanni et al. [24] use three scalarization approaches to create a greener, more sustainable supply chain network.

3. **Single facility**: When only a single member or company from the supply chain is affected, this is considered to be a single stage crisis. This is very closely related with the single echelon network that will be described later on.

Natarajarathinam et al. [25] found that in 2009 roughly 40 % of the research was focused on supply chain crisis, 40% on regional crisis and approximately 15% of the research is focused on single stage crisis. Also connected to the scale of the crisis is the duration and frequency as described by Helferich et al [26]. Caunhye et al. [9] find that research into managing manpower during large scale, regional or supply chain, crisis is lacking.

Besides the actual geographical scale of crisis, also the configuration of the supply chain plays a crucial part in solving an ER problem. Many types of facilities (e.g. suppliers, production facilities, warehouses) and specific flows between those facilities play their role in forming a supply chain. Each set of facilities with the same role and type is placed in a special layer, or echelon [27].

1. **Single Echelon network** Single echelon networks are networks with one layer. No information is used from either layers above or below, and both the inflow and outflow of products will have to be estimated [28]. Often stock control policies are researched in single echelon models [29]. Csermely et al. [30] use a single-echelon system to study the effect of dual sourcing. Hong et al. [31] study a route selection model within a single warehouse.

2. **Multi Echelon network** In the traditional multi-echelon network, products flow from up- to downstream. Flows of material in the same echelon are allowed as transshipments [29]. The difficulty of multi-echelon modelling can be found in the interdependencies accros stages and various stock nodes at facilities [32]. McGee et al. [33] used simulation to study the two-echelon network of depots and bases to study military aircraft spare parts activities. Ahmadizar et al. [34] used a hybrid genetic algorithm to study a three-echelon network of suppliers, cross-docks and customers to minimize storage costs. Doyen et al. [35] creates a two-echelon mixed integer linear programming model with lagrangean relaxation to study regional and local rescue centers. Laumanns et al. [32] use piece-wise linear convex approximations and find that compared to the models resulting from the Markov decision process, the first performs much better.

Stage

By using knowledge from other disciplines, in this case crisis management, a more distinguished specification of the emergency can be provided. Different stages can be used to create a better picture of what the optimization model should optmize. Four primary stages can be classified [25], mitigation, preparedness, response and recovery:

1. **Mitigation**: Mitigation deals with finding possible sources of disaster and finding ways of minimizing possible damage, or avoiding these disasters at all. A very important factor when considering the appropriate risk mitigation strategy is risk

attitude[29] as described later in this section. Both Hasani et al. [36] and Govindan et al. [37] study the effect of facility fortification in order to minimize damage. Whereas mitigation was the most studied stage before 2006 [38], in 2013 it was third on the list [16].

2. **Preparedness**: Preparedness focuses on offering the best training and plan for all people and organizations involved in case of an emergency. Both mitigation and preparedness are considered to be pre-disaster operations [9]. They are closely related with the strategic and tactical planning levels which will be discussed later. Preparedness planning should always be based on accurate knowledge of the threat, which includes the likely human response to the threat [39]. Maharjan et al. [40] introduce indexes to better model the preparedness in Nepal. Kalloz et al.[41] study flood control in order to prepare for drinkwater shortages in case of a flooding. Leknes et al. [42] prepare by strategically positioning ambulance locations using a mixed integer model. Salman et al. [43] propose a tabu search algorithm to overcome the huge size of possible outcomes in preparation scenarios. Kaneberg et al. [44] find that it is very important to increase the awareness and cooperation between actors to have a better preparation. In 2009 preparedness was the most studied subject [25], in 2013 preparedness appears to be second on the list [16].

3. **Response**: The response combines the preparation with an immediate action. Having an effective response reduces problems on the short term, but also lightens the burden of the recovery phase. An et al. [45] developed a mixed integer non-linear programming model and combined this with a Lagrangian relaxation approach in order to take into account possible congestions during mass evacuations. Fiedrich et al. [46] created a model to optimize search-and-rescue missions after an earthquake disaster.

4. **Recovery**: The objective of recovery is to get all the people and organizations involved back to a normal state in the long run. Both response and recovery are considered to be post-disaster operations as they are only activated when the disaster has occurred [9]. Galindo et al. [16] find that out of the four primary stages, a lack of research is noticed in the area of recovery.

Planning horizon

Now that the emergency type, scale and stage are discussed, the next item is to discuss planning horizon. Namely, for every stage an optimization can be done on a different planning horizon. For example, to optimize the recovery phase of an emergency it is possible to determine where long-term storage facilities should be located for optimal results. However, also time schedules of trucks that are required to deliver goods can be optimized in this stage. Long-term storage facilities and time schedules of trucks both have a very different planning horizon. When looking at the research area of supply chain management, three levels of planning horizon can be distinguished [20], strategic, tactical and operational:

1. **Strategic planning level**: At the highest level, decisions are made for several years or even decades. An example of this would be the decision of building new warehouses or roads. Govindan et al. [37] include, as one of few, the customer behaviour into the strategic planning level, which is usually studied at the tactical level. Benalcazar et al. [47] study the effect of the strategic planning horizon on

the coal mining supply chain, which involves the difficulty of different qualities of coal combined with multiple market players.

2. **Tactical level**: Whereas the strategic planning level is concerned with long-term decisions, the decisions on the tactical level usually influence the supply chain for one month up to a year. An example of this would be the number of stock on different locations, the number of personnel at each warehouse or the amount of trucks that are used at different locations. The tactical level are usually taken into account together with the strategic planning decisions. Any disturbance in this time frame is generally said to be temporally independent, which means that the occurrence of one disruption does not affect the probability of disturbances in the following periods [37].

3. **Operational levels**: The operational level of planning is very short-term, or sometimes even real-time decisions. Examples of this are re-routing a truck's route or last-minute changes in employee schedules. Typically, the information from the strategic and tactical level is used as boundary conditions for the operational level. This means for example that the number of trucks and locations of warehouses is fixed.

In order to solve the problem, two options emerge. Either solving the problem for one single period or multiple periods.

1. **Single-period**: As the name suggests, the input will be given and an optimal result for the end of the period will be generated. Pre-disaster problems, mitigation and preparation, are usually solved with single-period models [9].

2. **Multi-period**: The other option is to optimize over multiple periods, taking into account stock levels, or truck movements depending on the planning horizon in between the beginning and end of the optimization solution for example. Many examples of multi-period research can be found [9],[29]. An excellent example is periodic re-optimization as described by Govindan et al. [9].

Risk

The last characteristic is used to provide the model with the right quantitative information. Since it is very hard to define exactly the specific characteristics of any disaster, leading to an emergency situation, estimating the risk of disaster characteristics is of utmost importance. Supply Chain Security Management uses the following steps to process risk [48]; Identify risk, Asses risk, Mitigate risk (where possible) and finally the response to risk incidents. Risk incidents can either be internal/operational or external. For example internal risk can be employee rated (e.g. workers strike), criminal related (e.g. fraud, sabotage), infrastructure (e.g. industrial accidents), product related (e.g. recalls), IT related (e.g. computer network crash) or finance related (e.g. supplier bankruptcy) [25]. Besides that uncertainties of parameters such as demand, supply, cost and lead-time cause internal risk as well [37]. Examples of external risks will be discussed in the subsection of emergency types.
Often emergency modelling is done using deterministic models, these are models that use one single situation. For example the worst case scenario [15]. Another method is to assume to know the uncertainty and model different scenarios with different probabilities, based on the aforementioned uncertainties [49] [50]. For example, stochastic parameters can be a varying cost, response time, demand, location safety and many

more depending on the problem [40]. Numerous other parameters can have an influence, but even if their values and probability distributions were known it would still be very hard to define a joint probability distribution function for all the scenarios [49].

In some cases it is even required to use a stochastic model as the nature of the problem can be stochastic, for example real-life transportation problems. In these cases a deterministic model will often be oversimplified and thus be less effective [17]. Bounou et al. [12] model spare parts shortage based on probabilistic models. By using a risk management tree, the set of available scenarios can be reduced to the most likely ones [37]. This results in a smaller computational demand.

This leads to the formulation of specific ER problems and a range of methods that can be used to solve them. The following section will discuss both the problems as well as the methods.

2.2 Emergency response specific problems

Moving over from the emergency scenario description towards a somewhat focused approach on modelling. When considering the research area of ER, three clear consecutive distinctions can be made in real life problems that comprehend the entire emergency preparation and response: facility location, product allocation and vehicle routing problems.

2.2.1 Facility location problem

When preparing for an ER situation, a well studied problem is the question of where to place the required facilities to store or facilitate products and services. In other words, where should ambulance stations be located to reach a high service grade [42] or for example, where to locate warehouses that are not always reachable [51].
The first facility location model was introduced by Alfred Weber, with his theory of "three weighted points". This became the industries standard, called; the Weber problem, and generated the location of facilities in such a way to have the least transportation cost between them. Mirzapour et al. [52] use this method, combined with a distributed customer locations in such a way that the maximized facility locations has the minimized customer distance. Tanash et al. [53] study the effect of locating hub facilities, where product flows can be combined, in the supply chain network using the branch-and-bound method combined with a lagrangean relaxation. Ramenazian et al. [18] make it more convenient for blood donors to donate blood by locating blood donation facilities to minimize traveling time for blood donors using mixed integer linear programming incorporating the stochastic nature of demand and cost parameters. Maharjan et al. [40] applies the simplex method and branch-and-bound relaxation to the maximal coverage problem to facility location for three relief distribution situations in Nepal. Zokae et al. [54] solves a three level relief chain model consisting of suppliers, relief distribution centres and affected areas, using stochastic scenario programming. Karatas et al. [55] compares two classic models, p-median and the maximal coverage problem, by using the q-coverage requirements. Their objective function minimizes the distance between origins and destinations. Miskovic et al. [56] use a variable neighborhood search heuristic for police forces in Serbia, where they minimize the maximum load of established emergency units. Rodriguez-Espindola et al. [57] combine the geographical information system rasters with optimization algorithms to prepare locations for flooding.

2.2.2 Product allocation problem

The product allocation problem can be researched in two ways, either the general distribution of products distributed over multiple warehouses, or the specific product location within a warehouse. The latter is outside the scope of this research and will not be dealt with any further than this. The product allocation over multiple warehouses however is quite interesting. Tanksale et al. [21] study multi-region, multi-facility product allocation using mixed integer programming and a decomposition heuristic which solves the mismatch of procurement, demand and availability in the Indian public distribution system. They minimize inventory holding costs, inventory setup costs and transportation costs. Bani-Asadi et al. [22], as mentioned earlier, formulated a mixed integer programming model and dealt with the uncertainty using rectangular fuzzy numbers and tested two metaheuristics, namely genetic algorithm and particle swarm optimization. They minimized the total cost including ordering and backorder costs, to solve a vendor managed inventory problem, which is a vendor-customer cooperation of keeping the right amount of stock. As mentioned in the scope, internal product allocation processes will not be included in this research. Related approaches:

1. *Guaranteed service approach-* Another research are of the product allocation problem is the guaranteed service approach. Even though it is not commonly used as operations research method, it is worth mentioning it for the sake of completeness. This focuses on the required amount of stock at the different nodes in the supply chain to be able to guarantee a certain service level [58], [59].

2. *Transport problem-* The transport problem deals with sources where a supply of some commodity is available and destinations where the commodity is demanded. As opposed to the guaranteed service approach, this is a basis operations research problem and is thus specifically included. In a balanced transport problem the total amount of available supplies is equal to the demand, every source has a certain amount of stock. Transporting the commodity from the supply to the destination costs money and often the objective is to meet the demands while optimizing towards lowest costs [60].

2.2.3 Vehicle routing problem approach

The last major problem is the problem of vehicle routing. Once the facilities are located and the number of products is distributed over these facilities, it is important to know how to transfer the products to the area of demand, using different modes of transport such as rail, road, sea and air. Using vehicle routing models, the routes can be optimized towards costs, delivery time or travel distance for example. Another research area which is often connected to the vehicle routing problem is the cross-docking problem. Cross-docking is the manner of re-arranging several product flows at a cross-dock facility. In general products are not supposed to be stored longer than absolutely necessary to transfer them to an outgoing truck or other means of transport. Nikolopoulou et al. [61] studied many-to-many relationships between suppliers and customers with a focus on cross-docking using an adaptive memory programming method and tabu search algorithm, while maximizing profit of the supply chain network. Pillac et al. [62] studied dynamic routing methods and found that dynamic routing occurs in many areas such as providing services, transporting goods and transporting persons. Frequently the objective is to minimize total costs. Ahmadizar et al. [34] use a hybrid genetic algorithm in a three-echelon supply chain, focusing on minimizing storage between operations. Moons et al. [63] find that integrating production and distribution in one coordinated model generally leads to an improvement of 20 % and up to 40 % in costs (product decay, setup and transportation costs). Also due to the high standards of the industry the focus should shift from either optimizing towards costs or service levels to a multi-objective approach. Zokaee et al. [54] use pre-defined nodes in a three level relief chain model and applies this to real data from an earthquake disaster area. It minimizes costs and indirectly maximizes people's satisfaction through shortage penalties. Tsadikovich et al. [64] apply the routing problem to a military context and uses two performance measures: time of response and military effectiveness. Mota et al. [32] studied the distribution of products, using trucks, for the oil industry by optimizing their routes using mixed-integer linear programming and minimizing costs. Lee et al. [65] use a tabu search algorithm to create an integrated model combining both cross-docking and vehicle routing scheduling. They find the number of required vehicles, best route, schedule and arrival time by minimizing the transportation cost.

In general, facility location problems are coupled with one of the other two problem types [9], [45]. For example, Ouyang et al. [66] take into account a continuous traffic equilibrium while planning the location of facilities using integer programming combined with a Lagrangian relaxation. Besides the earlier mentioned KPI's Huang et al. [49] have defined common ER supply chain KPI's such as; responsiveness, cost efficiency, minimum travel time and maximum demand satisfaction. KPI's defined in this research can be briefly summarized as follows:

- supply chain costs e.g setup, holding, (back-) order, transportation and product decay costs) [21], [22], [62], [63], [65]
- profit/effectiveness [61],[64]
- storage levels [34]
- service levels [42]
- travel distance [52],[55]
- travel/response time [18],[64]
- work load [56]
- stakeholder satisfaction [54]

2.3 Available methods

Quite some methods found in literature for the emergency response problem have been mentioned already in previous sections. This section aims to give a brief overview of the two main categories found in ER literature in order to make a well-considered decision on how to proceed with the problem at hand. It will discuss the two most used categories; mathematical programming and simulation methods. Appendix B provides additional examples of specific methods and current literature for each category.

2.3.1 Mathematical programming models

The first category of methods is mathematical programming. Mathematical optimization programming is the optimization of a function dependent on many variables and often subjected to a set of constraints. A specific type of mathematical programming is the linear programming model. In figure 2.1 an example from the book "Introduction to Operations Research 10th edition" [67] is given, where the value of Z needs to be maximized by choosing the values x1 and x2 smartly while staying within their boundaries. Normally, larger models are solved by computers, however this particular example can be solved by hand. (The answer is provided in the conclusion of this chapter, goodluck!)

To summarize, in the mathematical language of linear programming, the problem is to choose values of x_1 and x_2 so as to

$$\text{Maximize} \quad Z = 3x_1 + 5x_2,$$

subject to the restrictions

$$\begin{aligned} x_1 \qquad &\leq 4 \\ 2x_2 &\leq 12 \\ 3x_1 + 2x_2 &\leq 18 \end{aligned}$$

and

$$x_1 \geq 0, \qquad x_2 \geq 0.$$

Figure 2.1: Example from "Introduction to Operations Research"

Heuristics are part of mathematical programming methods, they are specific approaches of solving problems that lead to quick, but not necessarily optimal or perfect answers. Heuristics are very useful in complex problems or cases where no optimum exists but a reasonably good answer is required or suffices.

2.3.2 Simulation models

The second category is the option of using simulations. Hu et al. [68] shows that in the last years simulation has become widely used. It can be used to analyse complex problems, that sometimes cannot be solved analytically, but can also be used as an addition to analytic solvers by simulating the analytic solution and testing how well it works. A well known method is discrete event simulation, that focuses on the events taking place on specific times in a finite time frame. For every event that happens, a change is marked in the state of the system. Since it is assumed that the state of the system only changes when an event occurs, the simulation can move from one discrete event to the other while solving the problem [69]. Simulation often involves 2D or 3D visualizations as depicted in figure 2.2.

Figure 2.2: Examples of 3D simulations [70]

Analytic models are often preferred due to the fact that developing simulation models is more time-consuming and thus, costly. However, sometimes it is more useful to use simulation because analytic models need assumptions that are often simplified. In some cases that leads to unusable models [68]. Many more different models, theories and heuristics exist of which several are described in appendix B, but the writer is confident that those, and the items previously discussed, will allow for a well-considered choice of method to answer the research question.

2.4 Knowledge gap

For the past 50 years a lot of research has been done on the topic of Emergency response. Back in 2006 Altay et al. [38] had determined seven main directions for research in disaster operations management. More recently Galindo et al. [16] found that all of these still remained relevant in the year 2013, and quite a few are still unanswered. Based on their effort and the literature research performed for this thesis several important research items have been found.

No previous research was found that studies the design of the RNLA supply chain based on service level and stock distribution performance indicators, in case of emergency response situations. Whereas many supply chain models exist, this has mainly to do with the fact that in many papers a large emphasis is placed on the costs performance indicators. Another finding was that stock distribution is studied in several cases, however no papers have been found that study the decentralization of stock motivated by safety reasons.

The relevant findings from Galindo et al. [16] consist of two items. Firstly, most papers address a specific emergency situation and find the optimal solution, given a set of parameters. However, it would be interesting to extend research into finding alternatives. This can be achieved by altering the supply chain designs or adjusting parameters. Secondly, Galindo et al. [16] also find that disruption during the planning horizon deserves more research.

In case of multi-objective solutions it is found that researchers frequently use only one multi-objective method to solve the problem, while multiple options exist. By using different multi-objective methods a more compleet picture can be created of the range of feasible solutions.

2.5 Chapter conclusion

In this chapter a comprehensive literature review of the emergency response (ER) area, ER specific problems and available methods to solve them is performed. It is interesting to see that the research area, which emerges after a series of incidents in the late 1970s, emergency response turned out to contain some key challenges such as additional uncertainties, complex communication and coordination, shortage of resources and thus harder to achieve efficient en timely deliveries, which are applicable to many situations. Compared to regular supply chain activities, this is a separate research area. The following question is answered in this chapter:

- *What are the characteristics, specific problems and methods related to emergency response models as described in literature?*

The answer to this question is divided into three sub-items: characteristics, specific problems and methods. A quick overview of the results is given in Table2.1.

Characteristics	Specific problems	Available methods
Type	Facility location	Mathematical programming
Scale	Product allocation	Simulation
Stage	Vehicle routing	
Planning horizon		
Risk		

Table 2.1: ER Characteristics, specific problems and available methods

Characteristics
The type can be either a natural or man-made emergency and might require an all-hazard approach. The scale answers the question: Does the problem involve regional, supply chain wide or single facility effects? And besides that, is it a single or multi-echelon supply chain? The stage describes the model's time window relative to the emergency: mitigation, preparedness, response or recovery stage? Planning Horizon describes how far ahead in time the model is operating in: strategic planning level, tactical level or operational level? Besides that, does it do so in a single- or multi-period? Then finally, what are the specific risks that need to be taken into account?

Specific problems
Three specific problems were identified in case of emergency response models: facility location, product allocation and vehicle routing. It is interesting to see that a pattern can be distinguished here as well. When designing a supply chain from scratch it is important to decide where the facilities are going to be located. Once that is done, it

is possible to determine in which facility a specific number of products is going to be allocated. Finally vehicles can be routed between facilities and to end-users in order to transport the products as required.

Available methods
Two main methods of solving the earlier described problems are found in literature: Mathematical programming and Simulation. Mathematical programming is used to find an optimal solution, whereas simulation can be used very well to study what the effect would be of applying or adjusting a setting in the optimal solution.

Knowledge gap
No previous research was found that studies the design of the RNLA supply chain based on service level and stock distribution performance indicators, in case of emergency response situations. The relevant findings from Galindo et al. [16] consist of two items. Firstly, most papers address a specific emergency situation and find the optimal solution, given a set of parameters. However, it would be interesting to extend research into finding alternatives.Secondly, Galindo et al. [16] also find that disruption during the planning horizon deserves more research. In case of multi-objective solutions it is found that researchers frequently use only one multi-objective method to solve the problem, while multiple options exist.

By following the steps of determining the characteristics, deciding which problem (or problem combination) needs to be solved and choosing the right available method a constructive model can be created. The next chapters will deal with the practical case of the Royal Netherlands Army supply chain.

Answer to problem in figure 2.1: Z=36, x_1*=2,* x_2*=6.*

3 Current state analysis

From the literature research it becomes clear that emergency research comprehends many characteristics and available methods to solve problems. This chapter will aim to analyze the problem to the extend that is required to create a model that adds not only value to the RNLA, but also reduces the knowledge gap as described in chapter 2. The following sub question is addressed:

- *How is the RNLA supply chain currently arranged and performing?*

The first section will describe the analysis scope and approach, section two describes the current RNLA situation and the related supply chain at the required aggregation level. The last section provides a short conclusion to the chapter. The next chapter discusses the situations that the RNLA would like to have studied, in short the future situation.

3.0.1 Analysis scope

The scope is both defined by the characteristics as described in the literature chapter, as well as the desires and requirements of the RNLA. These are dictated by the main question, which tries to answer the question on how a decentralized distribution of products effects the RNLA in an emergency situation. The focus will be the highest aggregation level of the RNLA supply chain to get a general sense on the effects on supply chain level. It is also important to mention that the "Rapid Reaction Force" situation will be studied as part of the emergency repsonse character of this research.

3.0.2 Analysis approach

As described in the introduction, the RNLA is a very diverse, large cooperation with many stakeholders, objectives and constraints. In order to create a meaningful and complete analysis, the subject has been discussed with several employees throughout the organization. As is customary for military references to employees, only the first names are provided in this report. By contacting Major Niek van Schip, the other employees can be identified. Sorted on the first date of contact:

1. **Major Niek van Schip -** As the graduation project supervisor, Niek van Schip has a clear perspective on the current state, as well as the future requirements.
2. **Antoine -** NATO Operations Manager Antoine discussed the relevance of creating more insight in this problem. NATO would be very interested in a solution on large scale, which depicts the societal relevance of this research.
3. **Major Peter and Major Nout -** Majors Peter and Nout shared at a national RNLA logistics conference that in the near future the army needs to be able to react and transport goods faster as the pace of warfare is speeding up, and so should the pace of the supply chain.
4. **General Hans -** General Hans stressed the importance of looking at the complete supply chain, from supplier to user, in order to create a more usable model for the staff level.

5. **Major Rik -** Major Rik is the manager of the largest RNLA warehouse facility (Lettele depot). He supplied a down to earth insight in the practicalities of the RNLA supply chain and warehouse.

6. **Drs. Koos -** Senior Data-Analyst Koos has provided insight in the SAP system of the RNLA.

3.1 Current state description

Based on insights resulting from the interviews, four aspects concerning the current state are discussed in this section. The current state description, supply chain analysis, supply chain data and supply chain key performance indicators are used to analyze the current state. The RNLA is an organization that is task driven, it receives a target which it needs to fullfill to the best of their abilities. To do so, it requires material and materiel for their employees, vehicles and machinery to perform well. Currently the RNLA buys goods from the industry and distributes it to their users via their own supply chain. It does so by using the internal, regular transport service (lijndienst). Within the scope of the analysis, the following main stakeholders can be described: suppliers, RNLA warehouse and users. Other stakeholders such as army staff, army buyers and the ground personnel at the RNLA warehouses can all be placed under one or more of the (common) interests of the main stakeholders. It is the job of the supplier to deliver goods to the RNLA warehouse within the agreements of a contract. The RNLA receives and stores these products, see Figure 3.1. When a user requires products, it can put in a request at the RNLA stock control, which passes the message to the RNLA warehouse, from where the goods are shipped to the user. It is also possible to ship products from one user to another but this is not desirable. To keep the right amount of stocks in storage, the RNLA uses a software package called "Slim 4". This program tracks the current stocks and based on the R,Q (fixed replenishment method) and s,S (min/max method) policies provides the supply chain managers with an ordering proposal. The supply chain managers are free to deviate from this model, but often stick to the given advice. Recently SAP has been introduced to create better insight in the inventory and inventory management. Currently the goal is to keep a high level of stock in RNLA owned storage facilities, such as the Lettele depot, in order to have enough supplies to deliver the required products to users, however this might not be the most effective goal. More on this in the next chapter. Besides the discussed stakeholders, another type of stakeholders are the European countries and NATO, as they are influenced by the functioning of the RNLA supply chain and encounter similar problems, making this research also interesting on international level. It might even be possible to share resources in the future.

3.1.1 Rapid Reaction Force

A practical example of an emergency response situation is the employment of the Rapid Reaction Force. The Rapid Reaction Force [71] is part of the NATO Response Force (NRF). As soon as all the member states give their consent to a specific mission, the NRF is able to deploy forces all over the world within 5 to 30 days. It is composed of three branches, the first branch is the Very High Readiness Joint Task Force (VJTF) which is a spearhead force or basically the first responders. The second branch is the Initial Follow-on Forces Group (IFFG), which has a longer response time but is able to enforce the VJTF. The third branch is the Follow-on Forces Group (FFG), which can be send if the mission has a longer duration. In 2018 the RNLA will contribute to the NRF with a part of their ground forces such as a mechanised infantry battalion with its own combat and logistics support, an anti-tank company, a field artillery battery and a reconnaissance platoon for example. The supplies for the spearhead force are always ready to be deployed. However, based on the situation eventually these stocks will run out and the units will need to be resupplied with additional products.

Figure 3.1: Out- and inside views of RNLA warehouse Lettele

3.2 Supply chain analysis

Figure 3.2 displays the results of the flowchart analysis of the current supply chain design. Supply chain analysis is a very broad research area and thus a single supply chain can be studied extensively on multiple logistics topics such as stock levels, product flow, travel times, communication lines, routing or internal processes. Studying all these topics would go beyond the scope of the research To stay within the scope of this research, which is the study of distribution of products, the study of communication lines and internal processes have been downgraded to the acknowledgement of their existence. When considering straight deliveries from a supplier to the users two different product groups can be distinguished; strategic and non-strategic. In the current situation non-strategic products can be delivered straight to the users. Strategic products, such as weapons, are only delivered using the RNLA warehouse. Once a threat level goes up, due to political reasons for example, the users might not be equipped or allowed to receive straight deliveries. The RNLA makes use of a cross-dock in the RNLA warehouses but little research has been done into this and it is used using best practices. This system is currently not optimized and quite some problems are encountered. A very practical problem is the fact that suppliers often deliver products in an unsorted batch of items, which takes the RNLA warehouse quite some time to sort and place at the right location. For this reason, both the straight deliveries and the cross-dock function are not modelled in the current supply chain model.

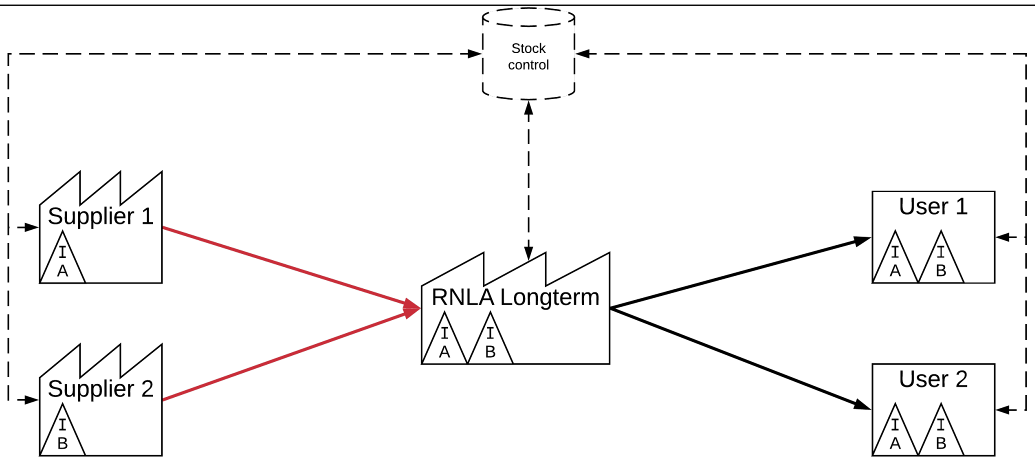


Figure 3.2: Example current supply chain design: two suppliers, two users

3.2.1 Supply chain data

The RNLA supply chain data can be categorized into 4 main categories. These are the following: products, suppliers, RNLA warehouses and RNLA users. The products come in many shapes, sizes, weights and numbers. Over 200.000 unique products are handled by the RNLA. Appendix C goes into more detail on the specifics. Over 100 suppliers are responsible and required for supplying these products to the RNLA warehouses. The current RNLA warehouse, a (long-term) storage facility in Lettele, has over 16 on-site storage facilities, ranging from outdoors floor storage to indoors stacked storage to fixed climate storage facilities. An impression of this is given in Figure 3.1. The users are the last RNLA facilities in the supply chain. They are the ones that require products to perform their tasks. An overview of the currently known supply chain information types given in table 4.1. The actual data is confidential.

	Current state supply chain data
Products	
Identifier	Over 200.000 unique products are handled by the RNLA supply chain network. These are all identified within the SAP system. These range from batteries, to car tires to tissues.
VED value	Every product is classified according to the VED analysis. The VED analysis stands for Vital, Essential or Desirable products and describes the importance of having a specific product available when required. For example, if a vital product is lacking during a military mission this means that the mission cannot go on and might have to be aborted or delayed.
Suppliers	
Identifier	More than 100 suppliers deliver to the RNLA and are identified in the SAP system.
RNLA facility	
Identifier	Currently one RNLA facility is taken into consideration, which is in Lettele.
Current inventory	Current stock levels are mostly registered in the SAP system.
Users	
Identifier	More than 50 users are part of the supply chain and in need of products.
Demand	Required products, or demand, is notified using the SAP system.

Table 3.1: Current state supply chain data

3.2.2 Supply chain key performance indicator

Key performance indicators (KPI's) are a type of performance indicators [72] and are quantifiable measurements used to define the success, or performance, of a system. Several of these have been discussed in chapter 2 and this section will discuss the current KPI's. Currently the logistics department of the RNLA uses mainly one KPI:

1. *Service level RNLA warehouse-* The service level is measured by following a specific category of vital products and tracking the number of unique items that can be delivered to a user right out of stock when needed. The RNLA considers a high rate of available products and thus a high service level a good thing. The exact value of the service level is classified.

3.3 Chapter conclusion

This chapter discusses the analysis of the current state of the Royal Netherlands Army (RNLA) supply chain. It determines the right scope and analysis approach and thoroughly describes the current state, supply chain data and key performance indicators. To get a good overview of the current state interviews have been held with employees working with the supply chain. This chapter answers the following sub question:

- *How is the RNLA supply chain currently arranged and performing?*

This question is answered by describing four aspects of the current state: the current state description, supply chain analysis, supply chain data and supply chain key performance indicators (KPI):

- *Current state description*- The RNLA is an organization that is task driven, it receives a target which it needs to full-fill to the best of their abilities. Currently the RNLA buys required materiel and keeps a certain amount of it in stock based on set values (R,Q and s,S) in their SAP system.
- *Supply chain analysis*- Studying the allocation of stock, three actors are found: Supplier, RNLA transfer/storage facility and the RNLA end-users. Currently the RNLA storage facility keeps the earlier set amount of products in stock. End-users can order from the RNLA storage facility which will deliver it to the end-user and will order new products if a threshold is reached. Barely any direct deliveries from suppliers to end-users and no RNLA transfer facilities (cross-docks) have been studied using an operations research approach.
- *Supply chain data*- The complete supply chain consists over 100 suppliers, 200.000 unique products and over 40 end-users. The specific supply chain data is classified.
- *Supply chain KPI*- Currently the supply chain performance indicator is the service level of the RNLA storage facility which is also classified.

By taking the information from the literature study and the results from the current state analysis a gap can be identified that can be filled by an adjusted supply chain, the future state. The next chapter will go into the analysis of a possible future state.

4 Future state design

This chapter discusses a possible future state of the RNLA supply chain, which can be modelled in the coming chapters. It will deal with the following sub-research question:

- *What additional supply chain design options could improve the current supply chain?*

Based on the interviews mentioned in the previous chapter it was found that the RNLA is very interested in creating more insight in the effect of decentralized distribution of products in case of an emergency situation. Their question is to know how much stock needs to be placed at the available facilities in order to meet a desired user service level in case of different emergency scenarios. This section covers the emergency response analysis, supply chain design, supply chain data and supply chain key performance indicators of the future design.

4.1 Emergency response analysis

Chapter 2 dealt with the emergency response characteristics. This paragraph applies these characteristics, as depicted in Figure 4.1, to the problem at hand in order to create a complete overview of the basic supply chain characteristics that need to be included in the model. Some of the following items will be used to design the future supply chain, others are used to design different experimental scenarios.

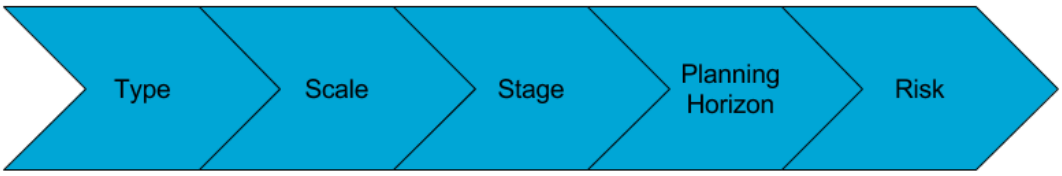


Figure 4.1: Emergency response characteristics

1. *Type*- The research will be considering an all-hazard type approach as the RNLA has to take many situations into account, such as war, which means that specific high-target facilities or delivery routes might get targeted. Or such as a hurricane on Sint Maarten [73] which means that any kind of facility can be compromised. In both cases, destruction of facilities or routes means that products from a specific source can become delayed or permanently unavailable.

2. *Scale*- It is important to take the entire supply chain into account. Regional effects such as supplier's supply chains are left outside the scope of this research, because the RNLA has no influence over this and a failing suppliers supply chain will have the same effect in the end; a failing or delayed delivery within the RNLA supply chain. The RNLA supply chain consists of multiple echelons such as suppliers, warehouses, cross-docks and users. Studying a single one of these echelons or/and at different aggregation levels can be very useful to improve specific conditions of the supply chain. However, since no research has been performed on this topic within the RNLA, it is more important to look at the RNLA supply chain from

supplier to user. This means that automatically the model becomes a multi-echelon problem.

3. *Stage-* To study the effects of decentralized distribution in case of the RNLA rapid Reaction Force it is most useful to study the recovery stage. It would seem to be more logical to study the response stage in case of an emergency, but the RNLA has a fixed "iron inventory" which can be used as a first response. The size of the iron inventory is classified and will not be studied during this research. However, at a certain time the iron inventory is going to run out and the users will need to receive additional supplies. Hence the recovery phase, which is quite similar to the response phase but differs in the number of days it spans. Effectiveness is of higher importance than costs in this stage, therefore the main focus will be on the response (effectiveness) as opposed to the preparedness (costs). Other phases such as mitigation, preparedness depend on other aspects such as politics and budgets and exert less strain on the supply chain. Therefore it is most interesting to study the recovery phase.

4. *Planning horizon-* According to the RNLA, the recovery phase lasts roughly 30 days. This leaves two options; either take the planning horizon as a whole, or divide it up in parts. In order to create most insight in the flow of products it is most interesting to divide the planning horizon up in equal parts of complete days. So if the planning horizon spans 30 days, the shortages, possible bottle-necks and KPI can be studied per day.

5. *Risk-* Many forms of risk can be identified. This research will deal with the following forms of risk:

    - *Demand:* It should come as no surprise that both the required demand is not a deterministic value that is known in advance. Every response situation is different and only a possible demand can only be determined by experts estimation.
    - *Facility- and route failure:* To allow for certain emergency scenarios, the model will need to be flexible and scalable. Flexible to allow the decision maker to adjust parameters in order to create different scenarios and scalable to allow the decision maker to alter the supply chain within certain boundaries.
    - *Industry thrust worthiness:* Besides physical facility- and route failure, also the inability or the lacking desires of a supplier to deliver products for political reasons for example should be taken into account.
    - *Product groups:* Working with military equipment brings along responsibilities to take good care of the items. Not all products can be stored decentralized, nor should all products be stored centralized. This risk of determining the right preference is important to take into consideration.

6. *Goal-* At last it is very important to define the goal of the emergency response problem. Based on the interviews as described in chapter 3 it was found that the current goal is to keep a high level of stock in RNLA storage facilities, but that after inquiring about the reasons why, the actual goal is to be able to facilitate the soldiers in the field with the right amount of materials at the right time. Instead of keeping a high level of stock, the RNLA supply chain goal will be to maximize the user service level. This will be combined with the research goal of this thesis

which is to study the decentralized stock distribution. As these are expected to be conflicting objectives the user service level will be constrained by having a specific number of products that need to be delivered in a set number of days, per product. For example, 100 % of product A needs to be delivered within 3 days.

4.2 Supply chain design options

After describing basic the response characteristics, it is important to consider which emergency response problem needs to be solved. In chapter 2 three problems where described: facility location, product allocation and routing models. Of these, the product allocation is the most applicable, as the RNLA has already decided where to build their new storage facility and is now studying the best ways of distributing their stock over the current storage facilities, their new storage facilities but also possibly elsewhere. Based on the current supply chain, emergency response analysis, interviews and the writers own input this means that the possible locations for storage are pre-determined and can be described as:

- RNLA owned, RNLA controlled storage facilities
  e.g. Lettele depot, RNLA cross-docks or users storage facilities
- RNLA owned, non RNLA controlled storage facilities
  e.g. New cooperation forms with industry
- Non-RNLA owned, non-RNLA controlled storage facilities
  e.g. suppliers storage facilities
- Non-RNLA owned, RNLA controlled storage facilities
  e.g. industry cross-docks

By continuing to build on the knowledge gained about the emergency response situation, based on the characteristics study, it is possible to add new design options to the supply chain that might improve the overall performance.

- *Direct deliveries:* Besides delivering to the RNLA warehouse, suppliers can also deliver straight to the users. This might be faster than the current situation. Important to mention is that these deliveries are considered unsafe, which means that they have to be checked at the users gate. Hence a red coloured line will be used in graphical representations of the supply chain. This takes time and compromises the safety of the user, therefore a limited number of deliveries are allowed depending on the political threat level.
- *Cross-dock:* The cross-dock does not have any storage options, it simply receives and sends a number of products within the response time. The cross-dock is RNLA owned, so its shipments are considered safe. Cross-docks are used frequently in other similar supply chains and thus make them interesting to be studied in the RNLA supply chain as well. It might however encounter delays, and thus have varying service levels. Vogt et al. [74] describes cross-docks as great potential of improvement in efficiency and effectiveness if studied and applied well to the supply chain.

- *Multiple suppliers:* Suppliers can be the sole suppliers of a product, or range of products, but it might also be possible as Yao et al. [29] suggest to source the same product from multiple suppliers. This contributes in a military context to a more resilient supply chain. Kampen et al. [48] suggest multiple suppliers strategy as part of the future adaptive capabilities of the RNLA.

- *Exclusive suppliers:* Restricted the SAP system the complete product delivery needs to be transported via a single transport option. This means that it is currently not possible to deliver half of the delivery from the supplier and half of the delivery from the RNLA warehouse. The complete shipment needs to come either from the supplier or from the RNLA warehouse. It would be interesting to test the future design with and without this functionality.

- *Pop-up cross-docks:* Warfare will go faster and faster in the future, and thus the supply chain needs to be agile enough to cope with this. This model can explore the option of borrowing a large set of cross-dock facilities from the industry in times of need and independently and randomly use them for just one or two days. In this way the flow of products will be different every two days and the enemy force will have a hard time tracking the supply chain flows. Even though these are non-RNLA owned storage facilities, they can be utilized as such for a short term of time and thus be modelled as such.

Adding these options to the supply chain results in the supply chain as is depicted in Figure 4.2.

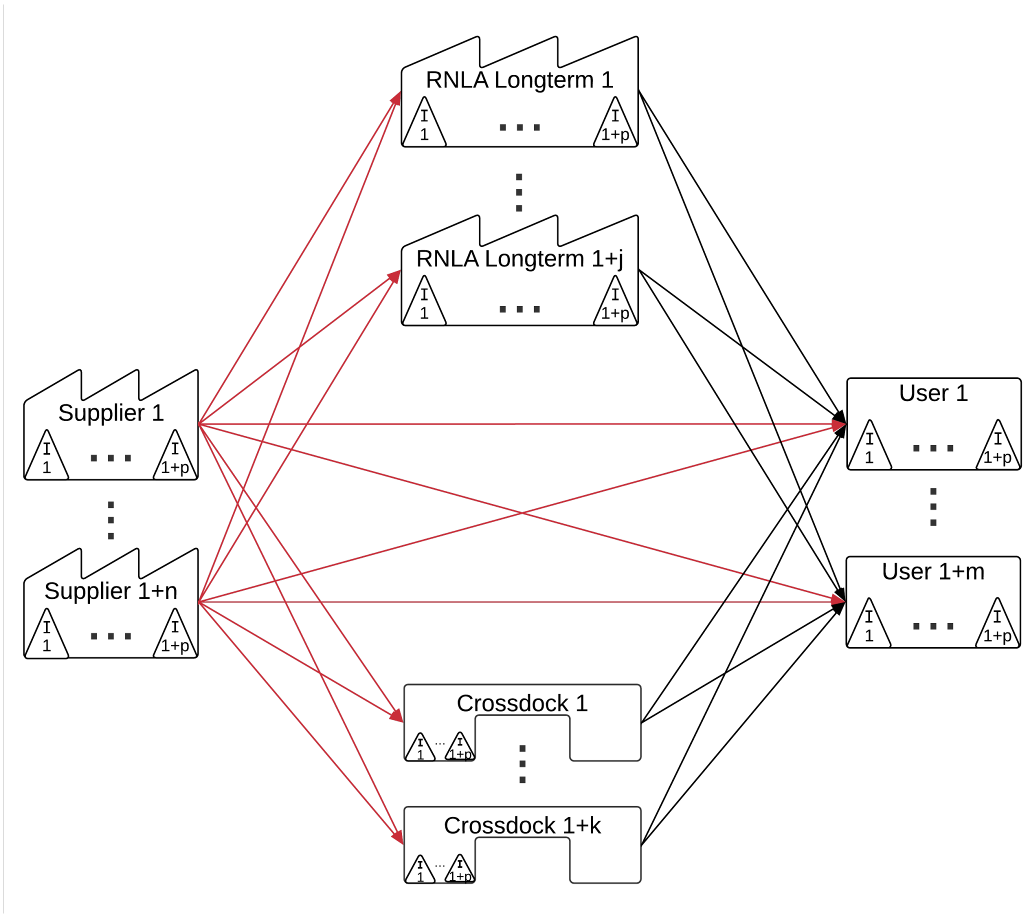
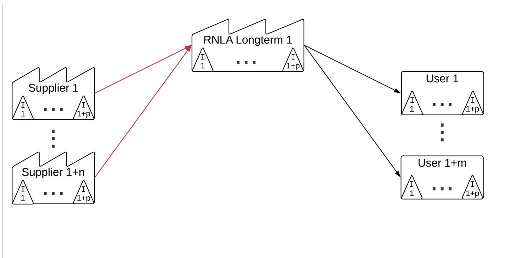
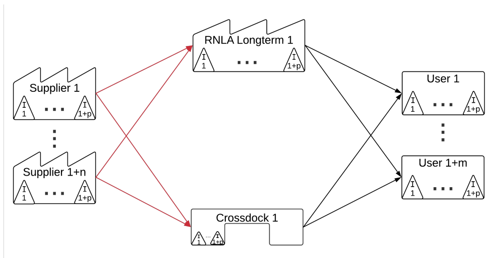


Figure 4.2: Supply chain design model

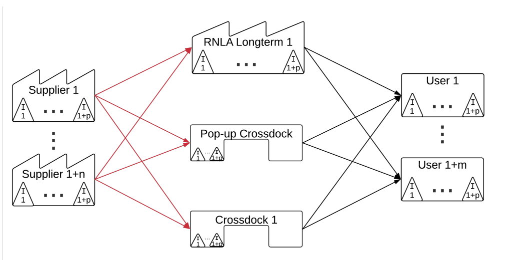
By turning options on and off, different supply chain configurations can be evaluated for different scenario's. Loads of configurations can be tested, however for this research five setups will be studied. The following setups are examples of the supply chain topologies and depending on a dataset can differ in size. The first setup is the current arrangement, Setup 0, so that it can be used as comparison for the other setups. Setup 1 can be described as a combination of Setup 0 and the cross-dock functionality, in order to test the effect of a cross-dock. Setup 2 can be described as a combination of setup 1 with an additional pop-up cross-dock, to test the effect of pop-up cross-docks. Setup 3 can be described as a combination of Setup 0 and the direct deliveries functionality in order to study direct deliveries. Setup 4 is the combination of a cross-dock, direct deliveries and multiple suppliers to experiment with the possible future state. All the setups are currently bound by the exclusive supplier functionality, because to effectively experiment with this a much larger data set needs to be available. Neither of the example figures show the separate product flows as this would become to cluttered. In real life these numbers can go up to 100 suppliers and 50 users. Setups 0 to 4 are displayed respectively in Figures 4.3(a), 4.3(b), 4.3(c), 4.3(e). These situations will be discussed further in Chapter 7.



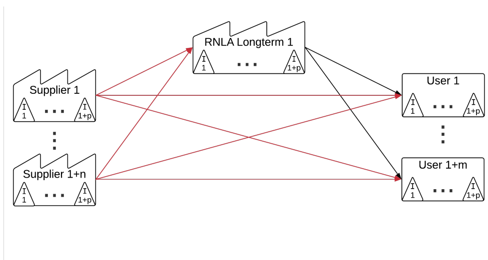
(a) 0- Current



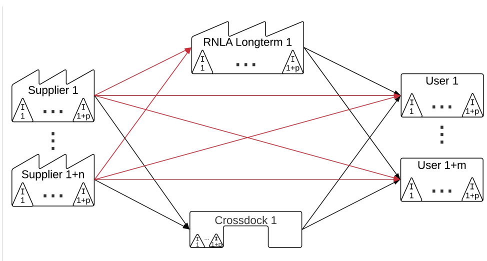
(b) 1- Fixed cross-dock



(c) 2- Pop-up cross-dock



(d) 3- Direct deliveries



(e) 4- Extensive

Figure 4.3: Experimental setups

4.2.1 Supply chain data

On top of the discussed supply chain data in the current state, additional supply chain data is required as part of the future design. This section provides Tables 4.1 and 4.3, which give an overview of the current state and future design supply chain data. The actual numerical data is confidential.

	Current state supply chain data
Products	
Identifier	Over 200.000 unique products are handled by the RNLA supply chain network. These are all identified within the SAP system. These range from batteries, to car tires to tissues.
VED value	Every product is classified according to the VED analysis. The VED analysis stands for Vital, Essential or Desirable products and describes the importance of having a specific product available when required. For example, if a vital product is lacking during a military mission this means that the mission cannot go on and might have to be aborted or delayed.
Suppliers	
Identifier	More than 100 suppliers deliver to the RNLA and are identified in the SAP system.
RNLA facility	
Identifier	Currently one RNLA facility is taken into consideration, which is in Lettele.
Current inventory	Current stock levels are registered in the SAP system.
Users	
Identifier	More than 50 users are part of the supply chain and in need of products. Users are identified as either deployed troops or barracks.
Demand	Required products, or demand, is notified using the SAP system.
Current inventory	Current stock levels are mostly registered in the SAP system.
Service level	In case of a Rapid Reaction Force situation, the users need their demands full filled within a set number of days. This is currently set to 100% complete within 30 days

Table 4.1: Current state supply chain data

	Additional required supply chain data
Products	
Location preference	Some products might be preferred to be kept at the supplier's warehouse (e.g. deteriorating products) others might be preferred to be held at RNLA warehouse (e.g. weapons).
Suppliers	
Storage capacity	The capacity of the suppliers is mainly the amount of products they are willing to store and/or the number of products they can deliver within the required response time
Sending capacity	Both the sending capacity to the specific users and RNLA facilities are required.
Transport times	Accompanied with the sending capacity are the specific transport times to users and RNLA facilities
RNLA facility	
Storage capacity	The capacity is not specified for the new RNLA facility, this might be useful to stay within certain boundaries.
Receiving capacity	Capacity can be described in two ways; the number of products and the number of deliveries. The number of products is straightforward as it is simple the summed up number of products that arrive per day. The number of deliveries is the total sum of deliveries for a day. Whereas products are defined by their product identifier, a delivery is a combination of several unique product. For example a combination of 100 batteries and 30 tissues. Due to the number of employees at the site and available delivery lots for trucks a maximal receiving capacity needs to be taken into account.
Sending capacity	Similar to "Receiving capacity"
Transfer time	The time it takes for an order to enter the cross-dock and leave it again.
Current inventory	All stock levels should be registered in the SAP system.
Transport times	Based on the internal RNLA delivery service, the transport times between the RNLA facility and users can be estimated using Google maps [75] information.
Users	
Storage capacity	To utilize the storage of the users, it is important what their maximum storage capacity is.
Receiving capacity	Whereas the RNLA deliveries are bounded only by the available employees and incoming gates, direct deliveries from suppliers are also bounded by guidelines. In times of higher threat levels, no direct deliveries could be allowed for example.
Sending capacity	To share resources with other users, the sending capacity needs to be known.

Service level	In case of a Rapid Reaction Force situation, after the first wave of products (iron stock) the users need their demands full filled within a set number of days.
Demand foresight	It is important to have a better understanding of the demand that might occur. Some is obviously influenced by the emergency state, others such as maintenance parts might be able to be predicted.
Importance	an indication should be structurally given to users on their rank within the supply chain priority range.

Table 4.3: Future design required supply chain data

4.3 Supply chain objectives

By combining the information from the literature research, current state analysis and the writers own input, an overview can be made of the possible KPI's for the future situation. Currently the RNLA cares mainly about the service level of the long term storage location as described earlier. However, as it is effectiveness that drives the RNLA and it are the users that need to accomplish the required tasks effectively, in order for the entire RNLA to be effective it would be way more interesting to look at the service level they receive from the RNLA supply chain, this can be called the new main goal of the RNLA supply chain. Besides that, the literature research shows that many more factors exist, such as: Supply chain costs (e.g setup, holding, (back-) order, transportation and product decay costs), profit/effectiveness, storage levels, service levels, travel distance, travel/response time, work load, stakeholder satisfaction, agility. Besides that other KPI's can be considered such as: manpower utilization, truck utilization, budget utilization, total required budget, supplier utilization, total number of required suppliers, storage space utilization, service level: (early, on time, late, maximal lateness), origin preference: (trusted supplier, decentralized vs centralized). Many more might exist, however for this research the following rough categorization can be made:

1. *Effectiveness*- This can be defined well by the result that the user experiences from the supply chain. For example, are products delivered on time, what happens when a route becomes unavailable etc.
   (a) *Time:*
   e.g. Communication time, delivery time, handling time
   (b) *Agility:*
   e.g. Number of suppliers
   (c) *Reliability:*
   e.g. Origin supplier, number of possible routes, centralized/decentralized storage
2. *Efficiency*- This can be defined well by what it takes to accomplish the effectiveness. For example, what are the costs of extra storage space, how much of the available hours are our employees waiting or working.
   (a) *Costs:*
   e.g. Location setup, product holding, product decay, manpower, transportation, order, back-order, broken delivery

(b) *Utilization:*
e.g. Location, manpower workload, transportation vehicles, deliveries, supplier

For an actual transition to a decentralized stock distribution supply chain two things need to happen; the most effective distribution of stock needs to be studied and the most cost efficient distribution of stock needs to be known. However, the costs are greatly dependent on the negotiations with suppliers, which are dependent on a number of things such as the delivery terms and number of products that is going to be stored at the suppliers location. This, in it's turn, is dependent on the general distribution of stock. Therefore a decision was made to study the most effective distribution of stock in this research, and if decentralized product distribution seems achievable, the recommendation would be to study the a cost efficient distribution of stock based on the results of this research.

Therefore the following two KPI's, and sub-KPI's, have been chosen for this research to ensure both effectiveness and decentralization:

1. *Effectiveness: Service level* The main goal of the RNLA supply chain is to facilitate the users by ensuring the availability of enough supplies as described in paragraph 6. From now on, references the the user service level will indicate the main goal of the RNLA. The service level of the user entails several sub items:

   (a) *Service level objective value:*
   It is important to optimize using the total objective value, which consists out of the number of products multiplied with their respective penalty values.

   (b) *On time arrival [%]:*
   The late arrival KPI describes the percentage of products that arrives on time at the users destination.

   (c) *Early arrival [%]:*
   The late arrival KPI describes the percentage of products that arrives early at the users destination.

   (d) *Late arrival [%]:*
   The late arrival KPI describes the percentage of products that arrives late at the users destination.

   (e) *Max. lateness [days]:*
   The maximum lateness KPI describes the maximum number of days by which a product is late.

2. *Decentralization: Stock distribution*- By measuring the products that arrive at the users location either directly from the supplier or via the cross-dock the number of decentralized products is known, and thus the stock distribution. Comparing this to the total delivered products, a fraction of decentralized products can be calculated.

   (a) *Stock distribution objective value:*
   It is important to optimize using the total objective value, which consists out of the number of products multiplied with their respective penalty values.

   (b) *Decentralized stock [%]*: The decentralized stock KPI describes what percentage of products from the total demand arrives from decentralized stock facilities. These are defined as straight deliveries from suppliers as well as deliveries via cross-docks in this case.

In order to combine the two KPI's the service level objective value and stock distribution objective value can be combined, which will be explained futher in the next chapter. By implementing the extra supply chain functions and altered KPI's, the future design can suffice to both the RNLA requirements as well as a better integration of the academical world with the industry.

4.4 Chapter conclusion

By combining the literature research and current state analysis an indication could be made of what a future design could look like. In this way, this chapter answered the following question:

- *What additional supply chain design options could improve the current supply chain?*

Using the characteristics found in the literature review, the type, scale, stage, planning horizon and risks have been used to analyze the RNLA emergency response situation. Based on the resulting information direct deliveries, (pop-up) cross-docks and the option of having multiple suppliers are added as additional options. To model this, additional data such as storage capacities, transport times, sending/receiving capacities, transfer times and location preferences are required. Instead of measuring the service level of the RNLA storage facility, the future state goal will focus on the actors that really count; the end-users, because they 'add value' to the RNLA by completing tasks and are thus the ones who need the products. This translates into a user service level, which is the first key performance indicator. The second key performance indicator is the percentage of decentralized stored stock, which is the topic of this research.
The following chapter will translate the described supply chain and it's additional options into a conceptual model and a computer model.

5 Model development

By combining the findings from the literature research and analysis in chapters 2, 3 and 4 the proposed future design of the supply chain can be represented as a model. By applying an objective to this model, a transport problem from the stock distribution problems category can be solved. The following sub question is addressed:

- *How can the resulting supply chain design options be modelled?*

Before describing the actual model, first the method and assumptions will be discussed. Then the first step will be to describe the conceptual model which describes the model in words, after which it can be translated into a mathematical model. The mathematical model describes the conceptual model in mathematical formula's and can be translated into code, which is used by the computer to solve the problem.

5.0.1 Method

Chapter 2 refers to two methods that are available for solving emergency response problems; mathematical programming and simulation. Both are commonly used and have proven their worth in this matter. Mathematical programming can be used to find the optimal combination of values for a specific objective function, and thus the optimal solution . Simulation can be used very well to test a combination of values and determine by simulating the situation multiple times, and often accelerated, if the results are as desirable as predicted. A more elaborate description can be found in chapter 2 and appendix B.
Since this is the first research on this topic within the RNLA, no prior studied configurations of the future state variables are available. It is therefore important to first find the combination of variables that suggest the optimal solution using mathematical programming, instead of testing a range of possible configurations using simulation without knowing which configuration is even viable. Therefore, mathematical programming will be used for this research.

5.0.2 Assumptions

Before creating the model as described in this research, several assumptions are made. They are listed below:

1. The unit of time is in days. The first reason for this is that the available input is measured in days. The second reason is to reduce impact on computational demand.

2. Cross-dock and warehouse are modelled separately in order to increase agility of the model, this is important to acknowledge due to capacities that might be shared in real-life.

3. Cross-dock storage not based on the number of days a product can stay in storage, but on the maximum products in short-term storage.

4. Cross-dock is empty on beginning and end of planning horizon.

5. No deliveries between users.

6. Deliveries and products cannot be fractions and are thus required to be integers.

7. No trucks are modelled because they are in surplus available and will not be the bottleneck of the supply chain.

8. Most capacities are fixed during the planning horizon (e.g. Fixed transport times, transfer times, delivery capacities). Departing capacities for different days can be set before solving the problem.

9. Lead time altering factors such as communication time between order and delivery are fixed and included in the transport time between locations.

10. Demands are considered uncertain, the uncertainty is dealt with using fuzzy numbers.

5.1 Conceptual model

This research introduces a model that comprises the entire RNLA supply chain, including the characteristics as described in chapter 4. It will describe the flow of multiple products between multiple sources and sinks. In literature this is commonly described as a directed flow model. Instead of applying a monetary cost function, as is frequently done in flow models, the cost parameter in this case is defined by a delivery penalty. The model objective is to maximize the number of decentralized stock and user service level by minimizing the incurred penalties so that it can be used as tool to suggest a specific allocation of stock over available facilities. The less favourable a specific flow is, the higher it's penalty value. This is described in further detail in the "Pre-processing" subsection. A basic multi-commodity integer flow problem can be considered to be NP-complete if it is used as a decision model (yes or no result) [76]. For any decision problem in the NP-complete complexity class, the related optimization problem can be considered NP-hard [20]. Since the model objective is to optimize a flow problem with integer flows, it will be considered NP-hard. The design of the model is inspired by work from Rathi et al. [60], who created a multi-period, multi-commodity flow model which uses penalties to enforce several preferences. However, Rathi et al. only modelled direct deliveries, and did not include transfer facilities, multiple suppliers, exclusive suppliers, pop-up cross-docks and uncertainties, which are certainly applicable on the RNLA situation. To include transfer facilities this model includes work inspired by Lim et al. [77] and Buijs et al. [78]. The clear distinction between origins and destinations, as well as transfer times is based on work by Haghani et al. [79]. Yao et al. [29] and Kampen et al. [48] describe the option of applying a multiple-supplier theory, which can easily implemented in the model by adding more suppliers that offer the same products. To add the exclusive supplier model functionality, the users can only receive one delivery per day. By altering the daily departure limit of the available cross-docks, the cross-docks can be modelled as pop-up cross-docks Uncertainty methods included in this work are based on fuzzy number theory studied by Jimenez et al. [80] and applied by Bean et al. [81].

Figure 5.1 depicts an example overview of the described model.

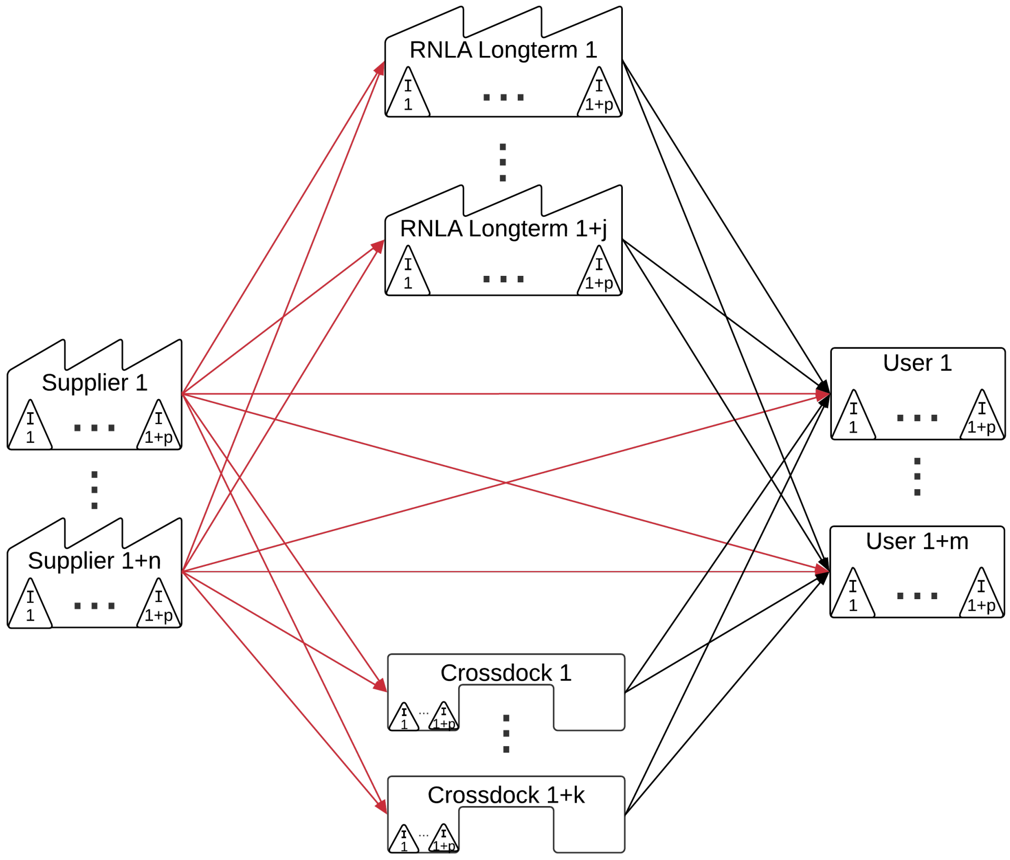


Figure 5.1: Supply chain design model

The next sections will describe the input, parameters, pre-processing, objective, constraints, key performance indicators (KPI's) and output of the model objective.

5.1.1 Input

The input for the model can be divided into several sets: origins, destinations, products and time. The origin set holds the entities in the model that are able to send products, such as the suppliers, transfers and users. The destination set holds the entities that can receive products, such as the transfers and users. The product set holds all the products and the time set holds the time periods. A more specific explanation of the entities is given in table 5.1.

Entities	Description
Products	The products are the entities that are being transported from the origins to the destinations. The RNLA ranks their products according to the VED analysis, which stands for Vital, Essential and Desirable products. Where Vital status is given to the most required products and Desirable the least.

Time periods	The planning horizon is divided into discrete non-overlapping time intervals called time periods [60]. For this model the time periods have the lengths of days. The set serves two purposes: a more realistic model by creating daily decision variables and better insight in the process by retrieving daily output information. To ensure the optimal decision values over the course of the planning horizon and satisfy balanced flow equations, the periods are coupled using a recourse method of carrying inventory shortages or surplus over to the next time period. In this way each subsequent period is coupled to the previous period, creating a chain of coupled periods. An example of this can be found in Bean et al. [81].
Transfers	Transfers are RNLA-owned facilities that handle and/or store products. They are divided into two sub-sets: long-term storage facilities and cross-dock facilities. The differences between these have been discussed in chapter 4, but a specific difference for the model is that the cross-dock has very little storage space compared to the long-term storage facility and cannot have stock at the beginning or end of the planning horizon.
Suppliers	Suppliers are non-RNLA affiliated companies that provide products to the RNLA. If a supplier delivers a product, either directly to the user or via the RNLA cross-dock transfer facility, the product is considered to be coming from a decentralized stockpile.
Users	The users exist out of all the Rapid Reaction Force units and other RNLA units or barracks that require products. They are the initiators of product flow as they demand a specific number of products

Table 5.1: Model input

5.1.2 Pre-processing

It would be more applicable to describe pre-processing in the mathematical model section, but it is important to have mentioned it before discussing the objective, constraints, KPI's and output of the decision model as it influences their description. This decision model has two pre-processing steps, fuzzy numbers and penalties.

Fuzzy numbers- As mentioned in chapter 2 it is important to acknowledge the stochastic nature of the real world. In this case that would point to the uncertainty in demand for example. This leads to a dilemma: a deterministic approach would be to simplistic, whereas a stochastic model would require probability distributions that are often not known [82]. Unfortunately, the RNLA does not have enough historical data on emergency response situations in order to create reliable probability distributions required for this model. However, another interesting approach to bridge the difference between deterministic and probabilistic models exists, namely the use of fuzzy numbers. Instead of referring to one deterministic value, a fuzzy number exists of a set of possible values each with it's own weight between zero and one. Based on work by Jimenez et al. [80] this range of values can be defuzzified to a crisp counterpart based on a feasibility degree. The feasibility degree ranges from 0 to 1, with linguistic scales ranging from completely unacceptable to completely acceptable. A 0.9 feasibility degree would indicate a practically acceptable solution. The crisp counterpart can be used as deterministic input for the model. For more information on fuzzy numbers please refer to the mathematical model or Appendix B. Of course it would be possible to implement a great deal of uncertainty in the model by using fuzzy supply values, fuzzy transport values etc. However this would require substantially more data and goes beyond the scope of this research.

Penalties- As mentioned earlier, this is a minimum cost flow problem. Minimum cost flow problems usually have some sort of cost parameter to distinguish between different flows. This might be a monetary cost, a value with some other unit or without a unit at all. In this case it is a value without unit and is described as the penalty of a flow. By combining the penalties described in table 5.2, a specific delivery penalty can be determined for every delivery, from every origin, to every destination, on every day.

penalty	Description examples
Product	Penalty according to VED value.
Supplier	Decentralized
User	e.g. Rapid Reaction Force units v.s. non-deployed units
Time	Advancement in planning horizon
Delay	Number of days late for a product delivery

Table 5.2: Model penalties

The final penalty value will be the sum of the separate penalties, as described more in depth in the next chapter. It is important to note that the specific values for each specific penalty are not meaningful, except that the relative penalties compared to each other are important as it allows the modeller to set the desired priorities [60].

5.1.3 Key performance indicators

As mentioned in the previous chapter, the main goal of the RNLA is to deliver products at the right time to the right user. In other words, the main goal of the RNLA is to have a high user service level. The goal of this research is to create a tool which can study the possibilities and effects of decentralized product storage. This translates into the following key performance indicators (kpi's):

1. *Service level user*- The main goal of the RNLA supply chain is to facilitate the users by ensuring the availability of enough supplies, therefore it is very interesting to

create more insight in the service level the users receives from the supply chain. From now on, references the the user service level will indicate the main goal of the RNLA.

(a) *Service level objective value:*
It is important to optimize using the total objective value, which consists out of the number of products multiplied with their respective penalty values.

(b) *On time arrival [%]:*
The late arrival KPI describes the percentage of products that arrives on time at the users destination.

(c) *Early arrival [%]:*
The late arrival KPI describes the percentage of products that arrives early at the users destination.

(d) *Late arrival [%]:*
The late arrival KPI describes the percentage of products that arrives late at the users destination.

(e) *Max. lateness [days]:*
The maximum lateness KPI describes the maximum number of days by which a product is late.

2. *Stock distribution-* The stock distribution, the research topic of the tool, can be measured quite simply. By measuring the products that arrive at the users location either directly from the supplier or via the cross-dock the number of decentralized products is known. Comparing this to the total delivered products, a fraction of decentralized products can be calculated.

   (a) *Stock distribution objective value:*
   It is important to optimize using the total objective value, which consists out of the number of products multiplied with their respective penalty values.

   (b) *Decentralized stock [%]*: The decentralized stock KPI describes what percentage of products from the total demand arrives from decentralized stock facilities. Which are straight deliveries from suppliers and deliveries via cross-docks in this case.

3. *Service level & Stock distribution-* To find the optimal solution, both the service level and stock distribution need to be taken into account.

   (a) *Total objective value:*
   The total objective value is calculated by adding the service level objective value to the stock distribution objective value of a single solution. Finding the lowest total objective value will give the optimal result.

It is important to note that the objective value KPI's are required for the numerical optimization, whereas the other KPI's are used to create insight in the results generated based on the objective value KPI's. The KPI's can be used in many different ways, at different levels of the supply chain. For example, the current KPI's for specific deliveries, to specific users. Or the current KPI's for all deliveries to a specific user. Other KPI's such as costs could also be involved, but as explained in the analysis chapter, that would be beyond the scope of this research.

5.1.4 Parameters

Based on the sets, the following accompanying parameters can be distinguished:

Parameter	Description
Origins	
Product departure capacity [$products/day$]	Based on the number of employees, production rate or other influences a departure capacity needs to be taken into account. Measured in the combined number of products, per facility, per day.
Delivery departure capacity [$deliveries/day$]	Based on the number of employees, production rate or other influences a departure capacity needs to be taken into account. A delivery is the combination of products transported from one origin to one destination on a specific day. The number or combination of products does not influence the delivery. If an origin is sending deliveries to multiple destinations, these count as separate deliveries.
Delivery flow capacity [$deliveries/day$]	Using this binary parameter specific product flows between origins and destinations can be activated or deactivated.
Destinations	
Delivery arrival capacity [$deliveries/day$]	The destination arrival capacity is similar to the discussed origin departure capacity. This time deliveries are the combination of products arriving from one origin to one destination on a specific day. If a destination is receiving deliveries from multiple origins, these count as separate deliveries.
Product storage capacity [$products$]	The destinations receive products, but cannot receive an infinite number of products as they are bounded by their physical size. Therefore a storage capacity is enforced.
End inventory [$products$]	The end inventory describes the required inventory at the end of the time horizon. For cross-docks this is zero.
Start inventory [$products$]	The start inventory is also applicable to the cross-dock transfers. Cross-dock transfers are required to have a zero start inventory, because any pre-determined inventory should be kept at the long term transfer. For the long term transfers, the start inventory is a decision variable.

Defuzzified product demand [$products$]	The supply chain is driven by the users demand. If a user has a certain demand, the suppliers and transfers supplies are utilized to full-fill this demand. To take into account uncertainty of demand, a method of fuzzy numbers is used, which will be described more in depth in the pre-processing paragraph.
Upper bound late arrival [$products$]	The upper bound late arrivals sets the maximum number of products that can be delivered late.
Upper bound early arrival [$products$]	Similar to the upper bound late arrivals, only applicable to the early arrivals in this case.
Time	
Transportation times [$days$]	To get products from one facility to another they need to be transported, mostly by truck. As the suppliers, transfers and users are on different locations it takes time to transport the products. Also included in transportation times are the lead times such as communication time from the user to the storage facility, or the time it takes the supplier to prepare a shipment. The transportation times are measured in days.
Transfer times [$days$]	At the transfer facilities (cross-docks and long storage) it takes time to receive a product and prepare it for shipment, this is defined as transfer times and is calculated in days.
Penalties	
Origin penalty [$-$]	The origin penalty describes the penalty of using a specific origin. When maximizing the number of decentralized stock, non-RNLA suppliers receive a lower penalty than RNLA facilities. It would also be possible to include a factor of supplier thrust worthiness, this could help differentiate between different non-RNLA suppliers if required.
Late arrival penalty [$-$]	Every product that arrives late receives a penalty.
Early arrival penalty [$-$]	Every product that arrives early receives a penalty.

Table 5.3: Model parameters

5.1.5 Variables

The model has several variables that it can alter in order to find the optimal solution. In this case there are five variables:

1. *On time product arrival:*
   This is the number of products that arrives on time at the specific location.

2. *Late product arrival:*
This is the number of products that arrives late at the specific location.

3. *Early product arrival:*
This is the number of products that arrives early at the specific location.

4. *Product delivery:*
Every batch of products, uniform or mixed, counts as a delivery. It is a binary variable, resulting in a value of 1 if there is a delivery of a specific product between an origin and destination at a specific day.

5. *Product inventory:*
The product inventory is a variable that is in most cases dictated by the number of products entering and leaving the inventory, or by start and end inventory constraints. Only the long-term transfer inventory at the start of time is variable.

5.1.6 Objective

The general objective is to optimize the two defined KPI's: user service level and stock distribution. This is done by applying objectives to the model that minimize the early and late deliveries a swell as minimize centralized/non-preferred product flows to the user. There are several methods for doing so [83], of which the following three will be attended in this research: Single-objective [67], Multi-objective using the Lexicographic method [83], Multi-objective using the Weighted Sum Method [84].

1. *Single objective*
The single objective method allows the modeller to find the maximum achievable result for one KPI value, hence the single value objective method. By optimizing one KPI, while fixating the other KPI at several increments it is possible to find the optimal solution for each fixated value. Graph 5.2 displays an example of this. For fixed values of KPI B, it is possible to find the minimal value for KPI A. However, at some point the value of KPI B is at it's lowest, and thus a range of values is possible for KPI A. This is shown by line 2. The other way around works aswell, by fixating KPI A and minimizing KPI B the same answers can be found. However at a certain point the solution is not going to get any better, which is shown by line 1. It would be very inefficient to just start optimizing without knowing the range between line 1 and 2.

2. *Multi-objective (lexicographic method)*
To downsize the number of samples that needs to be taken, the multi-objective lexicographic method can be used. The lexicographic method first optimizes KPI A and subsequently finds the best solution for KPI B without degrading the solution found for KPI A. This is called the pareto proof solution. In the example in graph 5.2 this means that instead of manually trying the KPI values of A for the range from 50 upward, the lexicographic method finds the point where first B is minimized and subsequently A. This can be found at point 4, where KPI B is 10 and KPI A is 50. By first minimizing KPI A and then B, point 5 can be found in the graph. Now the single objective method can be used to study the useful values between these points.

3. *Multi-objective (weighted sum method)*
Depending on the weight difference between KPI A and KPI B, one specific point

on the graph can be found that is the optimal solution. This point can always be found within the range between the two solutions found using the lexicographic method either leaning towards one or the other. Using the weigthed sum method, instead of subsequently solving the objectives, both methods are taken into account at the same time. In Figure 5.2 this is point 6 in the example graph. The advantage is that the the objective needs to be calculated only once. The downside is that it is highly dependable on the given weights, which are hard to determine in real-life.

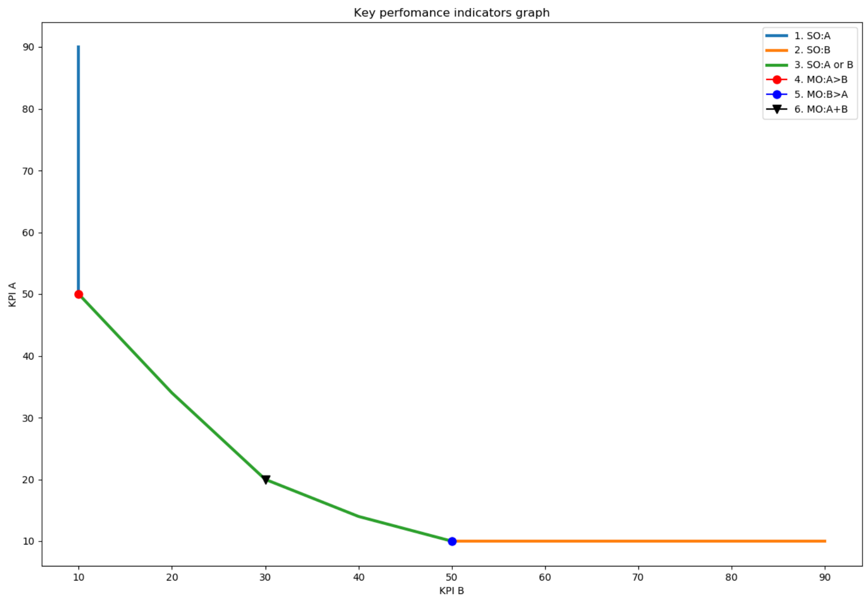


Figure 5.2: Example of objective methods and resulting values

It is up to the modeller to decide which method suits best for their goal. For this research all three methods will be experimented with to create more insight in their effect. If for example, it is faster to optimize the range of single objective values, than it is to optimize the weighted-sum method, it is better to choose the first option.

5.1.7 Constraints

As mentioned in chapter 4, the constraints will be a composition of current and future state constraints.

Name	Description
General	
Lower flow bounds (Constraint: 5.7)	Flow is larger than, or equal to zero.

Origin/Destination bound (Constraint: 5.8)	For all the combinations of origins and destinations, it is not allowed to compute or include the item when the origin is equal to the destination. This can also be written per constraint, but this would make the mathematical formulation unnecessary complex and therefore this general notion is given for all constraints. For example, the summation of flows to all destinations from origin 1, should skip the flow to destination 1, as this equals sending products to itself which does not occur and would only use up valuable computational power.
Origins	
Departure delivery bounds (5.11)	For all origins the departure bounds dictate the minimum and maximum departing products and deliveries.
Delivery flow bound (5.12)	Every flow option between origins and destinations can be activated or deactivated using binary values.
Deliveries coupled with products (5.13)	Products are coupled to deliveries as soon as the number of products is higher than zero.
Destinations	
Arrival delivery bounds (5.14)	For all destinations the departure bounds dictates the maximum arriving products and deliveries.
Inventory capacity (5.15)	Inventory capacities
Inventory start & end (5.16 & 5.17)	Start and end inventories differ for the destinations, see table 5.3.
Inventory transfertime (5.18)	Transfer time is modelled by holding products for a certain time, which is done by setting a minimum inventory level for the duration of the transfer time.
Current inventories (5.19)	The current inventory is modelled by taking the inventory from the previous time period and adding arriving and subtracting departing products. It is important to note that destinations cannot receive products from themselves. These constraints ensure product balance throughout the model.
Demand (5.20)	The constraint of demand is set by using the demand parameter. Subsequently the demand is met by adding the on time, late and early product arrivals. While taking into account the transport time between locations and the lateness of a product.
Delivered products (5.21)	The delivered products constraints couples the related early, late and current product arrivals to each other. This is necessary in case of overlapping product flows.
Upper bound late shipments (5.22)	Upper bound of late shipments, based on percentage of the total number of products delivered to a user.
Upper bound early shipments (5.23)	Upper bound of early shipments, based on percentage of the total number of products delivered to a user.

Table 5.4: Model constraints

5.2 Mathematical model

In the previous paragraphs the problem was described. According to Hu et al. [68] to solve analytic models, sometimes simplifications are required that make the models unrepresentative of the real world. However, in this case a mathematical model will be able to both satisfy the required level of detail and also generate a suggestion on how to prepare for an Rapid Response Force emergency recovery scenario.

In the following paragraph the mentioned pre-processing steps, sets, parameters, variables, objective, constraints and outputs will be described as mathematical formula's.

5.2.1 Pre-processing

Penalty
Based on the parameters as described in table E.1, the penalty can be calculated as follows:

$$pen_{podt} = pen_p + pen_o + pen_d + pen_t \quad o \in O, d \in D, t \in T \tag{5.1}$$

$$pene_{podtk} = pen_p + pen_o + pen_d + pen_t + pen_k \quad o \in O, d \in D, t \in T, k \in K \tag{5.2}$$

$$penl_{podtk} = pen_p + pen_o + pen_d + pen_t + pen_k \quad o \in O, d \in D, t \in T, k \in K \tag{5.3}$$

A more elaborate example can be found in Appendix E. In special cases the modeller can also choose to give a penalty a particular custom value.

Fuzzy numbers
To include the uncertainty of demand, the method from Jimenez et al. [80] can be used. In this way, a trapezoidal or triangular fuzzy variable can be transformed into it's crisp counterpart. For example if fuzzy demand $\hat{\text{d}}$ is described by triangular member function: $\hat{\text{d}}= (a_1, a_2, a_3)$, it's crisp counterpart would be calculated as:

$$D = \left[\frac{\alpha}{2} D^{u_{\hat{d}}} + (1 - \frac{\alpha}{2}) D^{l_{\hat{d}}}\right] \tag{5.4}$$

where:
Feasibility degree $\alpha = [0, 1]$
Lower defuzzification interval values $D^{l_{\hat{d}}} = \frac{a_1 + a_2}{2}$
Upper defuzzification interval values $D^{u_{\hat{d}}} = \frac{a_3 + a_4}{2}$

In table E.1, the crisp demand for users is described by the demand parameter: dem_{pdt} for $d \in D_3$, $p \in P$, $t \in T$.

Parameters

Parameters	Description
	Sets
L	Set of locations
$O \subset L$	Subset of origins
$D \subset L$	Subset of destinations
$O_1 \subset O$	Subset of suppliers
$D_1 \subset D \cup O$	Subset of cross-dock transfers
$D_2 \subset D \cup O$	Subset of long term storage transfers
$D_3 \subset D$	Subset of users
P	Set of products
T	Set of time windows
	Origin parameters
dp_{op}	Departure capacity products of origin o
dd_o	Departure capacity deliveries of origin o
dc_{odt}	Delivery flow capacity between origin o and destination d on day t
	Destination parameters
ad_d	Arrival capacity deliveries at destination d
s_d	Storage capacity of destination d
ei_{dp}	End inventory at destination d of products p
si_{dp}	Start inventory at destination d of products p
dem_{pdt}	Defuzzified demand of product p at locations d at time t
ul_{pd}	Upper bound late arrival products
ue_{pd}	Upper bound early arrival products
gl_{pd}	Maximum number of days late arrival of products
ge_{pd}	Maximum number of days early arrival of products
	Time parameters
$tport_{od}$	Transportation time of origin o to destination d
$tfer_d$	Transfer time (time to prepare a product for departure) at destination d
	Penalty parameters
pen_{podt}	penalty of delivery of product p from origin o to destination d at day t
$penl_{podtk}$	penalty of k days late delivery of product p from origin o to destination d at day t
$pene_{podtk}$	penalty of k days early delivery of product p from origin o to destination d at day t

Table 5.5: Mathematical model: Parameters

5.2.2 Variables

Variables	Description
Del_{odt}	Binary: 1 if a delivery arrives at destination d from origin o on day t, else 0
P_{podt}	Number of products p delivered to destination d from origin o on day t
PL_{podtk}	Number of products p delivered k days late to destination d from origin o on day t
PE_{podtk}	Number of products p delivered k days early to destination d from origin o on day t
I_{pdt}	Number of products p in inventory of destination d at day t

Table 5.6: Mathematical model: Decision variables

5.2.3 Objectives

As described in the conceptual model section, the two objectives for this research are the following two objectives. Objective one is the weighted sum of arrivals, with the weights as described earlier. Objective two is the weighted sum of products that arrive not on time, both late and early, with weights being penalties as described earlier. It is interesting to see that objective two is a weighted sum method objective on its own.
Objective 1: Minimize origin penalties

$$Min: \sum_p \sum_o \sum_d \sum_t P_{podt} * pen_{podt} \quad p \in P, o \in O, d \in D_3, t \in T, k \in T \tag{5.5}$$

Objective 2: Minimize late and early deliveries

$$Min: \sum_p \sum_o \sum_d \sum_t \sum_k (PL_{podtk} * penl_{podtk} + PE_{podtk} * pene_{podtk}) \quad p \in P, o \in O, d \in D_3, t \in T \tag{5.6}$$

They can be used in different ways, both in a single objective (SO) and multi-objective (MO) manner:

1. Objective 1 (SO)
2. Objective 2 (SO)
3. Objective 1 and subsequently 2 (MO 1, lexicographic method)
4. Objective 2 and subsequently 1 (MO 1, lexicographic method)
5. Objective 1 and 2 (MO 2, Weighted sum method)

5.2.4 Constraints

General constraints:
Lower flow bound:

$$P_{podt}, I_{pdt} \geq 0 \quad p \in P, o \in O, d \in D, t \in T \tag{5.7}$$

Orgin/Destination bound:

$$o \neq d \quad o \in O, d \in D \tag{5.8}$$

Goal constraint late arrivals:

$$PL_{podtk} = 0 \quad p \in P, o \in O, d \in D, t \in T, k > gl_{pd} \in K \tag{5.9}$$

Goal constraint early arrivals:

$$PE_{podtk} = 0 \quad p \in P, o \in O, d \in D, t \in T, k > ge_{pd} \in K \tag{5.10}$$

Origin constraints:

Departure delivery bounds:

$$\sum_{d} Del_{odt} \leq dd_{o} \quad o \in O, t \in T \tag{5.11}$$

Departure constraint:

$$Del_{odt} \leq dc_{odt} \quad o \in O, d \in D, t \in T \tag{5.12}$$

Delivery flow coupled with product flow:

$$\sum_{p} P_{podt} \leq dp_{o} * Del_{odt} \quad o \in O, d \in D, t \in T \tag{5.13}$$

Destination constraints:
Arrival delivery bounds:

$$\sum_{o} Del_{pod(t-tt_{od})} \leq ad_{d} \quad p \in P, d \in D, t \in T \tag{5.14}$$

Inventory capacity:

$$\sum_{p} I_{pdt} \leq s_{d} \quad d \in D, t \in T \tag{5.15}$$

Inventory start crossdock (+ longterm if required):

$$I_{pdt_0} = si_{dp} \quad d \in D_{1 \cup 2} \tag{5.16}$$

Inventory end crossdock:

$$I_{pdt_{max}} = ei_{dp} \quad d \in D_1 \tag{5.17}$$

Inventory transfertime:

$$\sum_{o} \sum_{t-tport_{od}-tfer_d+1}^{t-tport_{od}+1} P_{podt} \leq I_{pdt} \quad p \in P, d \in D_{1\cup 2}, t \in T \tag{5.18}$$

Current inventory $d \in D_1 \cup D_2$ (storage and cross-dock):

$$I_{pdt} = I_{pd(t-1)} + \sum_{o^* \in O_1} P_{po^*d(t-tt_{o^*d})} - \sum_{d^* \in D_3} P_{pod^*t} \quad p \in P, d \in D_{1\cup 2}, o \in d, t \in T \tag{5.19}$$

Demand $d \in D_3$ (users):

$$Dem_{pdt} = \sum_{o} P_{pod(t-tt_{od})} + \sum_{o} \sum_{k=1}^{T-t} PL_{podtk} + \sum_{o} \sum_{k=1}^{t} PE_{podtk} - \sum_{o} \sum_{k=1}^{t} PL_{pod(t-k)k} - \sum_{o} \sum_{k=1}^{T-t} PE_{pod(t+k)k} \quad p \in P, d \in D_3, o \in O, t \in T, k \in T \tag{5.20}$$

Delivered products:

$$\sum_{o} P_{pod(t-tt_{od})} \geq \sum_{o} \sum_{k=1}^{t} PL_{pod(t-k)k} + \sum_{o} \sum_{k=1}^{T-t} PE_{pod(t-k)k} \quad p \in P, d \in D_3, o \in O, t \in T, k \in T \tag{5.21}$$

Upper bound late shipments:

$$\sum_{o} \sum_{t} \sum_{k} PL_{pod(t-tt_{od})k} \leq ul_p * \sum_{t} Dem_{pdt} \quad p \in P, d \in D_3, k \in T \tag{5.22}$$

Upper bound early shipments:

$$\sum_{o} \sum_{t} \sum_{k} PE_{pod(t-tt_{od})k} \leq ue_p * \sum_{t} Dem_{pdt} \quad p \in P, d \in D_3, k \in T \tag{5.23}$$

For an explanation per constraint the reader is directed to table 5.4. The implementation of the model is described in Appendix D.

5.2.5 Key performance indicators

Due to the usage of penalty factors, the RNLA KPI's as discussed in the previous chapter can only be

Due to the usage of penalty factors the objective function is unrepresentative to be used as KPI directly because the results get skewed because of the penalties.

To get a clear picture of the actual product flows, separate KPI values have to be distilled from the results.

1. *Service level user*- The user service level can be described using two kpi's. The first describes the percentage of items that arrives late from a specific product, the second finds the maximum number of late days for this specific product.

   (a) *Service level objective value [-]:*

$$Min: \sum_p \sum_o \sum_d \sum_t \sum_k (PL_{podtk} * penl_{podtk} + PE_{podtk} * pene_{podtk}) \qquad p \in P, o \in O, d \in D_3, t \in T \tag{5.24}$$

   (b) *On time arrival [%]:*

$$\sum_{d \in d_3} \sum_t \frac{Dem_{pdt} - \sum_o (PE_{podtk} + PL_{podtk})}{\sum_o P_{podt}} * 100\% \quad k = 0, p \in P \tag{5.25}$$

   (c) *Early arrival [%]:*

$$\frac{\sum_o \sum_{d \in d_3} \sum_t \sum_k PE_{podtk}}{\sum_o \sum_{d \in d_3} \sum_t P_{podt}} * 100\% \quad p \in P \tag{5.26}$$

   (d) *Late arrival [%]:*

$$\frac{\sum_o \sum_{d \in d_3} \sum_t \sum_k PL_{podtk}}{\sum_o \sum_{d \in d_3} \sum_t P_{podt}} * 100\% \quad p \in P \tag{5.27}$$

   (e) *Max. lateness [days]:*

$$for \quad PL_{podtk} > 0 : max(k) \quad p \in P, o \in O, d \in D_3, t \in T \tag{5.28}$$

2. *Stock distribution*- The stock distribution kpi is the percentage of products that travels from decentralized stock.

   (a) *Stock distribution objective value [-]:*

$$Min: \sum_p \sum_o \sum_d \sum_t P_{podt} * pen_{podt} \qquad p \in P, o \in O, d \in D_3, t \in T, k \in T \tag{5.29}$$

   (b) *Decentralized stock [%]:*

$$\frac{\sum_{o \in o_1 \cup d_1} \sum_{d \in d_3} \sum_t P_{podt}}{\sum_o \sum_{d \in d_3} \sum_t P_{podt}} * 100\% \quad p \in P \tag{5.30}$$

3. *Service level & Stock distribution*- The combination of KPI's leads to the total objective value, of which the optimal result can be filtered.

(a) *Total objective value [-]:*

$$Min: \sum_{p}\sum_{o}\sum_{d}\sum_{t}(P_{podt} * pen_{podt} + PL_{podtk} * penl_{podtk} + PE_{podtk} * pene_{podtk}$$

$$p \in P, o \in O, d \in D_3, t \in T, k \in T \quad (5.31)$$

5.3 Chapter conclusion

The main challenge in this chapter is to translate the knowledge gap and wishes of the RNLA into model that can be used as tool for the RNLA. This chapter answered the following sub question:

- *How can the resulting supply chain design options be modelled?*

The question is answered in two sections: conceptual model and mathematical model. The conceptual model describes the exact representation of reality in words, whereas the mathematical model translates these functions into mathematical code. Both describe the sets, parameters, variables, pre-processing steps, objective, constraints, KPI's and output of the decision model. The sets consist of origins, destinations, products and time. The set origins consist of the entities: suppliers, long term storage facilities, cross-docks facilities and users. The set destination consists of the entities: long term storage facilities, cross-docks facilities and users. The set products consists of the products and the set time consists of time windows in the planning horizon. The parameters for the origins are product and delivery departure capacities and the origin penalty. The parameters for the destinations are the product and delivery arrival capacities, product storage capacities, start and end inventory boundaries and the destination's penalty. The time parameters are the transportation times, transfer times and time penalty. In the pre-processing steps the variation of penalties are combined into one delivery penalty per flow and the uncertain demand is turned into a discrete value using fuzzy logics. The decision variables are the deliveries per flow from origin to destination per day. Other variables are the number of departing products from an origin per day and the number of products in inventory at a destination per day. The objective of the model is to minimize the delivery 'costs' which equals the multiplication of deliveries from origins to destinations with the related delivery penalty. The objective is subjected to departure, arrival, inventory, balance and exclusive departures constraints. The key performance indicators are the stock distribution and the service level of the users. The first is measured as a fraction between RNLA or non-RNLA stored products, the second is measured by required days until demand full filled. Other KPI's are late, on time and early arrival, as well as maximal lateness of specific products. The KPI's are answered by retrieving information on the origins of departing product flows and arrival times of stock at destinations.

6 Verification & Validation

Whenever a model is created, it is a mere reflection or description of the real world situation. Frequently simplifications are performed by using assumptions, which help to focus on the important aspects and keep computational demand low and feasible. However, by simplifying the model it becomes less representative of the real world and if it looses to much if becomes less useful. This chapter will deal with the evaluation methods and evaluation of the model created in the previous chapter. The quality of a model can be determined by two methods that do not overlap, but complement, each other [85]. The first method is verification and answers the question if the model is right? Does the model do what the creator intended it to do? The second method is validation, which answers the question if it is the right model? To what extend does it mirror reality correctly? Figure 6.1 depicts this process nicely.

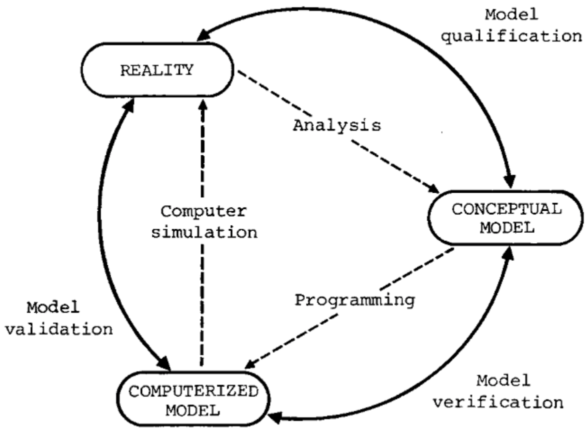


Figure 6.1: SCS report - visualized model credibility [86]

The next two sections will deal with the evaluation of the model described in the previous chapter, using both the verification and validation method.

6.1 Verification

To determine if the model is right, several verification methods are used. If the model passes the individual verification methods, the entire model is considered to be verified in general. The following methods; Tracing, Input checks, Continuity tests, Degeneracy tests and Consistency tests, are used in this research. The next subsections will be dealing with the separate tests and the results.

To keep consistent and comparable results, the same set of suppliers, transfers, users, products and time is used for all the tests, with varying values of parameters. This set consists of 2 suppliers, 1 RNLA storage facility, 1 RNLA transfer facility (cross-dock), 2 unique products, 2 users and a planning horizon of 10 days. This model can be solved within 1 minute on a 3.2 GHz Intel Core i5 Late 2015 iMac and offers all the possibilities a larger model would have which makes it very suitable for verification.

6.1.1 Tracing

The first method, rather cumbersome but straight forward, is to trace the model. By going through the model step-by-step and tracing the used sets, parameters, created lists and created constraints can be checked. This is very similar to the tracing method that is performed for time steps in simulation models. Checking if the sets, parameters and constraints are written properly is the first step of building confidence in the model. Table 6.1 and 6.2 display the traced items and the result. If the items were implemented correctly they receive a pass result.

Number	Traced sets and parameters	Result
	Sets	
1	Locations L	Pass
2	Origins O	Pass
3	Destinations D	Pass
4	Subset of suppliers O1	Pass
5	Subset of longterm transfers D1	Pass
6	Subset of cross-dock transfers D2	Pass
7	Subset of users D3	Pass
8	Products P	Pass
9	Time T	Pass
	Parameter groups	
10	Origin parameters	Pass
11	Destination parameters	Pass
12	Time parameters	Pass
13	Preference parameters	Pass

Table 6.1: Traced sets and parameters results

Sets 1 to 9 in Table6.1 describe the different sets, the sets that are the main ingredient of determining the size of the model. It is very important that the subsets are identified properly and that the right number of users is used for example. Sets 10 to 13 in Table6.1 describe the parameter groups as described in TableE.1. All the parameters in a group have to pass the test in order to receive a pass result for the group test.

Number	Traced constraints	Result
	Model Objective	
14	Objective	Pass
	General constraints	
15	Lower flow bound	Pass
16	Origin/Destination bound	Pass
	Origin constraints	
17	Departure product bounds	Pass
18	Departure delivery bounds	Pass
19	Departure constraint bounds	Pass
20	Flow coupling	Pass
	Destination constraints	
21	Arrival delivery bounds	Pass
22	Inventory capacity	Pass
23	Inventory start	Pass
24	Inventory end	Pass
25	Inventory transfer time	Pass
26	Current inventory D1 & D2	Pass
27	Current inventory D3	Pass

Table 6.2: Traced objective and constraint results

Set 14 in Table6.2 describes the objective. Sets 15 to 27 in Table6.2 describe the implemented constraints. Using the Gurobi package for python [87] these can be coded, which saves a lot of lines of code compared to manually coding all the constraints, and translated into a linear programming (LP) model which can be easily read by computers as well as humans. The LP model holds all the separate constraints making it quite a large file. Therefore, it is added to the programming files in case the reader wants to review it.

6.1.2 In- and output checks

The input checks verification verifies the model by testing for different inputs and checking if the results are as expected. It does so by applying several tests [85] on the model such as the consistency, degeneracy and continuity tests, which are briefly explained in the following list:

- Continuity test: the continuity test is performed by producing small variations in the input of the model. No sudden changes in results should occur, because that would indicate for errors, unless it is expected behaviour.
- Consistency: much like the continuity check, the consistency check determines if the model behaves as it should be. By changing the input and checking the output, it can be measured if the model is consistent. An example of this is to double the capacity and check if the utilization is halved for a system.

- Degeneracy test: the degeneracy test verifies the model for input data at the extremes of the models designed capabilities. Although those may never occur in real-life situations, it is a way to find the model's response to certain values and in this way determine any bugs.

Each paragraph has a brief results table. It is important to test the continuity and consistency tests for a feasible and non-trivial set of parameters as it would skew the tests otherwise.

Relative capacity

The relative capacities in the model are determined by the combination of demand, time and absolute capacities such as outgoing number of products and deliveries per day, incoming deliveries per day and storage capacities. It is more important to check the relative capacity of the model because there are many possible combinations between demand, time and absolute capacities which all have the same relative capacity. An example would be to half the demand, while halving the time. While this seems to be a different setting, it could very well have the same relative capacity. Therefore, where possible the capacity is tested by adjusting just one absolute factor. Table 6.3 depicts the tests done on relative capacity:

Continuity:

It is expected that small deviations of the capacity lead to small deviations in the outcome. A 5 % increase in supplier capacity is expected to lead to a small increase in decentralized stock usage, as less products need to be stored in a centralized storage. Similarly, a 5 % decrease is expected to lead to a small decrease of decentralized stock. The results are respectively 2.64 % increase and 1.58 % decrease. The results are as expected

Consistency:

It is expected that a larger deviations, such as doubling or halving the capacity will lead to substantial differences in outcome. It is expected that by doubling the capacity roughly twice the number of products can be transported decentralized and by halving the capacity the roughly halve the number of products can be retrieved from decentralized locations. The results are respectively 100 % decentralized stock, which can be expected as the basic solution gave a 42.61 % decentralized basic value, and 21.3 % which is exactly halve of the basic solution. The results are thus as expected.

Degeneracy:

It is expected that extreme capacities such as infinite or zero have a large effect on the outcome. A capacity of zero is expected to lead to a result of infeasibility or 0 % decentralized storage, whereas a very large capacity is expected to lead to 100% decentralized storage. The results are respectively 0 and 100 % decentralized storage. The results are as expected.

Test	Description	Result
	Continuity:	
28	Capacity: -5%	Pass
29	Capacity: +5%	Pass
	Consistency:	
30	Capacity: +100%	Pass
31	Capacity: -50%	Pass
	Degeneracy:	
32	Capacity: 0	Pass
33	Capacity: inf	Pass

Table 6.3: Capacities verification

6.1.3 Penalties

The penalties used in the decision model are influenced by the preference of the modeller, who wants to optimize towards a combination of weights of origins, destinations and time. It is valuable to note that it is not the absolute value of the penalties, but the relative differences between them, that is important. For this test a set of 2 suppliers, 2 transfers, 3 users, 2 products and 10 days is used. The basis input gave a result of 20.65 % early , 16.52% late and 62.85% on time delivery. Also on average 57.39 % of the products was delivered from a centralized storage and 42.61 % was delivered from a decentralized storage.

Continuity: time

It is expected that on small deviations should have a very low or no effect on the outcome. This is tested by altering the difference between the early and late penalties by plus and minus 5 percent. No difference in outcome was detected, as expected.

Consistency: time

It is expected that for larger deviations, such as doubling or halving the difference between penalties noticeable differences will be found in the outcome. By doubling the difference between the early and late penalties it is expected to have less than 16.52 % late deliveries which is mostly adjusted by delivering these products early. The outcome is an average late delivery of products of 8.26 % and an average increase of 7.4 % early deliveries. An increase of 0.86 % is delivered on time, but at the cost of delivering more products from a centralized location instead of the desired decentralized. By halving the value it is expected to have more than 16.52 % late deliveries. The result is an increase of 8.27 % late, a decrease of 1,08 % and a slight decrease of on time deliveries which seems off, but roughly twice the amount of products comes from decentralized stock which is quite favourable and explains the decrease of on time deliveries. Both the results are as expected.

Degeneracy: time

It is expected that for the largest deviations, such as no difference and a very large difference between penalties, noticeable differences will be found in the outcome. By having no difference between the penalties, it does not matter if products are delivered early or late and thus it is expected that the early and late number of products will roughly be equal. The result is 23,92 % late and 28,05 % late deliveries which is as expected. Once again a lower rate of on time deliveries is found, but a higher number of decentralized products is achieved. By creating an infinite, or very large, difference between late and early deliveries it is expected that no, or very little, late deliveries will occur. The result is 0 % late deliveries, at the cost of a lower decentralized stock distribution. Both these results are as expected.

Continuity: destination

It is expected that on small deviations should have a very low or no effect on the outcome. This is tested by altering the difference between the centralized and decentralized penalties by plus and minus 5 percent. No difference in outcome was detected, as expected.

Consistency: destination

It is expected that for larger deviations, such as doubling or halving the difference between penalties noticeable differences will be found in the outcome. By doubling the difference between the centralized and decentralized penalties it is expected to have more than 42.61 % decentralized deliveries. The outcome is an increase of average decentralized delivery of products of 16.52 %. By halving the value it is expected to have less than 42.61 % decentralized deliveries. The result is an decrease of 14.79 % decentralized deliveries, which seems correct as both the results have a similar deviation of the basic solution. The results are as expected.

Degeneracy: destination

It is expected that for the largest deviations, such as no difference and a very large difference between penalties, noticeable differences will be found in the outcome. By having no difference between the penalties, it does not matter if products are delivered centralized or decentralized thus it is expected that most products will be delivered from a centralized stock as this is often the fastest solution. The result is 21.95 % decentralized deliveries which is as expected. By creating an infinite, or very large, difference between centralized and decentralized deliveries it is expected that depending on the flow capacities the decentralized stock will be 100 % or the maximum achievable. The result is a utilization of 59.14 % decentralized stock. By cross-checking this with the results from the cross-dock unlimited capacities it is found that this is the highest achievable decentralized stock distribution.

The three results are as expected.

Table 6.4 depicts the tests done on penalties:

Test	Description	Result
	Continuity: time	
34	Penalty difference: -5%	Pass
35	Penalty difference: +5%	Pass
	Consistency: time	
36	Penalty difference: +100%	Pass
37	Penalty difference: -50%	Pass
	Degeneracy: time	
38	Penalty difference: 0	Pass
39	Penalty difference: inf	Pass
	Continuity: destination	
40	Penalty difference: -5%	Pass
41	Penalty difference: +5%	Pass
	Consistency: destination	
42	Penalty difference: +100%	Pass
43	Penalty difference: -50%	Pass
	Degeneracy: destination	
44	Penalty difference: 0	Pass
45	Penalty difference: inf	Pass

Table 6.4: Penalties verification

Fuzzy numbers

Even though the fuzzy numbers are part of the pre-process, it is important to check if the implementation is done right. Table 6.5 depicts the tests done on fuzzy numbers:

Continuity:

To verify the continuity small variations of plus and minus 5 % are applied to the fuzzy demand. An increase of 5% upper boundary and a decrease of 5 % upper boundary are expected to lead to a crisp demand of 171 and 165. The result is 171 and 165 and the variation in demand has already been verified so the results are considered verified.

Consistency:

A larger variation, such as doubling or halving the value of the upper demand boundary will lead to larger effects. The expected crisp demand is 190 for +100 % upper demand and 157 for -50% upper demand. The results are 190 and 157. The results are as expected.

Degeneracy:

To test the boundaries of the fuzzy function, the upper boundary is given a very low value and a very high value. The low value will match the middle demand value and the high value will be very large. For a value of 200 the expected return is 145. For a value of 30000 the expected return value will be 6850. The results are respectively 145 and 6850. The results are as expected.

Test	Description	Resultt
	Continuity	
46	Fuzzy difference: -5%	Pass
47	Fuzzy difference: +5%	Pass
	Consistency	
48	Fuzzy difference: +100%	Pass
49	Fuzzy difference: -50%	Pass
	Degeneracy	
50	Fuzzy difference: 0	Pass
51	Fuzzy difference: inf	Pass

Table 6.5: Fuzzy verification

6.2 Validation

As described earlier, the validation method answers the question, *is it the right model?*. To determine if the model is a reasonable representation of the reality most models can be validated on 3 aspects [88]:

- Assumptions
- Input parameter values and distributions
- Output values and conclusions.

According to Zimmerman [88] it is hard to achieve a fully validated model, especially if the studied system does not exist yet. In general three approaches can be applied: validation based on descriptive comparison, validation based on expert intuition and validation based on real system measurements. The next three sections will deal with the assumptions, input parameter values and output values based on the three approaches.

6.2.1 Descriptive comparison

The descriptive comparison will be used to determine how well the model matches reality based on its assumptions. In chapter 5, which describes the model, also a list of assumptions was given. This list is provided below as a short reminder.

Assumptions

During the creation of the model as described in this research, several assumptions were made. They are listed below:

1. The unit of time is in days. The first reason for this is that the available input is measured in days. The second reason is to reduce impact on computational demand.

2. Cross-dock and warehouse are modelled separately in order to increase agility of the model, this is important to acknowledge due to capacities that might be shared in real-life.

3. Cross-dock storage not based on the number of days a product can stay in storage, but on the maximum products in short-term storage.

4. Cross-dock is empty on beginning and end of planning horizon.

5. No deliveries between users.

6. Deliveries and products cannot be fractions and are thus required to be integers.

7. No trucks are modelled because they are in surplus available and will not be the bottleneck of the supply chain.

8. Most capacities are fixed during the planning horizon (e.g. Fixed transport times, transfer times, delivery capacities). Departing capacities for different days can be set before solving the problem.

9. Lead time altering factors such as communication time between order and delivery are fixed and included in the transport time between locations.

10. Demands are considered uncertain, the uncertainty is dealt with using fuzzy numbers.

It is clear that in real life situations the level of detail is not days. The RNLA is an organization that works 24/7 if required, therefore simplifying the situation to the precision level of days does not match the reality. The consequence is that the service level of users might be influenced, but in general this should not affect the distribution of products too much.
The cross-dock and storage facility can be modelled separately, which is not completely true in the current situation. Currently the cross-dock and storage facility are physically at the same place, which means that in reality personnel can be shifted from the cross-dock to the storage facility quickly whereas the capacities are fixed in the model. However, to be able to model additional pop-up cross-docks, they need to be modeled separately.
In reality there is no real start and end of the planning horizon, so the assumption that the cross-dock is empty at the boundaries of the planning horizon is slightly off. However, the cross-dock is not meant for long term storage, so no products should be stored there. The effect of this assumption on real-life is considered small. In real life sporadic exchange occurs between users, however this is not the emergency response preparation policy of the RNLA and is therefore not modelled. This usually involves small deliveries so the effect is considered neglectable. As the model does not include the routing problem, there was no need to include the modes of transport. In reality the products are delivered by trucks when the destination can be reached over land. When products need to be shipped overseas they are transported using ships or airplanes. This does not noticeably affect the distribution of products.
A major mismatch with the reality is the fixed capacities. The model takes several capacities into account, such as: departure of products, travel times, transfer times and

storage capacity. These are fixed numbers that are not altered during the planning horizon. In real life it can occur that delivery times increase or that the number of personnel changes which could alter the departure capacity.

Besides the mentioned assumptions, it is important to note that the parameter values are mostly based on estimations as well. Values such as supplier lead time, transport time, transfer capacity and penalties are quite trustworthy and measurable. However, user demand is an estimation because every emergency situation is different, which makes the ample available historic information quite hard to use.

6.2.2 Expert intuition

To get a better view on the validity of the model, two experts from the RNLA have been asked to give their views on the resulting model:

Major Niek van Schip

Major Niek van Schip has worked on many projects involving the RNLA supply chain. His view on the model is that even though it differs from the reality on quite some aspects, as described in the previous paragraph, the structural design of the model will be able to serve the purpose of distribution of products properly. It will be very useful to create a sense of the effect of parameters on the product distribution.

Drs. Koos Huijgen

Senior Data-analyst Drs. Koos Huijgen has looked at the model from a data-analyst point of view. He pointed out that the thrust worthiness of the data is an important aspect for the validity of the results. He estimated that the combined total of the parameters would provide a data thrust worthiness result of roughly 30% resemblance of the real situation. This renders it less useful for managerial decisions, but can still be used to create a sense of product distribution effects.

6.2.3 Real system measurements

It is very hard to compare this model to the real life situation, as the emergency situations rarely happen and are different each time. It is, however, possible to block specific functions such as direct deliveries between suppliers to users and additional cross-docks. This would then become a model of the current situation.

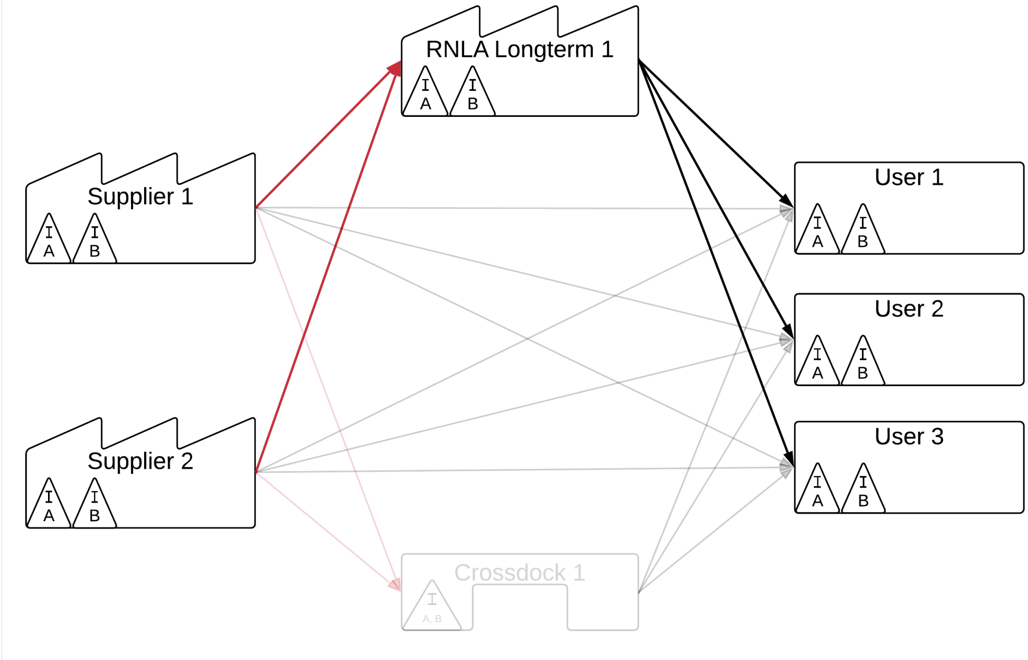


Figure 6.2: Validation model

Starting of with the same dataset as used for the verification; 2 suppliers, 1 long-term facility, 1 cross-dock, 3 users, 2 products and 10 days and disabling departing product flows between suppliers and users as well as suppliers and the cross-dock a model of the current situation emerges.

	Early		Late		On time		Total
	[%]	[-]	[%]	[-]	[%]	[-]	
Product 1:	54.19%	1234	13.18%	300	32.63%	743	2277
Product 2:	21.10%	16	20.56%	300	78.34%	1143	1459

Table 6.6: Flow time distribution: Future model

	Early		Late		On time		Total
	[%]	[-]	[%]	[-]	[%]	[-]	
Product 1:	0.00%	0	0.00%	0	100.00%	2277	2277
Product 2:	0.00%	0	0.00%	0	100.00%	1459	1459

Table 6.7: Flow time distribution: Current situation

	Centralized		Decentralized	
	[%]	[-]	[%]	[-]
Product 1:	34.83%	793	65.17%	1484
Product 2:	78.34%	1143	21.66%	316

Table 6.8: Flow origin distribution: Future model

	Centralized		Decentralized	
	[%]	[-]	[%]	[-]
Product 1:	100%	2277	0.00%	0
Product 2:	100%	1459	0.00%	0

Table 6.9: Flow origin distribution: Current situation

As no real data is available, it is only possible to study if both situations have feasible results if expected. It can be seen in Figures 6.6, 6.7, 6.8 and 6.9, that both situations deliver feasible results.

6.3 Chapter conclusion

By performing verification and validation tests the model is checked on different aspects, creating insight in it's usefulness and trustworthiness.

Verification

The verification is done by tracing the model and applying several input tests, such as consistency, degeneracy and continuity tests. The constraints and code in general have been traced and aspects such as capacities, penalties and input values have been verified to be working correctly as well. Therefore the model is considered to be verified for the scope of this research.

Validation

The validation is done by using descriptive comparison, expert intuition and real system measurements. The descriptive comparison focuses on the made assumptions and reflects on their validity in the final model. The expert intuition section combined the ideas of Major Niek van Schip and Drs. Koos Huijgen on the validity of the model and the data availability. Finally, it would be valuable to have real system measurements but this is at this stage not possible therefore the future design model has been deployed to study the current situation. In this way it's results can be validated and combined with the descriptive comparison and the expert intuition a general idea can be given on the validity of the model. The conclusion is that the model can be used to create an overall sense of the effects of decentralized product storage, but would need to be extended for managerial decisions.

7 Experiments and Results

This chapter goes into further detail on the application of the tool, by performing several experiments. Since multiple variations are possible, it is important to study these different supply chains in order to find the best one. Therefore this chapter will answer the following question:

- *How do different supply chain designs affect the supply chain performance?*

The experiments will be run on a 3.2 GHz Intel Core i5 Late 2015 iMac, which has 8 GB of DDR3 RAM memory and an R9 M390 AMD Graphics card with an additional 2 GB of RAM memory. While solving the experiments no other software programs will be used as to create a consistent outcome considering the solving time. To solve the optimization problems a state-of-the-art software package is used called Gurobi [87]. Gurobi is used worldwide as one of the leading mathematical programming solvers and users a range of tools (e.g. heuriscs) to solve mathematical problems. This chapter is divided into three parts, the experimental plan, the experiments and the results.

7.1 Experimental plan

To answer the question of this chapter an experimental plan is designed. It is important to not only compare different scenarios, but also elaborate on the methods used to find the solutions. This will create more insight on the found solutions. Therefore both the scenarios as well as the methods will be described in the experimental plan. At last the way of evaluating will be discussed.

7.1.1 Scenarios

Scenarios can be described as different input settings to the model, consisting out of the combination of a setup and specific parameters:

1. *Setup:*
   The setup consists out of two parts, the first being the topology of the supply chain. The second part is to describe the number of suppliers, long-term storages, cross-docks, pop-up cross-docks, users, products and days.

2. *Parameters:*
   To study the effect of different goals, parameters such as the maximum number of days late product arrival, upper- and lower bound of late deliveries and exclusive deliverer can be adjusted. To study the effect of altering the supply chain on actors level, values such as arrival and delivery bounds, inventory capacity and transportation times can be varied. By altering the parameter values to zero or infinite, constraints such as inventory capacity can be bypassed completely.

7.1.2 Methods

Results can be achieved by using multiple objectives. As described in chapter 5, different objective methods, such as single objective, lexicographic multi-objective and weighted-sum multi-objective are available. These will be evaluated by studying the solver time required as well as the resulting optimality gap values.

7.1.3 Evaluation

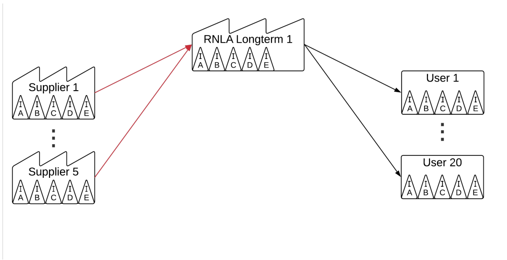
The results will be evaluated using several KPI's as described in chapters 4 and 5 as well as using the log information from the Gurobi solver, such as the time it took to find a solution and the optimality gap. The results can be discussed by comparing them both to each other as well as the results of the reference situation: setup zero, which is comparable to the current RNLA supply chain. The most important KPI's are the weighted user service level objective value and the stock distribution objective value. They do not have a unit and are merely the summation of products with their respective penalties. They will be presented in two graphs: service level vs stock distribution and total objective value vs stock distribution. The first graph will present the reader with a graph similar to the example in 5.2. The upper and lower bounds, as well as the optimal solution can be seen very clearly. The second graph shows the relation of the optimal solution with the total objective score. Comparing the total objective score of different setups leads to the best alternative. Besides these two main KPI's, the result can be evaluated by looking at specific product KPI's as well. For each product in the solution it is possible to calculate the percentages of it's decentralized stock flow, early arrivals, late arrivals and effect on the total objective score. Besides that also insight is created in the maximum number of days lateness. By comparing these values for different parameters and setups the best parameter settings can be determined. Finally, insight is created in the solutions by presenting log information such as calculation times and the optimality gaps. By utilizing the main KPI's, the practical KPI's and the solver logs the experiments are evaluated scientifically as well as on a practical usable level.

7.2 Experiments

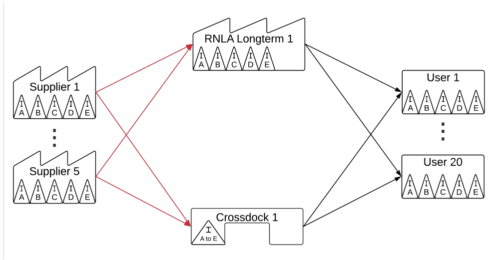
As explained in the experimental plan, the experiments consist of scenarios and methods. These are explained in the following paragraphs:

7.2.1 Scenarios

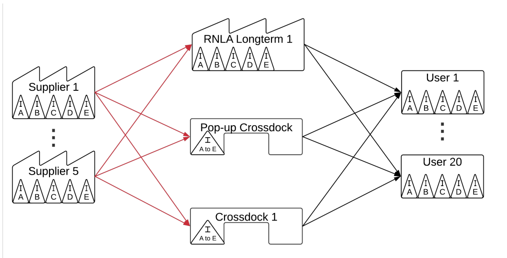
1. *Setup:*
   The topologies used for this experiments are the same as the ones described in chapter 4. Ideally a real-life data set would be used for the experiments, unfortunately this was not available. Therefore a fictional data sets were used. This chapter deals with the dataset containing 5 suppliers, 1 long-term storage, 1 cross-dock, 1 pop-up cross-dock, 20 users, 5 products and 10 days. This results in the supply chain setups as depicted in Figure 7.1. Other datasets were used, their results are similar and are added to appendix F.



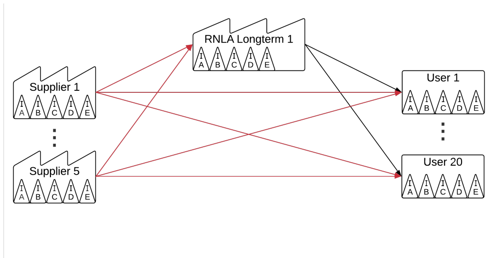
(a) 0- Current



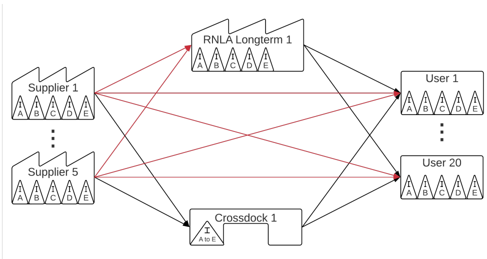
(b) 1- Fixed cross-dock



(c) 2- Pop-up cross-dock



(d) 3- Direct deliveries



(e) 4- Extensive

Figure 7.1: Experimental setups

2. *Parameters:*
   Many parameters can be studied, but for this set of experiments the specific product penalty will be adjusted to show it's effect on the service level. Two parameter values for the product penalty will be experimented with, zero and non-zero, resulting in weighted products and un-weighted products. Another important parameter that has to be taken into account is the maximum solver time, which is currently set to 600 seconds. The last parameter that needs to be mentioned is the fuzzy feasibility degree of 0.9. This indicates a practically acceptable solution. The other parameter values are included digitally with the algorithm files.

7.2.2 Method

It is possible to solve the experimental problems using just the single objective method. By fixating one KPI at several values, the results can be plotted in a graph and the optimal solution can be found. This gives more insight than just a singular solution, but is computationally demanding. Therefore, method 1, the lexicographic method will be used to determine the 'upper' and 'lower' bounds of the solution range as explained in chapter 5. After the lower and upper bounds have been determined, the single objective method is applied for the range of values between the lower and upper bound divided in equal steps. In this way only useful calculations need to be performed, as solutions found outside the upper and lower bound will always be inferior to the bounds themselves. By connecting the useful solutions in a graph, a curve can be made that approximates the solution space. Finally, method 2, the weighted sum multi-objective is utilized, not only to find the precise optimum but also to see if it matches the curve created by the single objective methods. In order to optimize the solver method further, it would be advisable to use variable stepsize. Small steps for interesting areas, such as near the optimal solution. Large steps for less interesting areas, which is up to the modeller to decide.

7.3 Results

This section describes the results from the experiments performed as described in the previous section. The experiments produce quite some similar looking results. This section discusses the main results, the complete collection of results can be found in Appendix F.

7.3.1 Evaluation: main KPI's

Based on the evaluation steps described in the previous section, this chapter section will start of with the two main KPI's: service level objective value, stock distribution objective value. Combined these form the total objective value for the multi-objective methods.

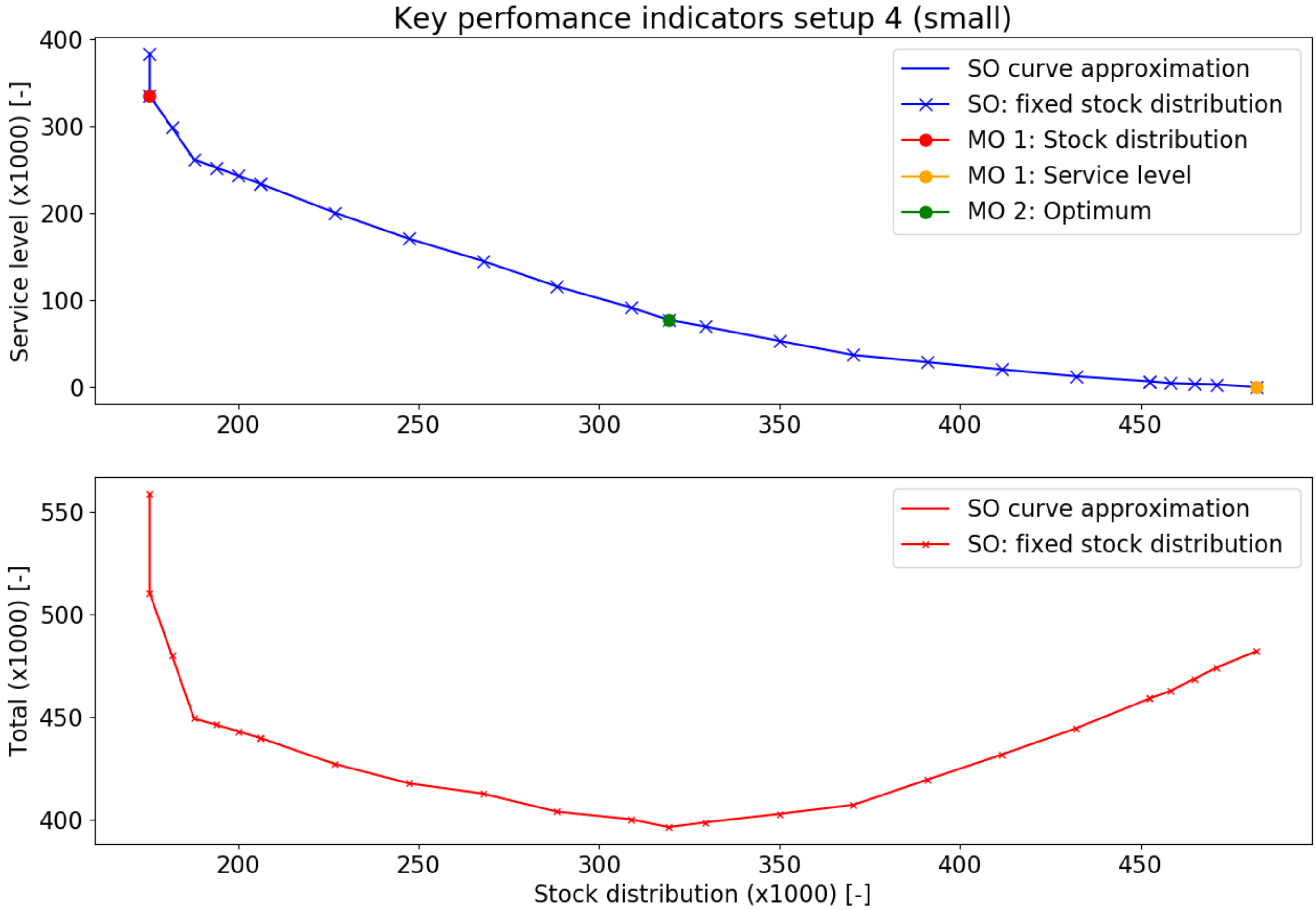


Figure 7.2: Service level & Stock distribution KPI objective values - (setup 4, method 3)

In the top graph of Figure 7.2 the service level objective values are plotted versus the stock distribution objective values. The lexicographic results clearly give the upper and lower boundary for each of the objectives. More than 20 single objective optimizations have been performed to create a curve, which is similar to the curve explained in chapter 4. Finally, the weighted-sum multi-objective indicates the optimal solution. It is hard to see how this would be the optimal solution from the top graph, therefore a second graph has been created. The lower graph of Figure 7.2 displays the total objective value plotted versus the stock distribution. This allows for a nice comparison of both graphs. In the lower graph it becomes clearly visible that the lowest total objective value matches the optimal solution in the upper graph. It is important to note that this is only true in case of a zero, or very small, gap. If the gap is larger than 0.01, it is not the overall optimal solution yet, but only the current best boundary found within the time limit. More on the gap later on in this chapter. By finding the best objective value for all setups the following values were found. These values are shown in Table 7.1. It becomes clear that Setup 4 would perform best in this case, followed by Setup 2. Based on objective value both perform much better than the original, setup 0, design.

Set	Best value
Setup 0	592
Setup 1	480
Setup 2	436
Setup 3	492
Setup 4	397

Table 7.1: Weighted-sum objective values, non-weigthed products (x1000)

7.3.2 Evaluation: Specific product KPI's

By using more specific KPI's it is possible to generate more insight in the specific product flows. Both Tables 7.2 and 7.3 displays the results for setup 4, solved by using method 3. The main difference is that the Table 7.2 display the solutions of the problem that was solved without product penalties (non-weighted) whereas Table 7.3 has a penalty on product 4, which means that product 4 is deemed more important than the other products. When looking at the tables, information is presented on the stock distribution (Decentralized product percentage) and user service level (late & early percentages, max lateness). Furthermore the effect of each product on the total objective value can also be displayed, which is very useful for decision making on future enhancements of the supply chain. When comparing the tables the difference with and without the penalty on product 4 it is noticeable that the flow of product 4 has improved in stock distribution and user service level KPI's. However, in general the other product flow solutions have degraded.

Product	Decentralized [%]	Early [%]	Late [%]	Late [max days]
1	17.73	8.87	0.00	0
2	14.85	11.42	0.00	0
3	68.30	17.61	0.00	0
4	0.00	47.87	20.62	3
5	35.34	18.39	0.00	0

Table 7.2: Flow results: setup 4, MO2 method (weigthed-sum) , non-weighted products

Product	Decentralized [%]	Early [%]	Late [%]	Late [max days]
1	14.72	5.85	0.00	0
2	9.15	5.72	0.00	0
3	68.30	23.99	0.00	0
4	52.37	18.01	0.00	0
5	41.99	27.15	0.00	0

Table 7.3: Flow results: setup 4, MO2 method (weighted-sum), weighted product 4

In a more extensive study it would be beneficial to create the KPI overview tables as discussed not only for product flows, but also for supplier and user effects in order to create better insight in the complete processes.

7.3.3 Evaluation: Overview setup log results

The third and last section of the results deals with the optimization log files. Specifically the solver time and solution gap are interesting. As they tell something about the computational demand and quality of the solution. Table 7.4 shows the absolute solver time, or if applicable the mean and variance, in seconds. The mean and variance are calculated for the single objective method as this is calculated roughly 20 times per experiment setting. Also the 'Total' value is the mean of the single and multi-objectives. It is important to note that the mentioned solver time is purely the time Gurobi needs to solve the problem, this does not include the computational time required for database creation and result processing.

Solver time

Method	Setup 1	Setup 2	Setup 3	Setup 4
SO (mean, n=26)	0.31	0.52	0.81	1.20
SO (variance, n=26)	0.03	0.23	1.59	2.76
MO I: stock distribution	0.29	0.54	0.53	29.16
MO I: user service level	0.19	0.24	0.21	0.21
MO II	0.30	0.27	0.47	0.64
Total (mean, n=29)	0.30	0.51	0.77	2.00
Total (variance, n=29)	0.03	0.21	1.46	25.60

Table 7.4: Solver time: setup 4, MO2 method (weighted-sum), non-weighted products

From the results in Table 7.4 it seems that as setups increase in complexity, so does the computational solver time. However, for setup 2, 3 and 4 also the variance increases drastically. Therefore it would require more research to form a scientifically sound conclusion on the correlation between setup complexity and solver time. Another result is that, based on these experiments, it seems that MO II (weighted-sum method) does not take a lot more time than the average single objective method. That means that it is perfectly reasonable to just use this single method when studying a specific scenario.

Gap

The solution gap [87], is calculated as percentage of the difference between the best objective bound and objective value, see equation 7.1. The best objective bound is obtained by taking the minimum of the optimal objective values of all of the current leaf nodes, in a branch-and-bound algorithm which is used by Gurobi.

$$gap = \frac{|ObjBound - ObjValue|}{|ObjValue|} \tag{7.1}$$

When the gap is 0 %, the current upper bound and lower bound are equal and thus optimality is proven. The standard allowable gap is 0.01%, which has been used for these experiments, but most frequently the solver will find a gap of 0 % anyway as can be seen in Table7.5.

Method	Setup 1	Setup 2	Setup 3	Setup 4
SO (mean, n=26)	0.0000	0.0000	0.0021	0.0019
SO (variance, n=26)	0.0000	0.0000	0.0000	0.0000
MO I: stock distribution	0.0000	0.0000	0.0000	0.0000
MO I: user service level	0.0000	0.0000	0.0000	0.0000
MO II	0.0000	0.0000	0.0000	0.0000
Total (mean, n=29)	0.0000	0.0000	0.0019	0.0017
Total (variance, n=29)	0.0000	0.0000	0.0000	0.0000

Table 7.5: Solver gap: setup 4, MO2 method (weighted-sum), non-weighted products

Table 7.5 clearly shows that most values are below 0.01 % and frequently 0 %. These are very good results and conclusions can be drawn that the found solutions are indeed optimal.

7.4 Chapter conclusion

This chapter answered the following sub questions:

- *How do different supply chain designs affect the supply chain performance?*

To study how different supply chain designs affect the supply chain performance, the model of the resulting supply chain is used. By combining different setups and parameters, several scenarios are created that can be evaluated using different solver methods. The generated database consists out of 5 products, 5 suppliers, 1 longterm storage, 1 or 2 cross-docks, 20 users and 10 days. Larger datasets were studied and added in appendix F. The varied parameter was the product penalty. The different problems are solved using multiple methods such as the single objective method, lexicographic multi-objective method and the weighted-sum multi-objective method. The results are evaluated on the following KPI's: service level objective value, stock distribution objective vale, total objective value, decentralized product percentage per product group, early product delivery percentage per product group, late product delivery per product group, the maximum number of days lateness per product group and the contribution to the objective value per product group. Also the solver time and gap are taken into consideration. In this way the model can be evaluated properly on a scientifically and practical usable level. It could be concluded that the result for the weighted-sum multi-objective matched with the lowest total objective value, which indicates optimality in the found solutions. When the accompanying gap is also 0 %, this indicates absolute optimality. Also, for the currently used datasets setup 4, the combination of functionalities, was consistently outperforming the other setups. Furthermore it is noticeable that the penalty on a product ensures a better outcome for that specific product, however this comes at a cost for the results of the other products. Considering the solver time, it can be mentioned that increasing dataset size means increasing solver time. This is important to acknowledge when studying larger models. A very important conclusion is that these experiments have shown that no large additional solver time is required for the weighted-sum method. This means that it is not necessary to use the array of single-objective methods and/or the lexicographic methods but it is most efficient to just use the weighted-sum method when optimizing a certain scenario to find the optimal solution.

8 Conclusion & Recommendations

This research was set out to create a tool that could study the effects of decentralized distribution of products on the Royal Netherlands Army service level. The objective was to create insight in the emergency response effects, determine the relevant KPI's and finally to develop a tool that could be used to study different situations. By performing a literature study and system analysis the problem, related factors and boundaries were analyzed. Based on the synthesis from the literature research and system analyses a model was created that could create insight without requiring the real-life situation to be altered or experimented with. The model was then verified, validated and used for a numerical example. The main question that drove this research was the following:

What RNLA supply chain design, with a focus on decentralized stock distribution, is the most effective in case of an RNLA emergency response situation?

This question is answered by answering the following sub-questions:

8.0.1 What are the characteristics, specific problems and methods related to emergency response models as described in literature?

The answer to this question is divided into three sub-items: characteristics, specific problems and methods. A quick overview of the results is given in Table 8.1.

Characteristics	Specific problems	Available methods
Type Scale Stage Planning horizon Risk	Facility location Product allocation Vehicle routing	Mathematical programming Simulation

Table 8.1: ER Characteristics, specific problems and available methods

Characteristics
The type can be either a natural or man-made emergency and might require an all-hazard approach. The scale answers the question: Does the problem involve regional, supply chain wide or single facility effects? And besides that, is it a single or multi-echelon supply chain? The stage describes the model's time window relative to the emergency: mitigation, preparedness, response or recovery stage? Planning Horizon describes how far ahead in time the model is operating in: strategic planning level, tactical level or operational level? Besides that, does it do so in a single- or multi-period? Then finally, what are the specific risks that need to be taken into account?

Specific problems
Three specific problems were identified in case of emergency response models: facility

location, product allocation and vehicle routing. It is interesting to see that a pattern can be distinguished here as well. When designing a supply chain from scratch it is important to decide where the facilities are going to be located. Once that is done, it is possible to determine in which facility a specific number of products is going to be allocated. Finally vehicles can be routed between facilities and to end-users in order to transport the products as required.

Available methods
Two main methods of solving the earlier described problems are found in literature: Mathematical programming and Simulation. Mathematical programming is used to find an optimal solution, whereas simulation can be used very well to study what the effect would be of applying or adjusting a setting in the optimal solution.

Knowledge gap
No previous research was found that studies the design of the RNLA supply chain based on service level and stock distribution performance indicators, in case of emergency response situations. The relevant findings from Galindo et al. [16] consist of two items. Firstly, most papers address a specific emergency situation and find the optimal solution, given a set of parameters. However, it would be interesting to extend research into finding alternatives. Secondly, Galindo et al. [16] also find that disruption during the planning horizon deserves more research. In case of multi-objective solutions it is found that researchers frequently use only one multi-objective method to solve the problem, while multiple options exist.

By following the steps of determining the characteristics, deciding which problem (or problem combination) needs to be solved and choosing the right available method a constructive model can be created.

8.0.2 How is the RNLA supply chain currently arranged and performing?

To get a good overview of the current state interviews have been held with employees working with the supply chain. This question is answered by describing four aspects of the current state: the current state description, supply chain analysis, supply chain data and supply chain key performance indicators (KPI):

- *Current state description*- The RNLA is an organization that is task driven, it receives a target which it needs to full-fill to the best of their abilities. Currently the RNLA buys required materiel and keeps a certain amount of it in stock based on set values (R,Q and s,S) in their SAP system.

- *Supply chain analysis*- Studying the allocation of stock, three actors are found: Supplier, RNLA transfer/storage facility and the RNLA end-users. Currently the RNLA storage facility keeps the earlier set amount of products in stock. End-users can order from the RNLA storage facility which will deliver it to the end-user and will order new products if a threshold is reached. Barely any direct deliveries from suppliers to end-users and no RNLA transfer facilities (cross-docks) have been studied using an operations research approach.

- *Supply chain data*- The complete supply chain consists over 100 suppliers, 200.000

unique products and over 40 end-users. The specific supply chain data is classified.

- *Supply chain KPI*- Currently the supply chain performance indicator is the service level of the RNLA storage facility which is also classified.

By taking the information from the literature study and the results from the current state analysis a gap can be identified that can be filled by an adjusted supply chain, the future state.

8.0.3 What additional supply chain design options could improve the current supply chain?

Using the characteristics found in the literature review, the type, scale, stage, planning horizon and risks have been used to analyze the RNLA emergency response situation. Based on the resulting information direct deliveries, (pop-up) cross-docks and the option of having multiple suppliers are added as additional options. To model this, additional data such as storage capacities, transport times, sending/receiving capacities, transfer times and location preferences are required. Instead of measuring the service level of the RNLA storage facility, the future state goal will focus on the actors that really count; the end-users, because they 'add value' to the RNLA by completing tasks and are thus the ones who need the products. This translates into a user service level, which is the first key performance indicator. The second key performance indicator is the percentage of decentralized stored stock, which is the topic of this research.

8.0.4 How can the resulting supply chain design options be modelled?

The question is answered in two sections: conceptual model and mathematical model. The conceptual model describes the exact representation of reality in words, whereas the mathematical model translates these functions into mathematical code. Both describe the sets, parameters, variables, pre-processing steps, objective, constraints, KPI's and output of the decision model. The sets consist of origins, destinations, products and time. The set origins consist of the entities: suppliers, long term storage facilities, cross-docks facilities and users. The set destination consists of the entities: long term storage facilities, cross-docks facilities and users. The set products consists of the products and the set time consists of time windows in the planning horizon. The parameters for the origins are product and delivery departure capacities and the origin penalty. The parameters for the destinations are the product and delivery arrival capacities, product storage capacities, start and end inventory boundaries and the destination's penalty. The time parameters are the transportation times, transfer times and time penalty. In the pre-processing steps the variation of penalties are combined into one delivery penalty per flow and the uncertain demand is turned into a discrete value using fuzzy logics. The decision variables are the deliveries per flow from origin to destination per day. Other variables are the number of departing products from an origin per day and the number of products in inventory at a destination per day. The objective of the model is to minimize the delivery 'costs' which equals the multiplication of deliveries from origins to destinations with the related delivery penalty. The objective is subjected to departure, arrival, inventory, balance and exclusive departures constraints. The key performance indicators are the stock distribution and the service level of the users. The first is measured as a fraction between RNLA or non-RNLA stored products, the second is measured by required days until demand full filled. Other KPI's are late, on time and early arrival, as well as maximal lateness of specific products. The KPI's are answered by retrieving information on the origins of departing product flows and arrival times of stock at destinations.

Verification

The verification is done by tracing the model and applying several input tests, such as consistency, degeneracy and continuity tests. The constraints and code in general have been traced and aspects such as capacities, penalties and input values have been verified to be working correctly as well. Therefore the model is considered to be verified for the scope of this research.

Validation

The validation is done by using descriptive comparison, expert intuition and real system measurements. The descriptive comparison focuses on the made assumptions and reflects on their validity in the final model. The expert intuition section combined the ideas of Major Niek van Schip and Drs. Koos Huijgen on the validity of the model and the data availability. Finally, it would be valuable to have real system measurements but this is at this stage not possible therefore the future design model has been deployed to study the current situation. In this way it's results can be validated and combined with the descriptive comparison and the expert intuition a general idea can be given on the validity of the model. The conclusion is that the model can be used to create an overall sense of the effects of decentralized product storage, but would need to be extended for managerial decisions.

8.0.5 How do different supply chain designs affect the supply chain performance?

To study how different supply chain designs affect the supply chain performance, the model of the resulting supply chain is used. By combining different setups and parameters, several scenarios are created that can be evaluated using different solver methods. The generated database consists out of 5 products, 5 suppliers, 1 longterm storage, 1 or 2 cross-docks, 20 users and 10 days. Larger datasets were studied and added in appendix F. The varied parameter was the product penalty. The different problems are solved using multiple methods such as the single objective method, lexicographic multi-objective method and the weighted-sum multi-objective method. The results are evaluated on the following KPI's: service level objective value, stock distribution objective vale, total objective value, decentralized product percentage per product group, early product delivery percentage per product group, late product delivery per product group, the maximum number of days lateness per product group and the contribution to the objective value per product group. Also the solver time and gap are taken into consideration. In this way the model can be evaluated properly on a scientifically and practical usable level. It could be concluded that the result for the weighted-sum multi-objective matched with the lowest total objective value, which indicates optimality in the found solutions. When the accompanying gap is also 0 %, this indicates absolute optimality. Also, for the currently used datasets setup 4, the combination of functionalities, was consistently outperforming the other setups. Furthermore it is noticeable that the penalty on a product ensures a better outcome for that specific product, however this comes at a cost for the results of the other products. Considering the solver time, it can be mentioned that increasing dataset size means increasing solver time. This is important to acknowledge when studying larger models. A very important conclusion is that these experiments have shown that no large additional solver time is required for the weighted-sum method. This means that it is not necessary to use the array of single-objective methods and/or the lexicographic methods but it is most efficient to just use the weighted-sum method when optimizing a certain scenario to find the optimal solution.

Through this research the described knowledge gap has been attended to by studying the designs of the RNLA supply chain based on service level and stock distribution performance indicators, in case of emergency response situations. Due to the model formulation it can be easily scaled or used to study alternatives as is performed using the experiments. Besides that, several capacities can be adjusted based on time, which can be used to model expected disruptions. At last, multiple methods have been used to solve the problems, which generate more usable information than just the optimal solution.

8.1 Recommendations

As initial testing shows positive results it is interesting to continue this research. The following recommendations for further research and improvements are proposed.

- *Additional performance indicators* - Currently two performance indicators are taken into account to study the viability of supply chain designs. However, in order for implementing the results in real life both effectiveness and efficiency performance indicators should be studied. For example, costs could be included and by iterating between available costs/negotiated prices and the optimal stock distribution, a solution emerges that can be applied in real-life circumstances.
- *Algorithm optimization* - Concerning both the mathematical model and the code implementation, it would be interesting to see how improved formulations could lead to faster solver times. Also, besides the objective methods used in this research many more exist. Therefore it would be interesting to study the effects of these methods, especially the effect of penalty factors on the outcome of the model need to be studied further.
- *Vehicle routing* - As described in the literature research, the follow-up problem would be to include vehicle routing. It is important to include vehicle routing to generate results that can be applied to how and when to utilize materiel.
- *Internal logistics* - Next step in improving the supply chain would be to study internal logistics of warehouses and cross-docks to optimize space usage, budget usage and transfer times.
- *Cross-dock integration* - Flow supply chain models and internal cross-docking flow models have been studied widely, however it would be interesting to combine the current flow model with existing, or new, internal cross-docking flow models. This could be coupled with a vehicle routing model for optimal result.
- *Information gathering*- The most important recommendation for the RNLA is to accumulate more data on their supply chain. Computers are becoming faster and more capable of solving complicated problems quickly. Therefore it is of high importance for the RNLA to study what data they need today, but also in the

future, and start accumulating it in order to prepare for tomorrow. Based on the current model information is required on supplier; sending capacities, transport times and RNLA storage facilities; product demand, receiving capacity, sending capacity, inventory sizes and transfer times.

- *Simulation-* As mentioned in the literature research and model chapter, another method is to simulate the problem. Now that the initial optimization has been studied, simulations can be performed to study the reliability of the model under different circumstances.

8.2 Research limitations

Due to the nature of the research and time available there are some limitations to this research. The experiments show interesting results but are based on generated data, real data would be required to study the real-life situation. It would take time and safety clearance to generate data sets based on real data, both of which are unavailable for this research. It is also important to note that Gurobi, while being one of the best solvers available, does not allow the user to choose between different optimization solver techniques. So even though the solution is generally solved faster than any other solver available, for research purposes it is less suitable when specific solver times or techniques need to be studied.

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A Scientific paper

Scenario-Based Approach to Decentralized Stock Distribution

A Royal Netherlands Army case study

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This paper introduces a tool that can study different Royal Netherlands Army (RNLA) supply chain designs, with a focus on decentralized stock distribution in case of an emergency response situation. It is important to study decentralized stock distribution, because currently the RNLA has a centralized stock, which poses a threat to the safety of the stock in case of war. Based on emergency response characteristics, the tool consists of a mathematical model of the current supply chain extended with additional design options such as cross-docking, direct supplier deliveries and pop-up cross-docks. These design options can be used to study different supply chain designs. Scenarios can be created by combining a supply chain design with different parameters. The effect of different scenarios is studied using a numerical example. This results, not only in the proven best supply chain design, but also creates insight in its product flow performance such as percentage of decentralized, late and early products. Using both single and multi-objective methods, insight is created in the range of possible solutions for each scenario.

I. INTRODUCTION

Currently the Royal Netherlands Army (RNLA) has a traditional three-echelon supply chain consisting of suppliers that deliver to a warehouse and the warehouse that delivers to customers (see Figure 1). However, the RNLA is interested in having its stock geographically spread as this is considered to be more safe. A solution for this would be to re-design the supply chain into a decentralized stock distribution design. This means that instead of keeping the majority of the stock at a RNLA controlled storage facility, the stock will be stored at the suppliers location and delivered when required. Updating the current RNLA supply chain network towards a decentralized product storage network might lead to an improved network, but the downsides in case of an emergency response situation are still unclear. This lack of knowledge could severely jeopardize the safety of the Netherlands, its citizens and also the employees of the RNLA.

Emergency response situations are distinguished from regular operations due to additional uncertainties, complex communication and coordination, shortages of resources and harder-to-achieve efficient and timely delivery [13] [2]. Therefore several characteristics, which are considered key elements of analyzing an emergency response situation, are discussed. Caunhye et al. [5] describe the type, which differentiates between man-made and natural disaster. The scale [5] then defines the scope, or physical size, of the supply chain that is to be studied. Altay et al. [1] describe the stage of the emergency as mitigation, preparedness, response or recovery. Also introduced by Caunhye et al. [5] is the planning horizon, which describes for example the number of seconds, hours, days or weeks as range to be studied. Govindan et al. [6] describe the

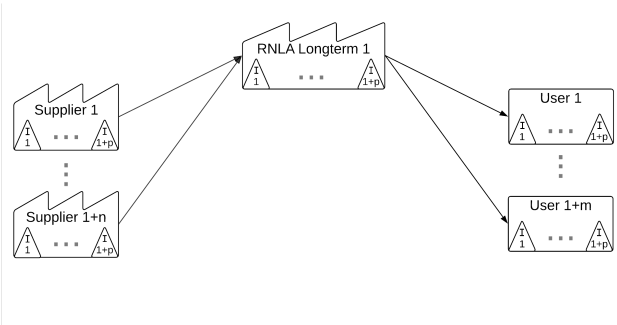


FIG. 1. Current state model

risks involved in emergency situations, of which the unknown demand, facility- and route failure, industry trustworthiness and product preference are taken into consideration in this research.

The design of the model is inspired by work from Rathi et al. [11], who created a multi-period, multi-commodity flow model which uses penalties to enforce several preferences. However, Rathi et al. only modelled direct deliveries, and did not include transfer facilities, multiple suppliers, exclusive suppliers, pop-up cross-docks and uncertainties, which are certainly applicable on the RNLA situation. To include transfer facilities, this model includes work inspired by Lim et al. [10] and Buijs et al. [4]. The clear distinction between origins and destinations, as well as transfer times is based on work by Haghani et al. [8]. Yao et al. [14] and Kampen et al. [12] describe the option of applying a multiple-supplier theory, which can easily be implemented in the model by adding more suppliers that offer the same products. To add the exclusive supplier model functionality, the users can only receive one delivery per day. By altering the daily departure limit of the available cross-docks, the cross-docks can be modelled as pop-up cross-docks. In reality pop-up cross-docks could be the utilization of the industry's cross-docks. Uncertainty methods included in this work are based on fuzzy number theories studied by Jimenez et al. [9] and applied by Bean et al. [3]. No previous research was found that studies the design of the RNLA supply chain based on service level and stock distribution performance indicators, in case of emergency response situations. Even though many supply chain models exist, the lack of such a model has mainly to do with the fact that in many papers a large emphasis is placed on the costs performance indicators. Another finding was that stock distribution is studied in several cases, however no papers have been found that study the decentralization of stock motivated by safety reasons.

II. METHOD

This research introduces a tool that can determine the most effective RNLA supply chain design, with a focus on decentralized stock distribution, in case of an RNLA emergency response situation.

Model

Based on the emergency response characteristics as described in the introduction and using the method of mathematical programming a multi-period, multi-commodity, multi-objective model has been created that describes the flow between multiple sources and sinks. Penalties are used as cost function to differentiate between desirable and less desirable product flows. A graphical display of the model, with n suppliers, j longterm storage facilities, k cross-docks, m users and p products, can be found in Figure 2.

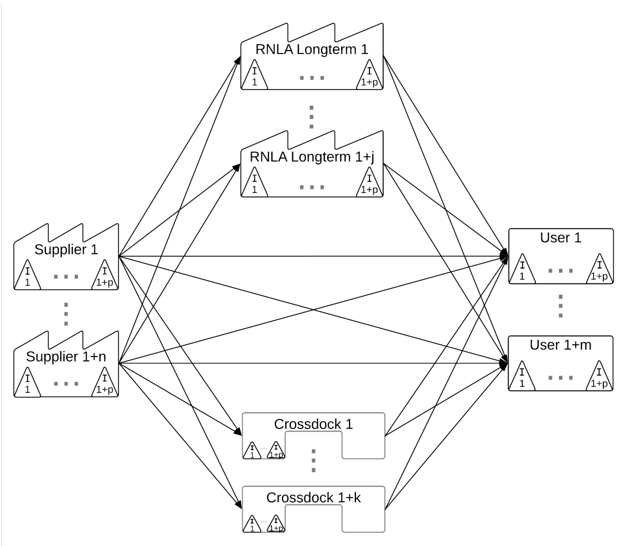


FIG. 2. Supply chain design model

By activating and de-activating the newly added supply chain functionalities such as cross-docking, direct supplier deliveries and pop-up cross-docks, different supply chain designs can be experimented with. An example could be the current situation, as depicted in Figure 1. Other examples are setup 1 to 4, which are depicted in Figure 3. Setup 1 utilizes only one cross-dock, whereas setup 2 includes a pop-up cross-dock. Setup 3 allows for the study of direct deliveries, while setup 4 can be used to study the effect of both direct deliveries and a cross-dock.

Objective

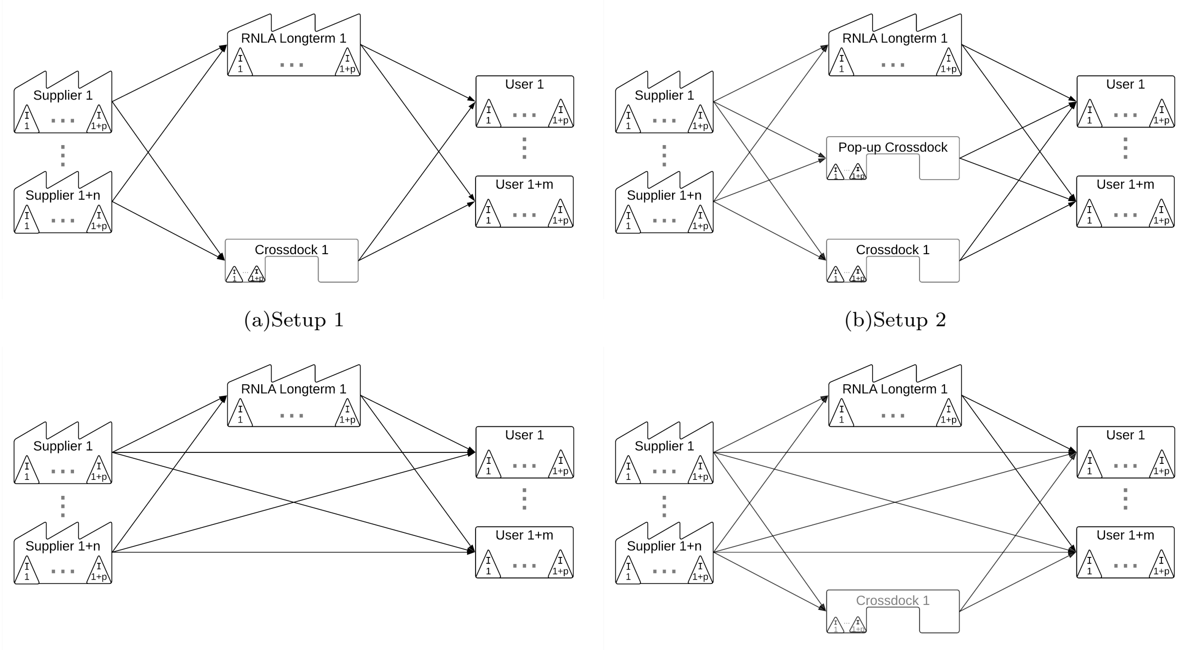
The supply chain designs are assessed using two main key performance indicators (KPI's): users service level and stock distribution objective values. The user service level objective value is obtained by the sum of the multiplications of each late or early arrival of a specific product with the number of products in that delivery to a user. The stock distribution objective value is obtained by the sum of the multiplications of each flow penalty between origins and destinations with the number of products. It is valuable to have more insight in the flows of products, therefore a more specified set of key performance indicators is added. These are the on time, early and late arrival of products in percentages. Also the maximal lateness of a product is tracked. Finally, even though they are not key performance indicators of the supply chain, a very relevant KPI to trace is the total solver time and gap of a solution, which provides information on the quality of the solution.

Objective methods

Using different methods such as: single-objective, lexicographic multi-objective and the weigthed-sum multi-objective a clear overview can be generated of the solutions. The lexicographic method, (MO 1) is used to find the Pareto solution of either the most optimal user service level objective, or the most optimal stock distribution objective. Everything in between those values can be found using a single objective method (SO), while fixating the other objective with a set interval. Finally, the optimal combination of the user service level and stock distribution objectives can be found using the weighted-sum objective (MO 2). In this case no specific, additional weights are given to the objectives as this is already done using the flow penalties.

Experimental plan

Experiments have been performed on a 3.2 GHz Intel Core i5 Late 2015 iMac, which has 8 GB of DDR3 RAM memory and an R9 M390 AMD Graphics card with an additional 2 GB of RAM memory. While solving the experiments no other software programs were running as to create a consistent outcome considering the solving time. To solve the optimization problems a state-of-the-art software package is used called Gurobi [7]. Gurobi is used worldwide as one of the leading mathematical programming solvers and uses a range of tools (e.g. heuriscs) to solve mathematical problems. By combining different setups and parameters, several scenarios are created that can be evaluated using different solver methods.



(a)Setup 1 (b)Setup 2

(c)Setup 3 (d)Setup 4

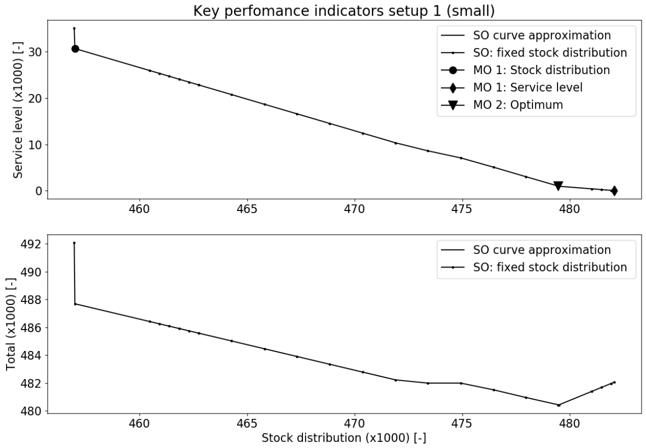
FIG. 3. Setup examples

III. RESULTS

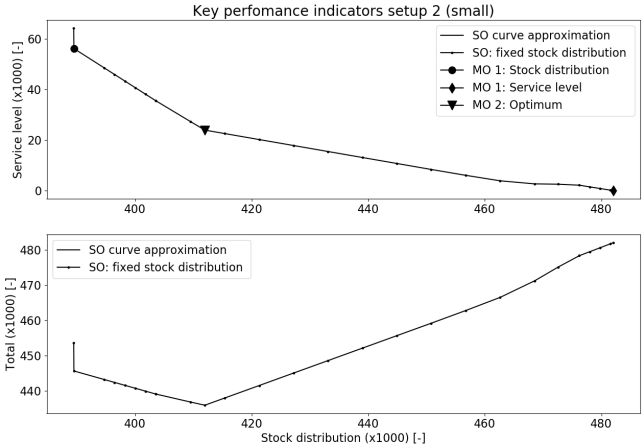
Numerical example

A numerical example problem is solved using a fictional dataset consisting out of 5 suppliers, 1 long-term storage, 1 cross-dock, 1 pop-up cross-dock, 20 users, 5 products and 10 days. The preference of a specific product is varied by adjusting its flow penalty. Based on the user service level and stock distribution objective values, the graphs in Figure 4 could be created for setups 1 to 4, as presented in Figure 3. In Figure 4, the top graphs of sub-figures 4(a) to 4(d) represent the stock distribution versus the service level objective value. The bottom graphs of sub-figures 4(a) to 4(d), display the stock distribution versus the total objective value, which is the summation of both KPI's. In the top graph the most outer dots represent the lexicographic solutions. The blue crosses show the single objective solutions, whereas the dot in the middle displays the weighted-sum solution. When comparing the location of the weighted-sum solution with the bottom graph it is clear that this point matches the lowest value of the bottom graph, suggesting an optimal solution.

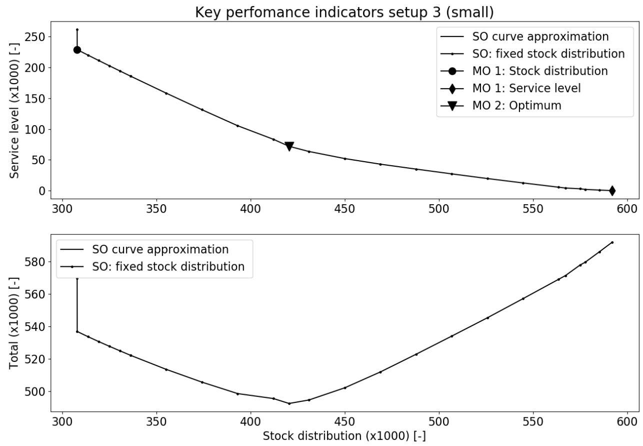
The combined objective values for setups 1 to 4 are relatively: 480, 436, 492 and 397. Based on the combined objective values it can be concluded that setup 4 is performing most effectively. Besides that, information is provided about the product flows. Table I shows the product flow results of the un-weighted product scenario for setup 4, solved with the multi-objective 2 (weighted-sum) method. It can be seen that even though some products are early and late, this is never more than a set maximum lateness, which was 3 days in this case. When these results are compared to the weighted situation as described in Table III, it is clearly visible that the results for product 4 have improved to the point that no products are delivered late anymore and 52.37 % can be stored decentralized. However, this comes at a cost for other products, which will need to be stored centralized, or will be delivered earlier than the expected time of demand. Tables II and IV hold the solver time and resulting gap values. An important observation to take away from these results is the fact that the weighted sum method takes approximately the same, or less, time to find a solution as the single-objective method does. This is true for all the tested setups. This means that it is not required to use the single objective or lexicographic methods to find the optimal solution. In fact it would be faster to use the weighted sum method directly instead of solving an array of single objectives. The solution gap, which is defined as the gap between the current solution value and the best branch value, indicates the quality of the solution. Table IV displays that the gaps for setup 1 to 4 are well below the accepted 0.01 value. This means that the found solutions can be considered optimal, and are not just some sub-optimal solutions.



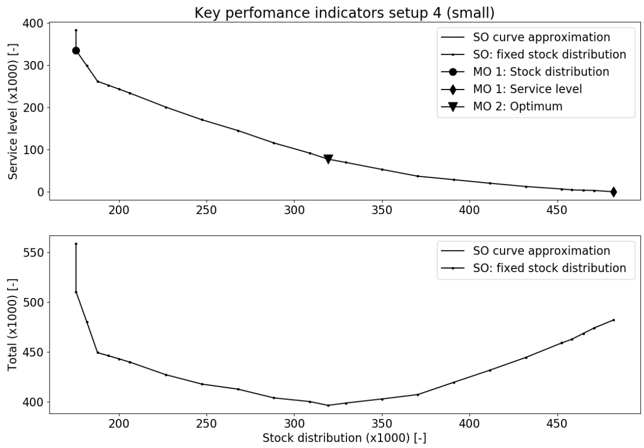
(a)Setup 1



(b)Setup 2



(c)Setup 3



(d)Setup 4

FIG. 4. Setup results

Product	Decentralized [%]	Early [%]	Late [%]	Late [max days]
1	17.73	8.87	0.00	0
2	14.85	11.42	0.00	0
3	68.30	17.61	0.00	0
4	0.00	47.87	20.62	3
5	35.34	18.39	0.00	0

TABLE I. Flow results: setup 4, MO2 method (weighted-sum), non-weighted products

Product	Decentralized [%]	Early [%]	Late [%]	Late [max days]
1	14.72	5.85	0.00	0
2	9.15	5.72	0.00	0
3	68.30	23.99	0.00	0
4	52.37	18.01	0.00	0
5	41.99	27.15	0.00	0

TABLE III. Flow results: setup 4, MO2 method (weighted-sum), weighted product 4

Method	Setup 1	Setup 2	Setup 3	Setup 4
SO (mean, n=26)	0.31	0.52	0.81	1.20
SO (variance, n=26)	0.03	0.23	1.59	2.76
MO I: stock distribution	0.29	0.54	0.53	29.16
MO I: user service level	0.19	0.24	0.21	0.21
MO II	0.30	0.27	0.47	0.64
Total (mean, n=29)	0.30	0.51	0.77	2.00
Total (variance, n=29)	0.03	0.21	1.46	25.60

TABLE II. Solver time: setup 4, MO2 method (weighted-sum), non-weighted products

Method	Setup 1	Setup 2	Setup 3	Setup 4
SO (mean, n=26)	0.0000	0.0000	0.0021	0.0019
SO (variance, n=26)	0.0000	0.0000	0.0000	0.0000
MO I: stock distribution	0.0000	0.0000	0.0000	0.0000
MO I: user service level	0.0000	0.0000	0.0000	0.0000
MO II	0.0000	0.0000	0.0000	0.0000
Total (mean, n=29)	0.0000	0.0000	0.0019	0.0017
Total (variance, n=29)	0.0000	0.0000	0.0000	0.0000

TABLE IV. Solver gap: setup 4, MO2 method (weighted-sum), non-weighted products

Conclusion

A tool is proposed that determines the most effective RNLA supply chain design, with a focus on decentralized stock distribution, in case of an RNLA emergency response situation. Based on several additional supply chain design options a model has been created. Based on different scenarios, consisting out of combinations of supply chain design setups and varying parameters, the best design alternative is found. A numerical example has shown that this works very well. Furthermore, it is noticeable that the penalty on a product ensures a better outcome for that specific product. However this comes at a cost for the results of the remaining products. It seems that no large additional solver time is required for the weighted-sum method. The most important conclusion from this research is that the tool is able to find the most effective RNLA supply chain design and suggest an optimal decentralized stock distribution, taking into account RNLA emergency response situations.

Recommendations

Currently, two performance indicators are taken into account to study the quality of supply chain designs. However, in order for implementing the results in real life both effectiveness and efficiency performance indicators should be studied. For example, costs could be included and by iterating between available costs/negotiated prices and the optimal stock distribution, a solution emerges that can be applied in real-life circumstances. Also, besides the objective methods used in this research, many more exist. Therefore, it would be interesting to study the effects of using different methods, especially the effect of penalty factors on the outcome of the model need to be studied further. Flow supply chain models and internal cross-docking flow models have been studied widely in literature, however it would be interesting to combine the current flow model with existing, or new, internal cross-docking flow models. This could be coupled with a vehicle routing model and/or other internal facility models for optimal result. The most important recommendation for the RNLA is to accumulate more data on their supply chain. Computers are becoming faster and more capable of solving complicated problems quickly. Therefore it is of high importance for the RNLA to study what data they need today, but also in the future, and start accumulating it in order to prepare for tomorrow. Based on the current model, information is required on supplier; sending capacities, transport times and RNLA storage facilities; product demand, receiving capacity, sending capacity, inventory sizes and transfer times. Simulations and further verification and validation studies can be performed to study the reliability of the model under different circumstances.

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B Methods

As mentioned in chapter 2, many methods exist. The following lists will provide you with methods most used in Emergency Response logistics within the scope of this research. Be aware that many more methods exist outside the scope of this research.

B.1 Mathematical programming models

The first category of methods is mathematical programming. Mathematical optimization programming is the optimization of a function dependent on many variables and often subjected to a set of constraints.

1. *Linear programming* - A specific type of mathematical programming is the linear programming model. It is characterized by the fact that the constraints need to be linear. An extension of linear programming is goal programming. This is usually a multi-objective problem and is characterized by the fact that every objective has a certain value, or goal, it needs to achieve.

2. *Non-linear programming* - Non-linear programming, as opposed to linear programming incorporates one or more non-linear constraint or objective [89].

3. *Integer programming* - On top of the linearity constraint of linear programming, integer programming also requires the solution to exist out of integers solely. Binary integer programming allows for only binary solutions.

4. *Stochastic programming* - Whereas the previously described models are deterministic, stochastic programming also includes the uncertainty which is encountered frequently in real world problems. By using probability distributions, the unknown values of parameters can be estimated, giving a more realistic result [90].

5. *Robust optimization* - Comparable to stochastic programming and often incorporated in a mathematical programming method is the robust optimization approach. In the case where parameters are known to be within certain bounds, but not their exact value, the robust approach tries to find a solution which is feasible for all the data and in some sense, optimal [90] [91].

6. *Fuzzy methods* - When the case arises that parameters cannot be used deterministic, the fuzzy method can be used to model the uncertainty while it is incorporated with a mathematical programming method [49]. A range of values can be used [92].

Heuristics

Heuristics are part of mathematical programming methods, they are specific approaches of solving problems that lead to quick, but not necessarily optimal or perfect answers. Heuristics are very useful in complex problems or cases where no optimum exists but a reasonably good answer is required. Li et al. [93] describes commonly used heuristic within emergency optimization techniques:

1. *Lagrangian relaxation* - Using the lagrangian relaxation, complex problems can be altered into simpler ones. This does not give the exact solution, but provides useful information. Lagrangian relaxation can be used on it's own [45][66][31][94] or can be combined with other heuristics such as local search [35] and branch-and-bound [53].

2. *Local search* - As the name suggests, local search takes a solution and by applying small changes compares the current solution to neighboring solutions. Moving in the search space from improved solution to the next it stops when a certain quality solution is found, or a time limit is reached. Morais et al. [95] studies crossdocking with 6 unique local search methods that are not based on Tabu search and have only feasible solutions in the search space. Two specific local search methods found in literature are Tabu search and Simulated annealing (SA). Tabu search relaxes the original rules, allowing the solver to visit worse solutions. It also prohibits the solver to visit solutions that have been studied already [96]. SA is a method that chooses the neighboring solution based on either an accepted value of a solution, or the probability of an unaccepted solution to be useful anyway. By time the algorithm will become more strict and will allow less values and demand higher probabilities, moving from the entire search space towards a feasible solution while minimizing the chance of a local optimum. Grahl et al. [97] use SA to solve multi-echelon safety stock placement problems and show that SA works better than the standard local search and simple genetic algorithm tested in 38 real-world instances.

3. *Evolutionary algorithm* - Evolutionary algorithms are based on the concept of evolution in the sense that they start of with a random population of individual solutions and then based on the best performing solutions, new solutions are generated based on crossovers, selections and mutations leading to the best performing solution. Ahmadizar et al. [34] solve a crossdock problem in a three echelon supply chain using a hybrid genetic algorithm. Momeni[98] combines SA and a genetic algorithm to model rail transportation of deteriorating items in a production-distribution problem.

4. *Swarm intelligence*- Based on biological phenomena swarm intelligence (SI) consists of a population of agents, which are entities that follow simple rules and communicate with each other and their environment. By sharing information a sense of intelligent behaviour is created [99]. Li et al. [100] applies ant colony optimization in a route optimization within a warehouse.

B.2 Simulation models

The second category is the option of using simulations. Hu et al. [68] shows that in the last years simulation has become widely used. It can be used to analyse complex problems, that sometimes cannot be solved analytically, but can also be used as an addition to analytic solvers by simulating the analytic solution and testing how well it works. Multiple methods are available for simulation:

1. *Discrete event* - Discrete even simulation (DE) is a simulation method that focuses on the events taking place on specific times in a finite time frame. For every event that happens, a change is marked in the state of the system. Since it is assumed that the state of the system only changes when an event occurs, the simulation can

move from one discrete event to the other while solving the problem [69]. Early on a very popular DE model was the queuing model, which can solve a queue of waiting customers in a store for example. However, as problems become more complex the queuing models are used less and less [68]. Van den Berg et al. [20] used DE simulation to evaluate different scenarios in modelling the logistics of emergency vehicles. Often Arena is used as software to model DE simulations [23] [33]. Other methods are agent based simulation and system dynamics, see figure B.1.

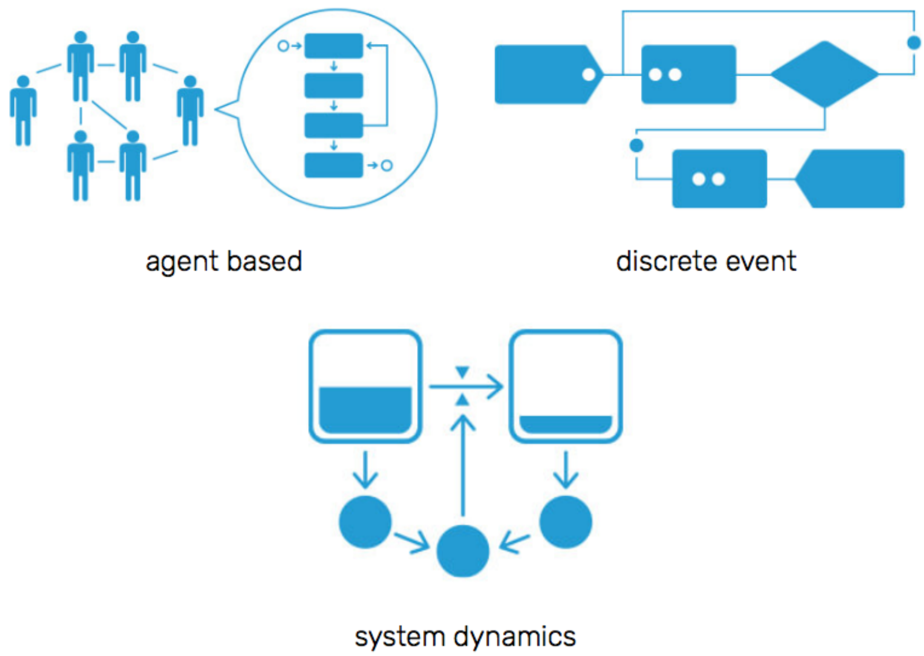

Figure B.1: Visualization of agent based, discrete event and system dynamics [70]

2. *Monte-Carlo* - The monte-carlo (MC) methods are based on repeated random sampling to obtain numerical results [101]. Afshar et al. [102] use MC to evaluate their risk-based genetic algorithm. Govindan et al. [37] use MC to generate a set of discrete scenarios based on relation used for their stochastic parameters.

3. *System dynamics* - System dynamics (SD) uses feedback loops to enhance scenario analyses, such as action/reaction effects [103]. Chang et al. and [104] Fan et al. [105] used SD to simulate military maintenance systems and reduce bullwhip effects. Compared to discrete event and monte-carlo simulations SD is used least in stocking policy methods [68].

4. *Decision and game theory models* - By taking possible, uncertain future events and/or actions of the supply chain into account these models come to a solution. Whereas game theory takes other actors into account, decision theory models consider the actors undependable from the supply chains actions [103].

C Royal Netherlands Army Assortment

The Royal Netherlands Army (RNLA) utilizes a broad range of products and military equipment. Since 2011 it is the RNLA's policy to buy materiel straight off the shelf whenever this is possible, a policy that has been succesfully applied by the United States of America for several years [106]. In 2012 a framework has been developed to explain and enforce the policy [107]. The following paragraphs will describe the distinguishes between the different gradations of materiel acquisition.

C.1 Commercial off the shelf

Commercial-off-the shelf (COTS) products are products that are developed and sold by numerous companies in the open market and are used "as-is" [108]. They are usually technological advanced, widely available at a low cost and have a reduced acquisition time [109]. Besides that they are usually available However, reliability is usually lower due to the fact the it is not specifically build for military purposes.
Examples of these products in the RNLA are [110]:

- Batteries
- Toilet paper
- Freight trucks
- Tires
- Alternators
- IT components such as TITAAN and BMS

C.2 Modified/Military off the shelf

If no COTS products are available that meet the requirements, the next step would be to purchase Military off the shelf products or Modified off the shelf products (MOTS). A modified off the shelf product is basically a COTS product that has been modified by a commercial vendor to prepare it for specific military requirements [108]. This can short-cut development time and save costs [106]. Military off the shelf products are for example [111][112]:

- Pantserhouwitser
- MRAT
- F-35
- AIM-120B Rockets for the F-35

C.3 Nato/Government off the shelf

Nato off the shelf products (NOTS) and Government off the shelf products (GOTS) are very similar. They are both products that are developed by the technical staff of the government, or in the case of NOTS, the NATO. These are usually products that cannot be found on the market and need to be designed according to special requirements [108].

D Implementation

Once the mathematical model is defined, the next step is to implement the model. The model is implemented using the Python programming language and Gurobi linear problem solver.

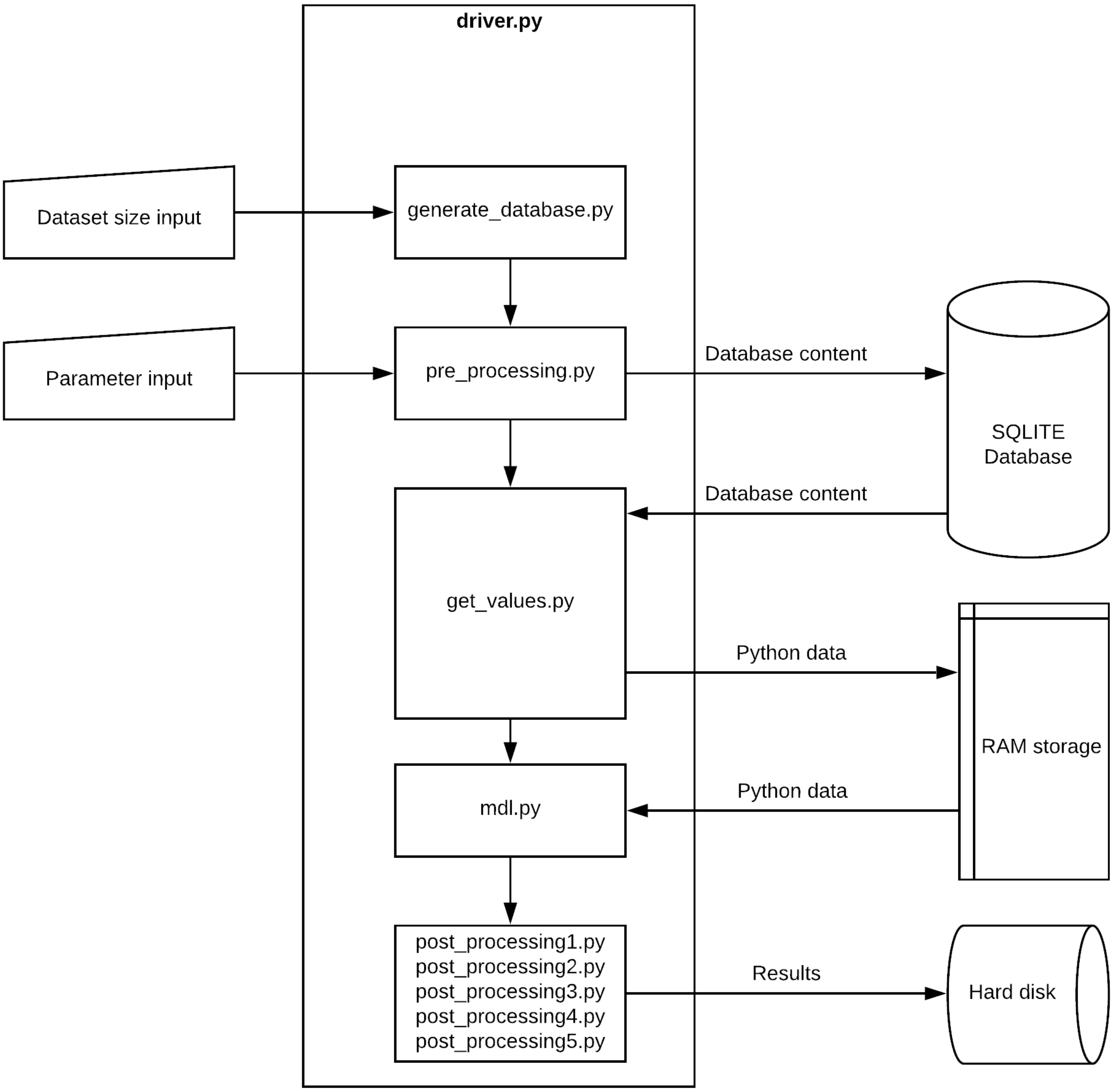

Figure D.1: Implementation

E Penalties

This appendix holds a small example of the penalties pre-processing. Let's take a simple example of the network with origins; A and B, destinations; C and D, and planning horizon; day 1 and 2. Example penalty values can be given to the origins (Pen_o), destinations (Pen_d) and days (Pen_t) as follows: A=1, B=2, C=1, D=2, day 1= 2, day 2 =1. Pen_{odt} is the combination of the penalties per set of origin, destination and day. This results in the following set of combinations:

Origins	Destinations	Days	Pen_o	Pen_d	Pen_t	Pen_{odt}
A	C	1	1	1	1	3
A	D	1	1	2	1	4
A	C	2	1	1	2	4
A	D	2	1	2	2	5
B	C	1	2	1	1	4
B	D	1	2	2	1	5
B	C	2	2	1	2	5
B	D	2	2	2	2	6

Table E.1: Values penalties example

Or graphically, where the penalties are depicted near the nodes per day. The combined penalties per specific flow are depicted near the arcs. This can be seen in figure E.1.

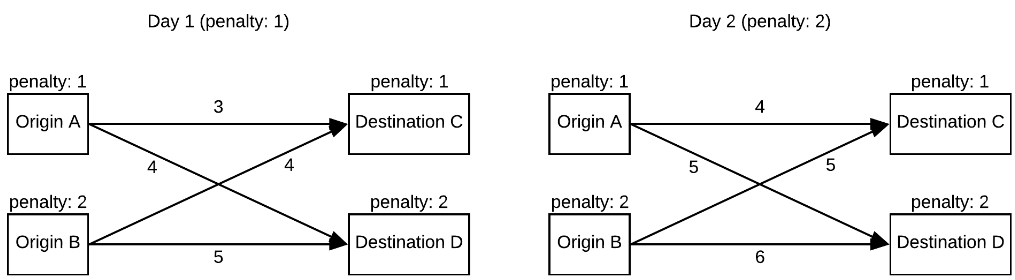

Figure E.1: Supply chain

Option 1

$$\sum_{o}\sum_{d}\sum_{t} Del_{odt} * pen_{odt} \quad o \in O, d \in D, t \in T \tag{E.1}$$

Results in:
$pen_{ac1} * D_{ac1} + pen_{ad1} * D_{ad1} + pen_{bc1} * D_{bc1} + pen_{bd1} * D_{bd1} +$
$pen_{ac2} * D_{ac2} + pen_{ad2} * D_{ad2} + pen_{bc2} * D_{bc2} + pen_{bd2} * D_{bd2}$

Using the example values, this equals:
$3 * D_{ac1} + 4 * D_{ad1} + 4 * D_{bc1} + 5 * D_{bd1} + 4 * D_{ac2} + 5 * D_{ad2} + 5 * D_{bc2} + 6 * D_{bd2}$

Option 2

$$\begin{aligned}\sum_{o} pen_o * (\sum_{t}\sum_{d} Del_{odt}) + \sum_{d} pen_d * (\sum_{o}\sum_{t} Del_{odt}) \\ + \sum_{t} pen_t * (\sum_{o}\sum_{d} Del_{odt}) \quad o \in O, d \in D, t \in T\end{aligned} \tag{E.2}$$

Results in:
$pen_a(D_{ac1} + D_{ad1} + D_{ac2} + D_{ad2}) + pen_b(D_{bc1} + D_{bd1} + D_{bc2} + D_{bd2}) +$
$pen_c(D_{ac1} + D_{bc1} + D_{ac2} + D_{bc2}) + pen_d(D_{ad1} + D_{bd1} + D_{ad2} + D_{bd2}) +$
$pen_1(D_{ac1} + D_{ad1} + D_{bc1} + D_{bd1}) + pen_2(D_{ac2} + D_{ad2} + D_{bc2} + D_{bd2})$

Which results in the same mathematical description as option 1 and thus, using the example values this also equals:
$3 * D_{ac1} + 4 * D_{ad1} + 4 * D_{bc1} + 5 * D_{bd1} + 4 * D_{ac2} + 5 * D_{ad2} + 5 * D_{bc2} + 6 * D_{bd2}$

Since option one and two result in the same mathematical representation, it would be justified to use any of the two options.

F Experiments and Results

Besides the small data set consisting of 5 suppliers, 1 long term storage facility, 1 cross-dock, 20 users, 5 products and 10 days, also larger datasets have been experimented with. The medium sized dataset consists of 7 products, 7 suppliers, 1 long term storage facility, 25 users and 10 days. The large dataset consists of 10 products, 10 suppliers, 1 long term storage facility, 1 cross-dock, 30 users and 10 days. An attempt was made on experimenting with larger datasets, however this superseded the available computer memory.

Dataset	**Products**	**Suppliers**	**Long term storage**	**Cross-dock**	**Users**	**Days**
Small	5	5	1	1 & 2	20	10
Medium	7	7	1	1 & 2	25	10
Large	10	10	1	1 & 2	30	10

Table F.1: Dataset sizes

Dataset	**Setup 0**	**Setup 1**	**Setup 2**	**Setup 3**	**Setup 4**
Small	591960.0	480417.0	435863.0	492333.0	396544.0
Medium	1101300.0	943866.0	849685.0	916970.0	758903.0
Large	-	1750897.0	1615930.0	1676427.0	1445832.0

Table F.2: Objective values

F.1 Small results

F.1.1 Objective and flow results: Setup 1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	0	0	0	12.35
Product: 2	0.00	0	0	0	29.47
Product: 3	65.12	0	12.75	1	15.14
Product: 4	34.36	0	3.27	1	14.37
Product: 5	0.89	0	0.89	1	28.67

Table F.3: Flow values- datasetsize:small, method: MO 1 (stock distribution), setup:1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	0	0	0	12.49
Product: 2	7.99	0	0	0	27.65
Product: 3	65.12	0	0	0	10.22
Product: 4	0.00	0	0	0	20.74
Product: 5	0.00	0	0	0	28.91

Table F.4: Flow values- datasetsize:small, method: MO 1 (service level), setup:1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	0	0	0	12.53
Product: 2	9.98	1.99	0	0	27.40
Product: 3	65.12	0	0	0	10.25
Product: 4	0.00	0	0	0	20.81
Product: 5	0.00	0	0	0	29.01

Table F.5: Flow values- datasetsize:small, method: MO 2, setup:1

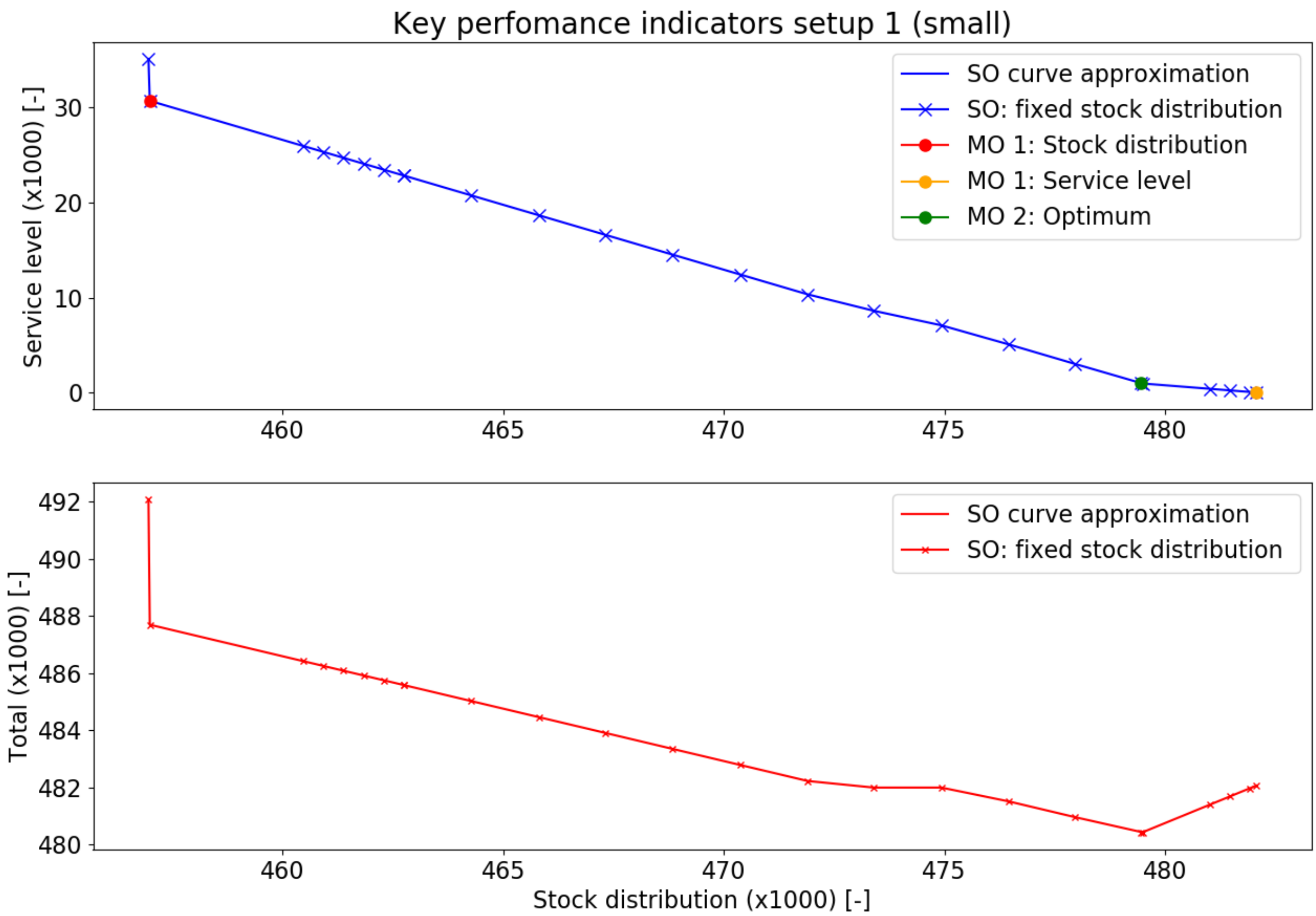

Figure F.1: Service level & Stock distribution KPI objective values - setup 1

F.1.2 Objective and flow results: Setup 2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	17.55	0	2.84	4	13.66
Product: 2	18.28	7.99	10.30	4	32.18
Product: 3	65.12	8.05	5.33	1	14.39
Product: 4	34.36	0	0	0	14.72
Product: 5	32.01	28.68	0	0	25.04

Table F.6: Flow values- datasetsize:small, method: MO 1 (stock distribution), setup:2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	0	0	0	12.49
Product: 2	7.99	0	0	0	27.65
Product: 3	65.12	0	0	0	10.22
Product: 4	0.00	0	0	0	20.74
Product: 5	0.00	0	0	0	28.91

Table F.7: Flow values- datasetsize:small, method: MO 1 (service level), setup:2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	0	0	0	13.81
Product: 2	7.99	7.99	0	0	31.46
Product: 3	65.12	12.45	0	0	12.92
Product: 4	26.83	26.83	0	0	19.24
Product: 5	32.01	4.26	0	0	22.57

Table F.8: Flow values- datasetsize:small, method: MO 2, setup:2

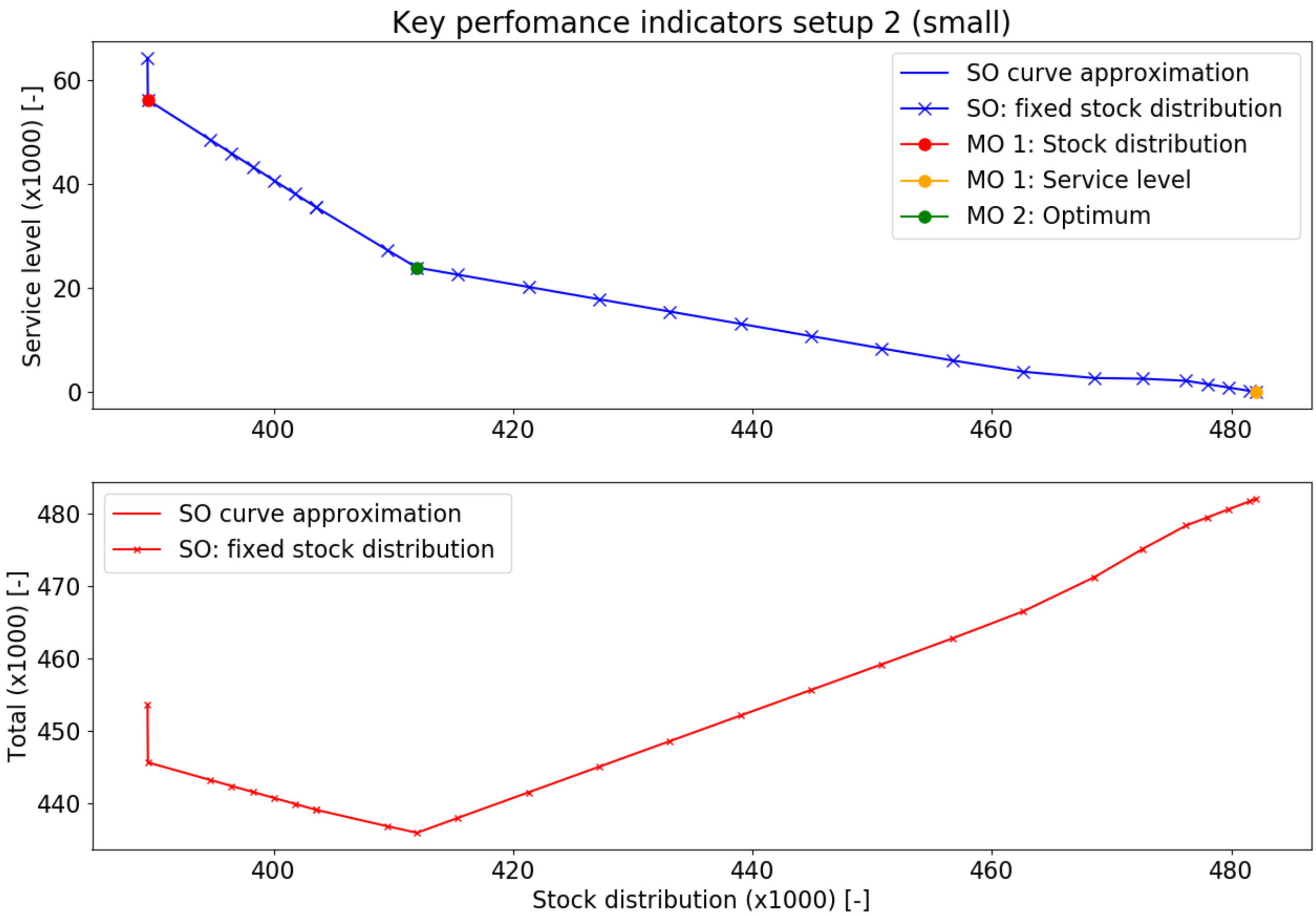

Figure F.2: Service level & Stock distribution KPI objective values - setup 2

F.1.3 Objective and flow results: Setup 3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	5.85	0	0	11.42
Product: 2	14.28	5.72	5.13	6	25.67
Product: 3	55.83	27.17	25.47	7	24.57
Product: 4	86.73	47.87	29.86	5	14.24
Product: 5	68.23	33.27	31.63	7	24.09

Table F.9: Flow values- datasetsize:small, method: MO 1 (stock distribution), setup:3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0.00	0	0	0	11.43
Product: 2	0.00	0	0	0	24.28
Product: 3	0.00	0	0	0	23.85
Product: 4	0.00	0	0	0	16.89
Product: 5	0.00	0	0	0	23.54

Table F.10: Flow values- datasetsize:small, method: MO 1 (service level), setup:3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	5.85	0	0	12.45
Product: 2	9.15	5.72	0	0	27.34
Product: 3	30.36	27.17	0	0	23.47
Product: 4	64.23	47.87	7.35	2	13.55
Product: 5	33.27	33.27	0	0	23.19

Table F.11: Flow values- datasetsize:small, method: MO 2, setup:3

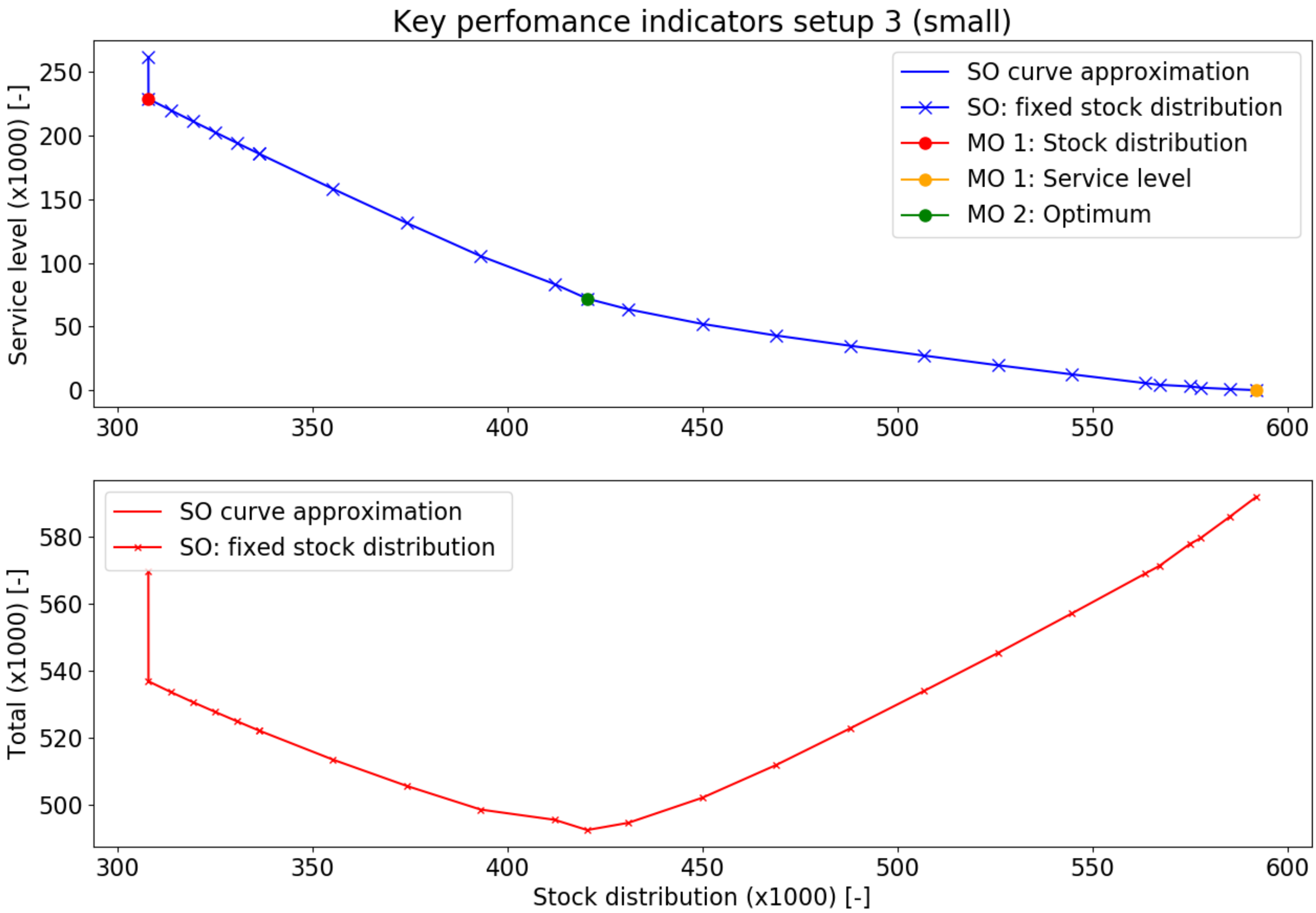

Figure F.3: Service level & Stock distribution KPI objective values - setup 3

F.1.4 Objective and flow results: Setup 4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	5.85	0	0	12.01
Product: 2	45.01	5.72	35.86	6	31.21
Product: 3	90.61	27.17	25.49	7	16.23
Product: 4	86.73	47.87	29.86	5	14.98
Product: 5	0	33.27	52.71	7	25.57

Table F.12: Flow values- datasetsize:small, method: MO 1 (stock distribution), setup:4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	14.72	0	0	0	12.49
Product: 2	7.99	0	0	0	27.65
Product: 3	65.12	0	0	0	10.22
Product: 4	0.00	0	0	0	20.74
Product: 5	0.00	0	0	0	28.91

Table F.13: Flow values- datasetsize:small, method: MO 1 (service level), setup:4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	17.73	8.87	0	0	15.23
Product: 2	14.85	11.42	0	0	32.77
Product: 3	68.30	17.61	0	0	13.81
Product: 4	0	47.87	20.62	3	12.49
Product: 5	35.34	18.39	0	0	25.70

Table F.14: Flow values- datasetsize:small, method: MO 2, setup:4

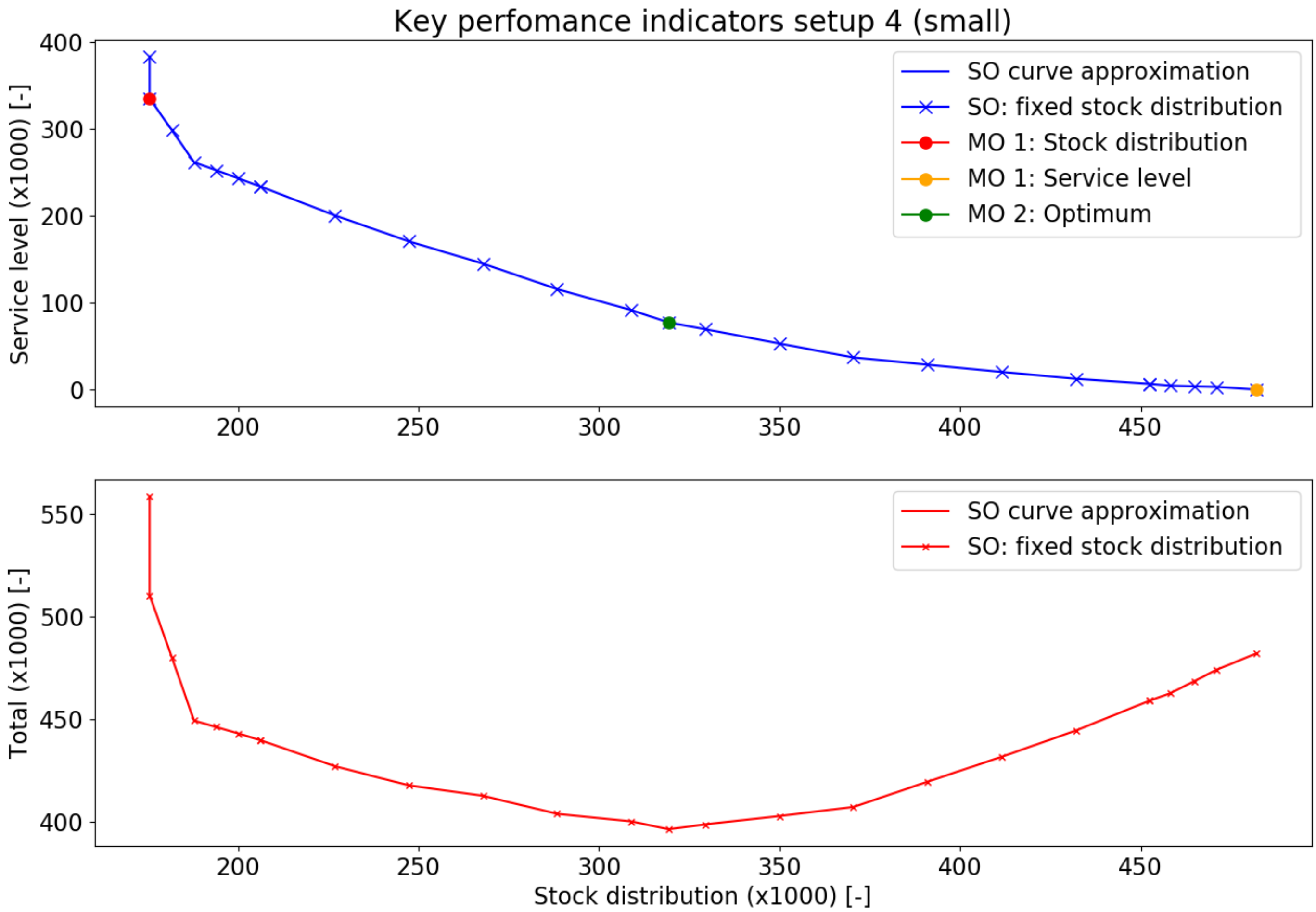

Figure F.4: Service level & Stock distribution KPI objective values - setup 4

F.1.5 Solver gap

	Setup 1	Setup 2	Setup 3	Setup 4
SO	0.0000 / 0.00	0.0000 / 0.00	0.0021 / 0.00	0.0019 / 0.00
MO Ia	0	0	0	0
MO Ib	0	0	0	0
MO II	0	0	0	0
Total	0.0000 / 0.0000	0.0000 / 0.0000	0.0019 / 0.0000	0.0017 / 0.0000

Table F.15: Solver gap small

F.1.6 Solver time

	Setup 1	Setup 2	Setup 3	Setup 4
SO	0.31 / 0.03	0.52 / 0.23	0.81 / 1.59	2.20 / 30.17
MO Ia	0.29	0.54	0.53	29.16
MO Ib	0.19	0.24	0.21	0.21
MO II	0.3	0.27	0.47	0.64
Total	0.30 / 0.03	0.51 / 0.21	0.77 / 1.46	2.91 / 49.10

Table F.16: solver time small

F.2 Medium results

F.2.1 Objective and flow results: Setup 1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	6.30
Product: 2	0	0	0	0	13.95
Product: 3	0	0	8.42	1	29.73
Product: 4	0	0	0	0	10.46
Product: 5	0	0	3.23	1	16.55
Product: 6	0	0	0	0	9.84
Product: 7	0	0	0	0	13.16

Table F.17: Flow values- datasetsize:medium, method: MO 1 (stock distribution), setup:1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	7.17
Product: 2	0	0	0	0	14.11
Product: 3	0	0	0	0	29.17
Product: 4	0	0	0	0	6.95
Product: 5	0	0	0	0	15.55
Product: 6	0	0	0	0	13.75
Product: 7	0	0	0	0	13.31

Table F.18: Flow values- datasetsize:medium, method: MO 1 (service level), setup:1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	6.38
Product: 2	0	0	0	0	14.12
Product: 3	0	0.07	0	0	28.49
Product: 4	0	0	0	0	10.59
Product: 5	0	0	0	0	13.34
Product: 6	0	0	0	0	13.76
Product: 7	0	0	0	0	13.32

Table F.19: Flow values- datasetsize:medium, method: MO 2, setup:1

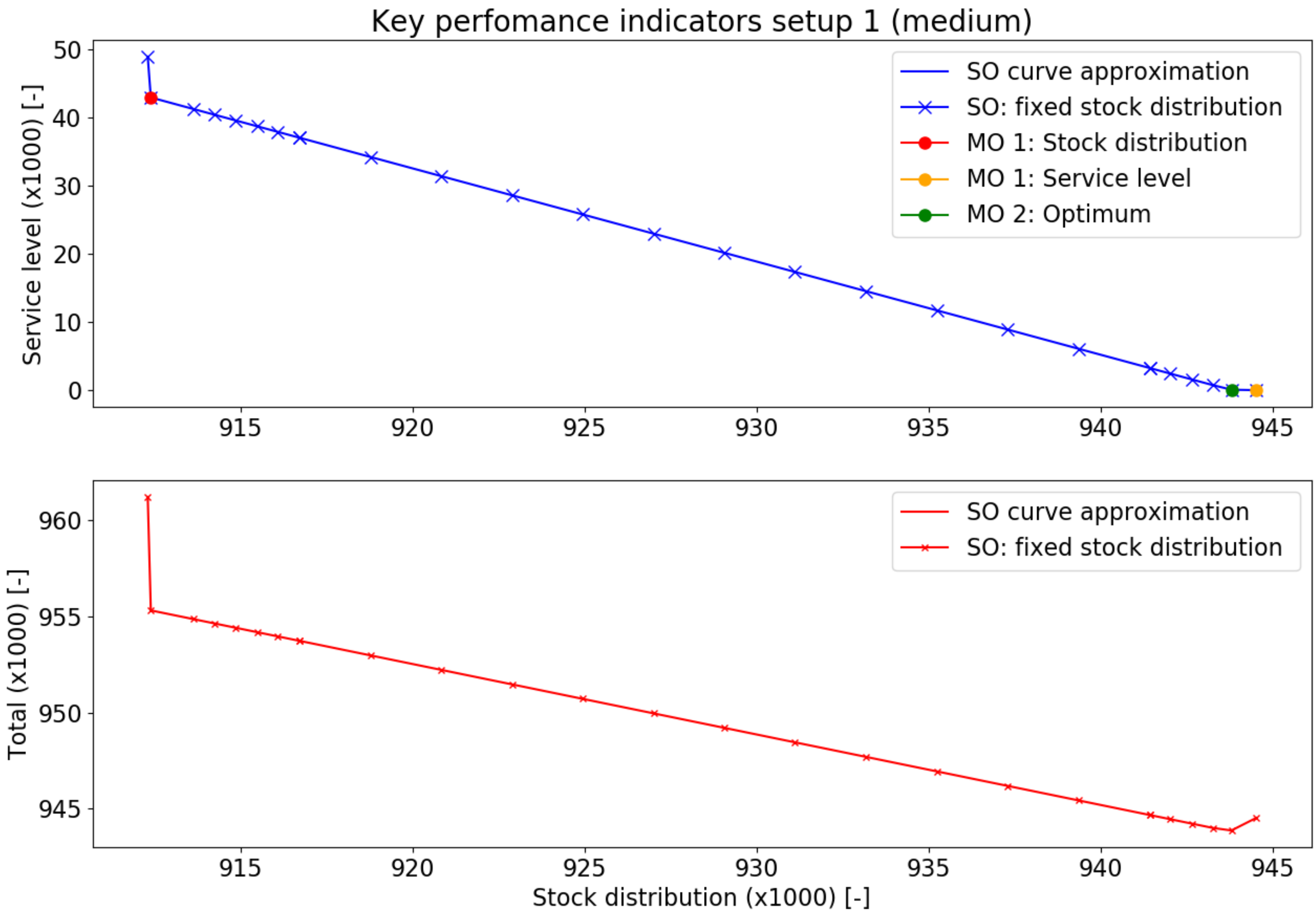

Figure F.5: Service level & Stock distribution KPI objective values - setup 1

F.2.2 Objective and flow results: Setup 2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	6.99
Product: 2	0	0	0	0	16.70
Product: 3	0	0	1.63	3	14.18
Product: 4	0	0	1.77	1	7.90
Product: 5	0	0	9.88	1	28.70
Product: 6	0	0	0	0	10.92
Product: 7	0	0	0	0	14.60

Table F.20: Flow values- datasetsize:medium, method: MO 1 (stock distribution), setup:2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	7.94
Product: 2	0	0	0	0	15.63
Product: 3	0	0	0	0	31.51
Product: 4	0	0	0	0	7.70
Product: 5	0	0	0	0	17.22
Product: 6	0	0	0	0	5.25
Product: 7	0	0	0	0	14.74

Table F.21: Flow values- datasetsize:medium, method: MO 1 (service level), setup:2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	7.97
Product: 2	0	0	0	0	15.68
Product: 3	0	0.26	0	0	23.68
Product: 4	0	0	0	0	7.72
Product: 5	0	0.13	0	0	14.87
Product: 6	0	0	0	0	15.28
Product: 7	0	0	0	0	14.79

Table F.22: Flow values- datasetsize:medium, method: MO 2, setup:2

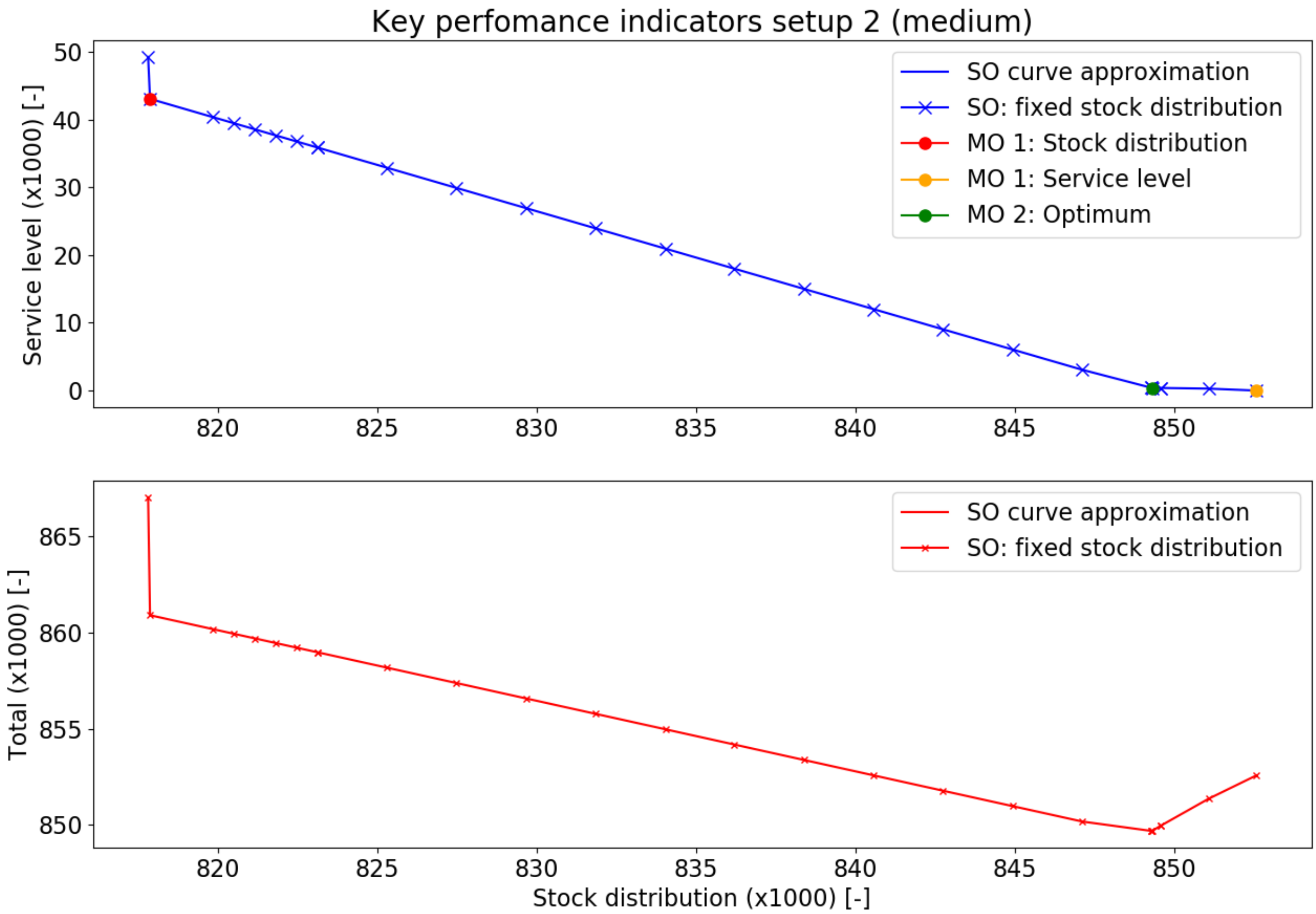

Figure F.6: Service level & Stock distribution KPI objective values - setup 2

F.2.3 Objective and flow results: Setup 3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	8.87	4.37	2	6.03
Product: 2	96.57	4.55	6.86	5	13.73
Product: 3	98.37	16.64	21.73	7	26.11
Product: 4	92.65	47.87	29.86	5	7.52
Product: 5	91.17	35.34	27.89	7	22.34
Product: 6	86.14	34.65	20.65	4	10.90
Product: 7	85.68	14.32	43.15	8	13.36

Table F.23: Flow values- datasetsize:medium, method: MO 1 (stock distribution), setup:3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	6.15
Product: 2	0	0	0	0	13.05
Product: 3	0	0	0	0	25.02
Product: 4	0	0	0	0	9.08
Product: 5	0	0	0	0	23.50
Product: 6	0	0	0	0	11.79
Product: 7	0	0	0	0	11.41

Table F.24: Flow values- datasetsize:medium, method: MO 1 (service level), setup:3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	8.87	0	0	6.58
Product: 2	98.88	4.55	0	0	14.78
Product: 3	96.73	18.82	2.13	2	25.92
Product: 4	91.00	47.87	7.35	2	7.28
Product: 5	98.23	35.34	1.14	1	22.29
Product: 6	82.67	41.58	6.79	2	10.65
Product: 7	92.84	14.32	0	0	12.50

Table F.25: Flow values- datasetsize:medium, method: MO 2, setup:3

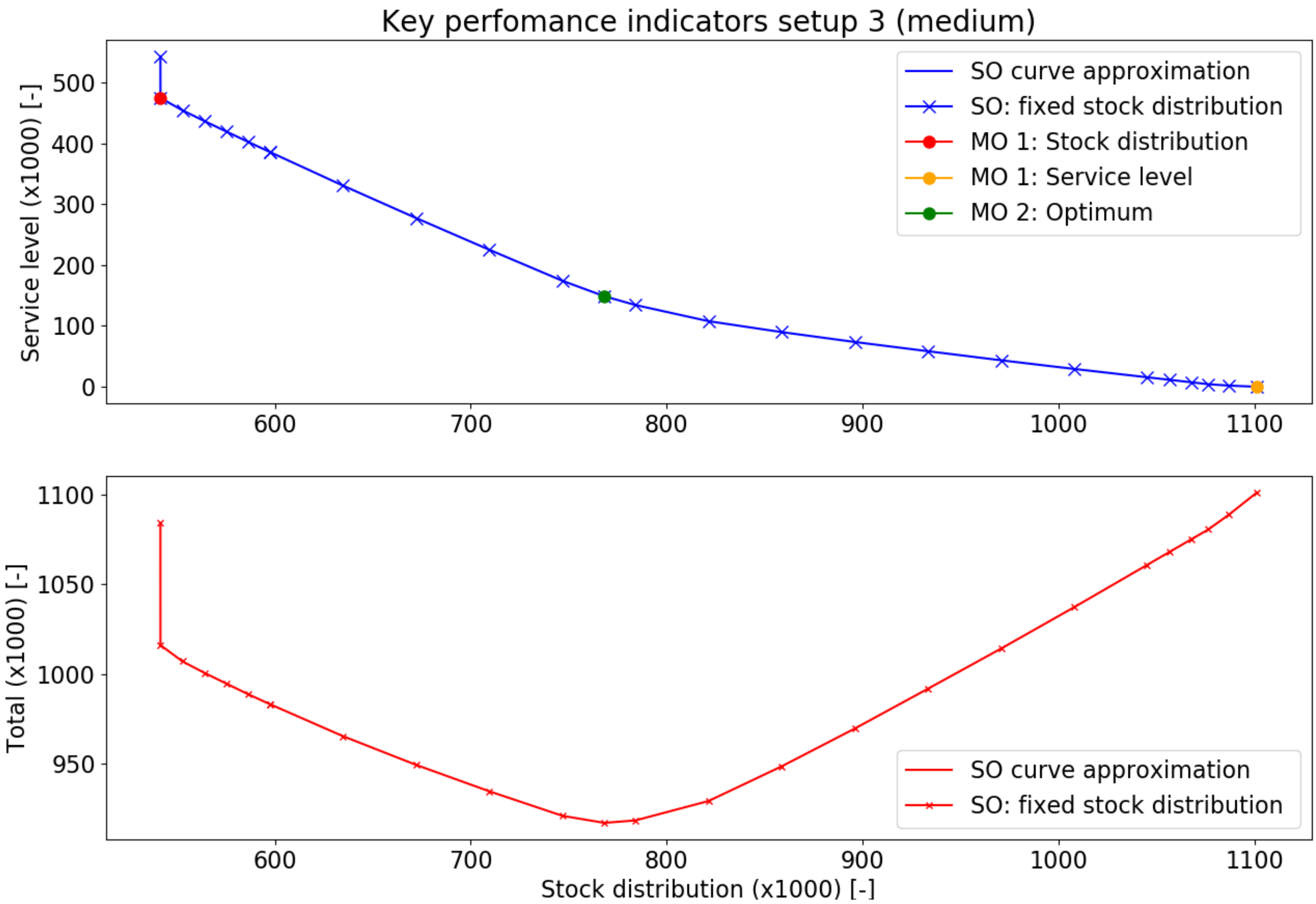

Figure F.7: Service level & Stock distribution KPI objective values - setup 3

F.2.4 Objective and flow results: Setup 4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	91.13	8.87	4	7.24
Product: 2	95.45	67.99	28.58	6	15.29
Product: 3	95.10	37.60	36.53	7	20.81
Product: 4	88.15	43.37	52.13	5	8.00
Product: 5	92.93	73.90	18.68	5	24.29
Product: 6	96.53	48.33	47.86	6	11.11
Product: 7	78.52	10.74	82.10	8	13.27

Table F.26: Flow values- datasetsize:medium, method: MO 1 (stock distribution), setup:4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	7.17
Product: 2	0	0	0	0	14.11
Product: 3	0	0	0	0	29.17
Product: 4	0	0	0	0	6.95
Product: 5	0	0	0	0	15.55
Product: 6	0	0	0	0	13.75
Product: 7	0	0	0	0	13.31

Table F.27: Flow values- datasetsize:medium, method: MO 1 (service level), setup:4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	8.87	0	0	7.96
Product: 2	96.57	4.55	0	0	17.86
Product: 3	99.14	22.09	2.13	2	13.69
Product: 4	86.49	47.87	7.35	2	8.79
Product: 5	93.56	35.34	4.01	1	26.69
Product: 6	93.07	32.71	6.79	2	9.91
Product: 7	96.42	14.32	0	0	15.10

Table F.28: Flow values- datasetsize:medium, method: MO 2, setup:4

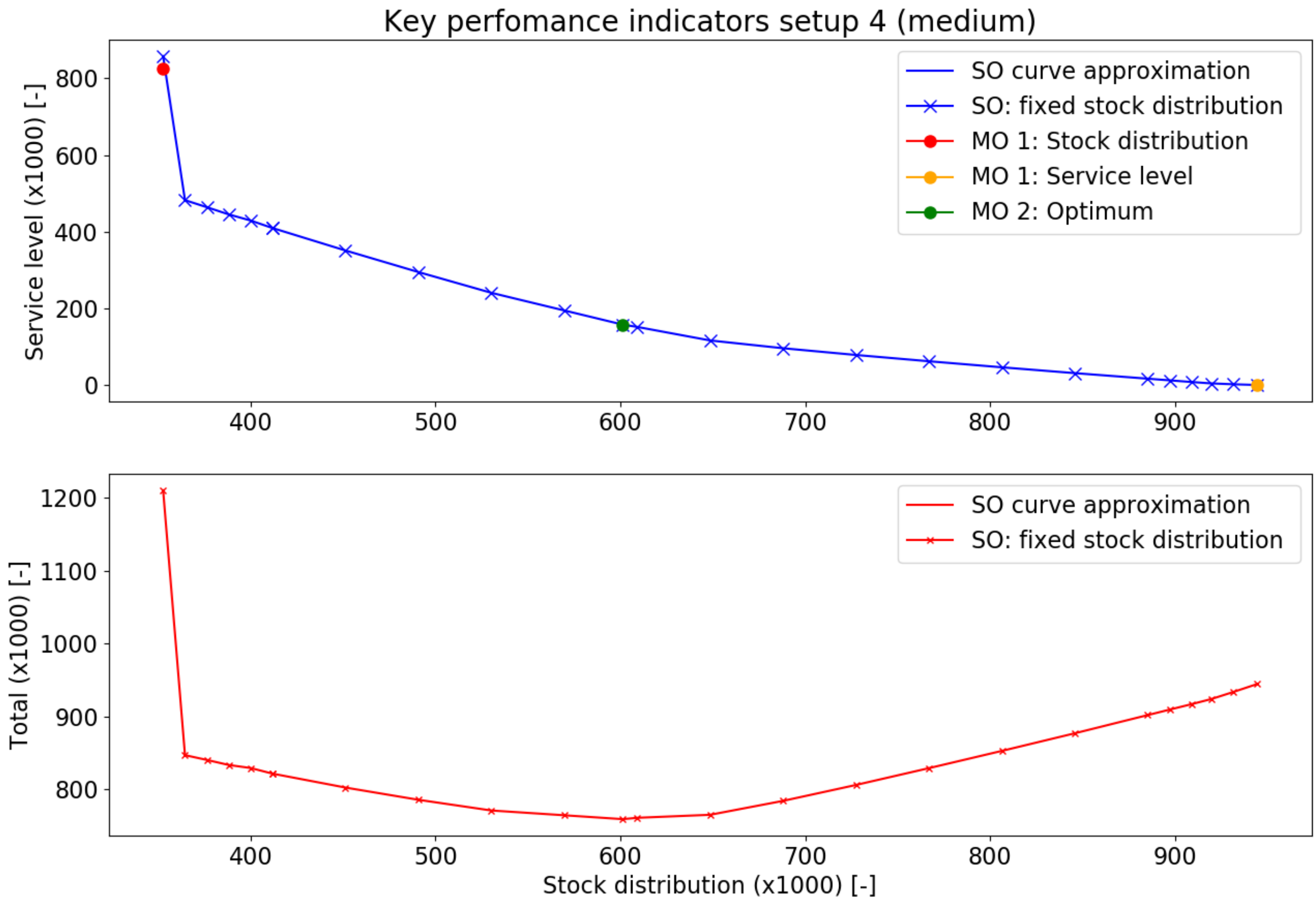

Figure F.8: Service level & Stock distribution KPI objective values - setup 4

F.2.5 Solver gap

	Setup 1	Setup 2	Setup 3	Setup 4
SO	0.0000 / 0.00	0.0000 / 0.00	0.0021 / 0.00	0.5370 / 1.47
MO Ia	0	0	0	0
MO Ib	0	0	0	2.3331
MO II	0	0	0	3.7288
Total	0.0000 / 0.0000	0.0000 / 0.0000	0.0019 / 0.0000	0.6905 / 1.7632

Table F.29: Solver gap medium

F.2.6 Solver time

	Setup 1	Setup 2	Setup 3	Setup 4
SO	0.57 / 0.01	1.77 / 1.00	22.88 / 11916.87	60.47 / 28331.34
MO Ia	0.46	2.26	6.12	0.37
MO Ib	0.46	0.56	0.39	2.06
MO II	0.76	3.12	1.26	600.29
Total	0.57 / 0.01	1.79 / 1.02	20.97 / 10835.28	88.08 / 41121.49

Table F.30: Solver time medium

F.3 Large results

F.3.1 Objective and flow results: Setup 1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	3.44
Product: 2	0	10.54	0	0	14.66
Product: 3	0	0	0	0	10.48
Product: 4	0	0	7.74	7	12.60
Product: 5	0	11.72	9.78	7	13.74
Product: 6	0	0	0	0	12.02
Product: 7	0	56.99	0	0	8.68
Product: 8	0	9.34	3.42	6	5.28
Product: 9	0	0	0	0	9.68
Product: 10	0	0	0	0	9.43

Table F.31: Flow values- datasetsize:large, method: MO 1 (stock distribution), setup:1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	3.79
Product: 2	0	10.54	0	0	11.87
Product: 3	0	0	0	0	10.29
Product: 4	0	0	7.74	7	9.35
Product: 5	0	11.72	9.73	2	15.88
Product: 6	0	0	0	0	15.35
Product: 7	0	56.99	0	0	8.51
Product: 8	0	12.75	0	0	6.21
Product: 9	0	0	0	0	9.50
Product: 10	0	0	0	0	9.25

Table F.32: Flow values- datasetsize:large, method: MO 1 (service level), setup:1

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	3.87
Product: 2	0	10.54	0	0	9.55
Product: 3	0	0	0	0	10.49
Product: 4	0	0.07	7.74	7	12.59
Product: 5	0	11.72	9.73	7	16.21
Product: 6	0	0	0	0	13.61
Product: 7	0	56.99	0	0	8.68
Product: 8	0	12.75	0	0	6.33
Product: 9	0	0	0	0	9.69
Product: 10	0	0	0	0	9.00

Table F.33: Flow values- datasetsize:large, method: MO 2, setup:1

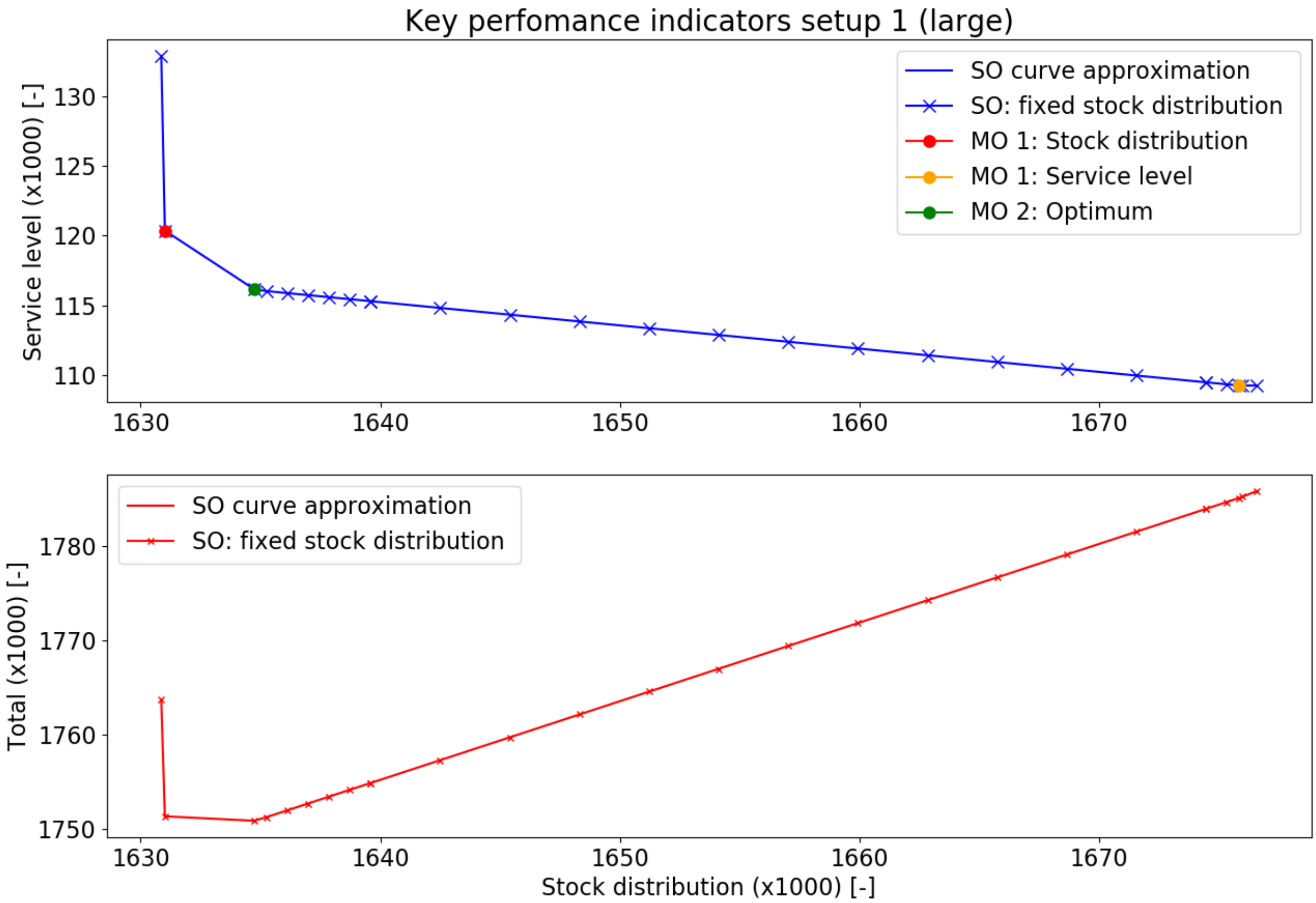

Figure F.9: Service level & Stock distribution KPI objective values - setup 1

F.3.2 Objective and flow results: Setup 2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	3.72
Product: 2	0	10.54	0	0	13.11
Product: 3	0	0	0	0	15.57
Product: 4	0	0.06	7.79	7	7.38
Product: 5	0	11.72	9.73	7	14.88
Product: 6	0	0	0	0	9.97
Product: 7	0	56.99	0	0	9.40
Product: 8	0	9.31	3.44	6	5.72
Product: 9	0	0	0	0	10.49
Product: 10	0	0	0	0	9.75

Table F.34: Flow values- datasetsize:large, method: MO 1 (stock distribution), setup:2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	3.65
Product: 2	0	10.54	0	0	10.13
Product: 3	0	0	0	0	16.70
Product: 4	0	0	7.74	3	8.02
Product: 5	0	11.72	9.73	2	11.52
Product: 6	0	0	0	0	14.92
Product: 7	0	56.99	0	0	9.21
Product: 8	0	12.75	0	0	5.57
Product: 9	0	0	0	0	10.28
Product: 10	0	0	0	0	10.00

Table F.35: Flow values- datasetsize:large, method: MO 1 (service level), setup:2

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	4.19
Product: 2	0	10.54	0	0	15.24
Product: 3	0	0	0	0	11.79
Product: 4	0	0.07	7.74	7	8.67
Product: 5	0	11.72	9.73	7	14.88
Product: 6	0	0	0	0	9.88
Product: 7	0	56.99	0	0	9.40
Product: 8	0	12.84	0	0	5.70
Product: 9	0	0	0	0	10.49
Product: 10	0	0	0	0	9.75

Table F.36: Flow values- datasetsize:large, method: MO 2, setup:2

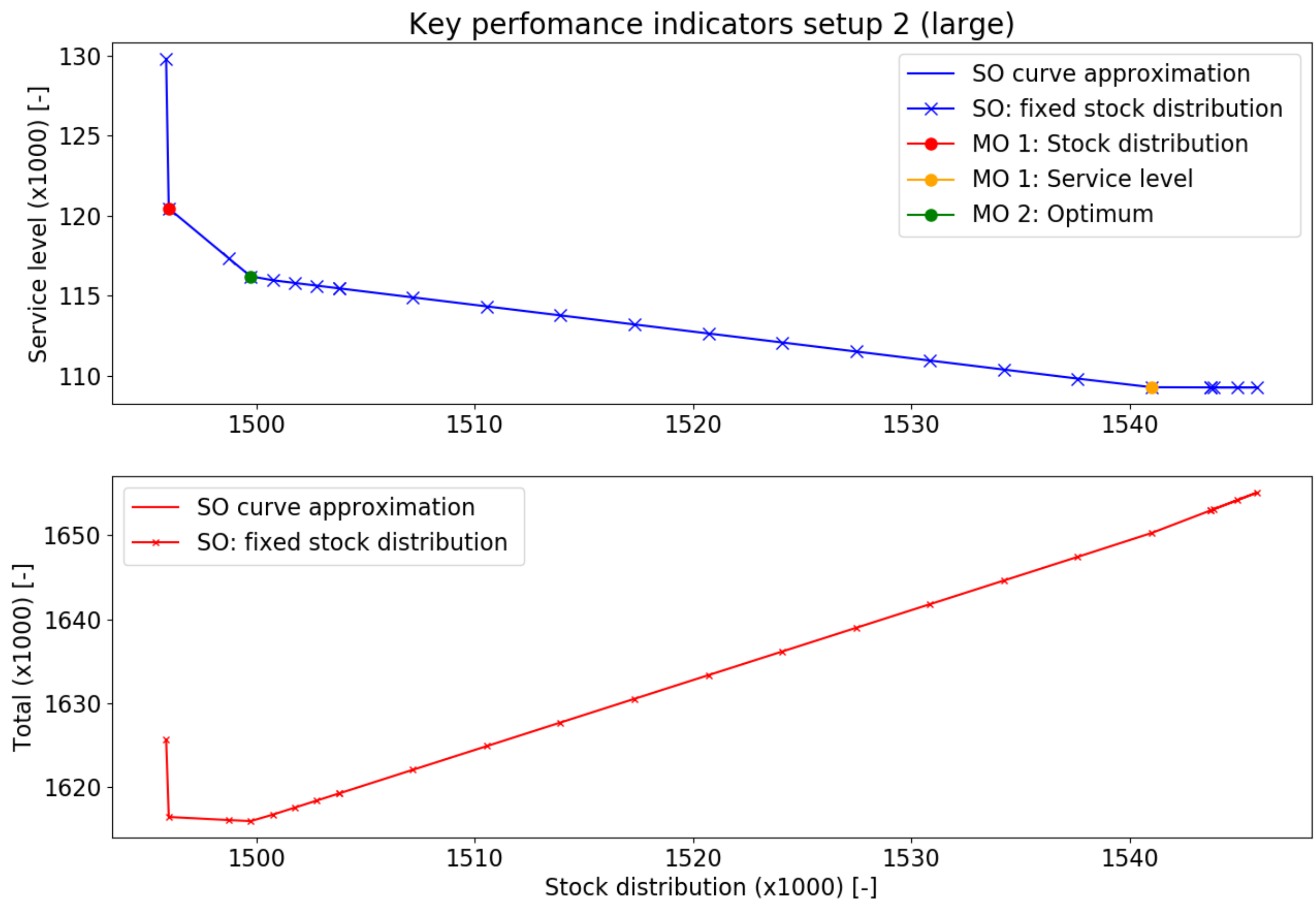

Figure F.10: Service level & Stock distribution KPI objective values - setup 2

F.3.3 Objective and flow results: Setup 3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	8.87	0	0	3.28
Product: 2	93.45	32.38	17.23	7	12.81
Product: 3	95.10	11.74	26.63	7	15.20
Product: 4	91.48	54.43	24.42	5	9.84
Product: 5	92.93	33.57	26.13	7	12.37
Product: 6	95.23	13.44	15.00	3	14.44
Product: 7	92.84	39.09	43.10	8	8.00
Product: 8	0	22.12	11.44	5	5.28
Product: 9	0	0	0	0	9.21
Product: 10	97.27	1.80	21.81	8	9.58

Table F.37: Flow values- datasetsize:large, method: MO 1 (stock distribution), setup:3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	5.85	0	0	3.29
Product: 2	0	8.63	0	0	13.46
Product: 3	0	0.86	0	0	14.48
Product: 4	0	16.25	3.48	2	10.00
Product: 5	0	11.72	6.20	6	14.33
Product: 6	98.36	8.49	0	0	14.73
Product: 7	96.42	7.16	9.69	3	6.47
Product: 8	0	8.48	0	0	5.61
Product: 9	0	0	0	0	9.11
Product: 10	0	1.80	0	0	8.52

Table F.38: Flow values- datasetsize:large, method: MO 1 (service level), setup:3

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	91.13	8.87	0	0	3.60
Product: 2	0	24.57	1.21	1	13.20
Product: 3	0	19.80	1.63	1	14.36
Product: 4	97.87	41.81	7.38	2	9.14
Product: 5	92.93	41.76	7.34	7	13.03
Product: 6	94.52	16.68	3.22	2	14.72
Product: 7	96.42	7.16	9.69	6	7.22
Product: 8	0	22.06	0	0	5.48
Product: 9	0	5.31	0	0	9.78
Product: 10	98.20	1.80	0	0	9.48

Table F.39: Flow values- datasetsize:large, method: MO 2, setup:3

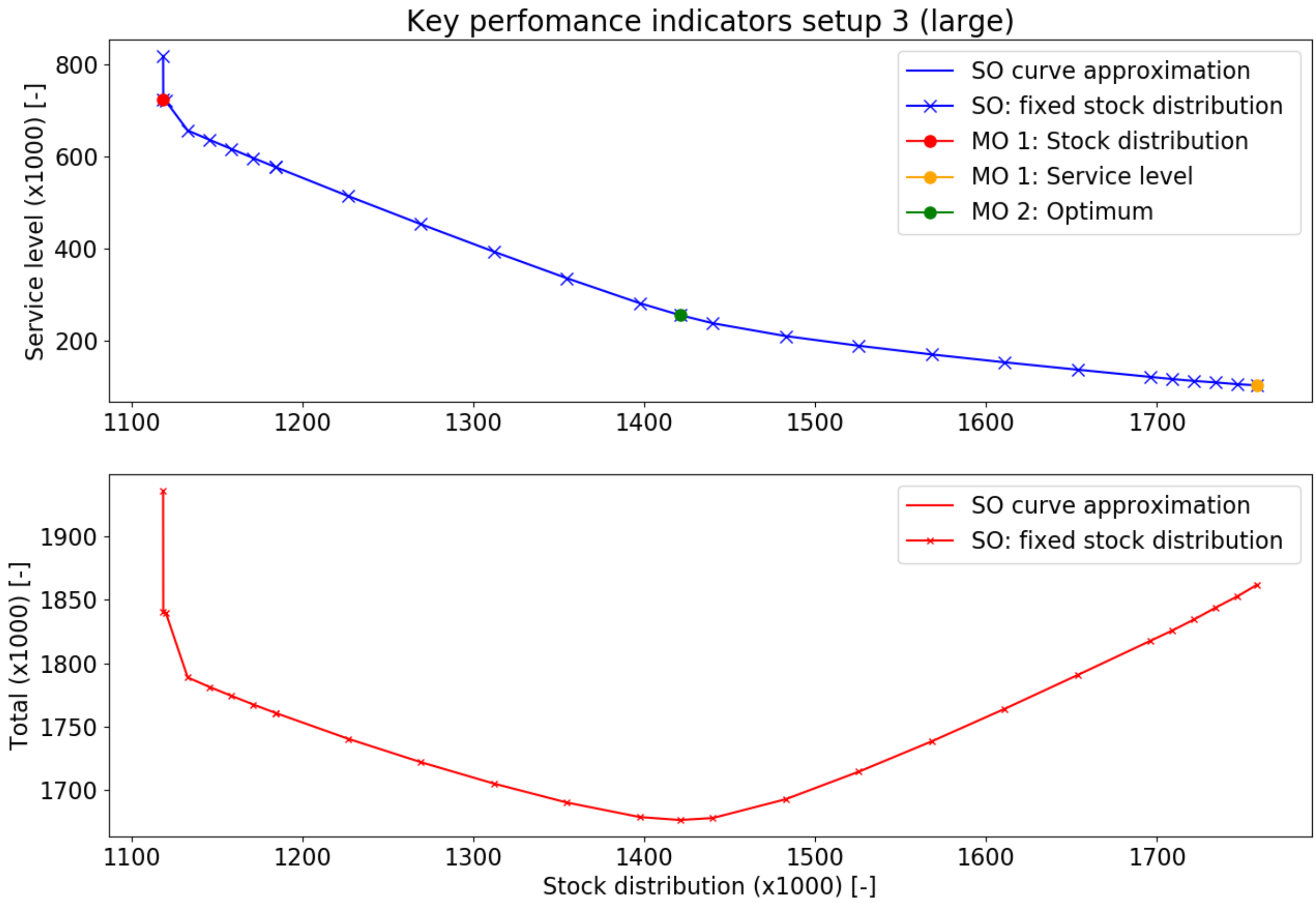

Figure F.11: Service level & Stock distribution KPI objective values - setup 3

F.3.4 Objective and flow results: Setup 4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	76.42	5.85	76.42	4	4.21
Product: 2	95.52	33.04	45.99	6	14.72
Product: 3	99.14	10.10	20.10	7	15.42
Product: 4	95.74	31.16	18.02	5	5.36
Product: 5	94.70	31.26	26.75	7	10.72
Product: 6	97.01	15.08	21.56	6	15.44
Product: 7	96.42	39.09	50.17	8	8.23
Product: 8	94.96	22.12	11.44	5	5.45
Product: 9	0	2.65	32.55	7	10.56
Product: 10	97.27	1.80	21.79	8	9.89

Table F.40: Flow values- datasetsize:large, method: MO 1 (stock distribution), setup:4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	0	0	0	3.99
Product: 2	0	8.63	0	0	11.53
Product: 3	0	0	0	0	11.86
Product: 4	0	2.13	3.48	2	12.20
Product: 5	96.47	11.72	6.20	4	12.36
Product: 6	0	0	0	0	16.17
Product: 7	0	7.16	9.69	2	7.09
Product: 8	0	8.48	0	0	5.05
Product: 9	0	0	0	0	10.01
Product: 10	0	0	0	0	9.74

Table F.41: Flow values- datasetsize:large, method: MO 1 (service level), setup:4

	Decentralized [%]	Early [%]	Late [%]	Max lateness [days]	Objective [%]
Product: 1	0	8.87	0	0	4.18
Product: 2	95.03	27.00	1.21	1	15.09
Product: 3	96.73	22.59	0	0	7.69
Product: 4	0	37.55	7.38	2	10.01
Product: 5	0	31.81	18.39	7	15.11
Product: 6	93.87	21.17	3.22	2	10.82
Product: 7	96.42	7.16	9.69	6	8.45
Product: 8	0	22.06	0	0	6.34
Product: 9	97.35	5.31	0	0	11.34
Product: 10	0	1.80	0	0	10.98

Table F.42: Flow values- datasetsize:large, method: MO 2, setup:4

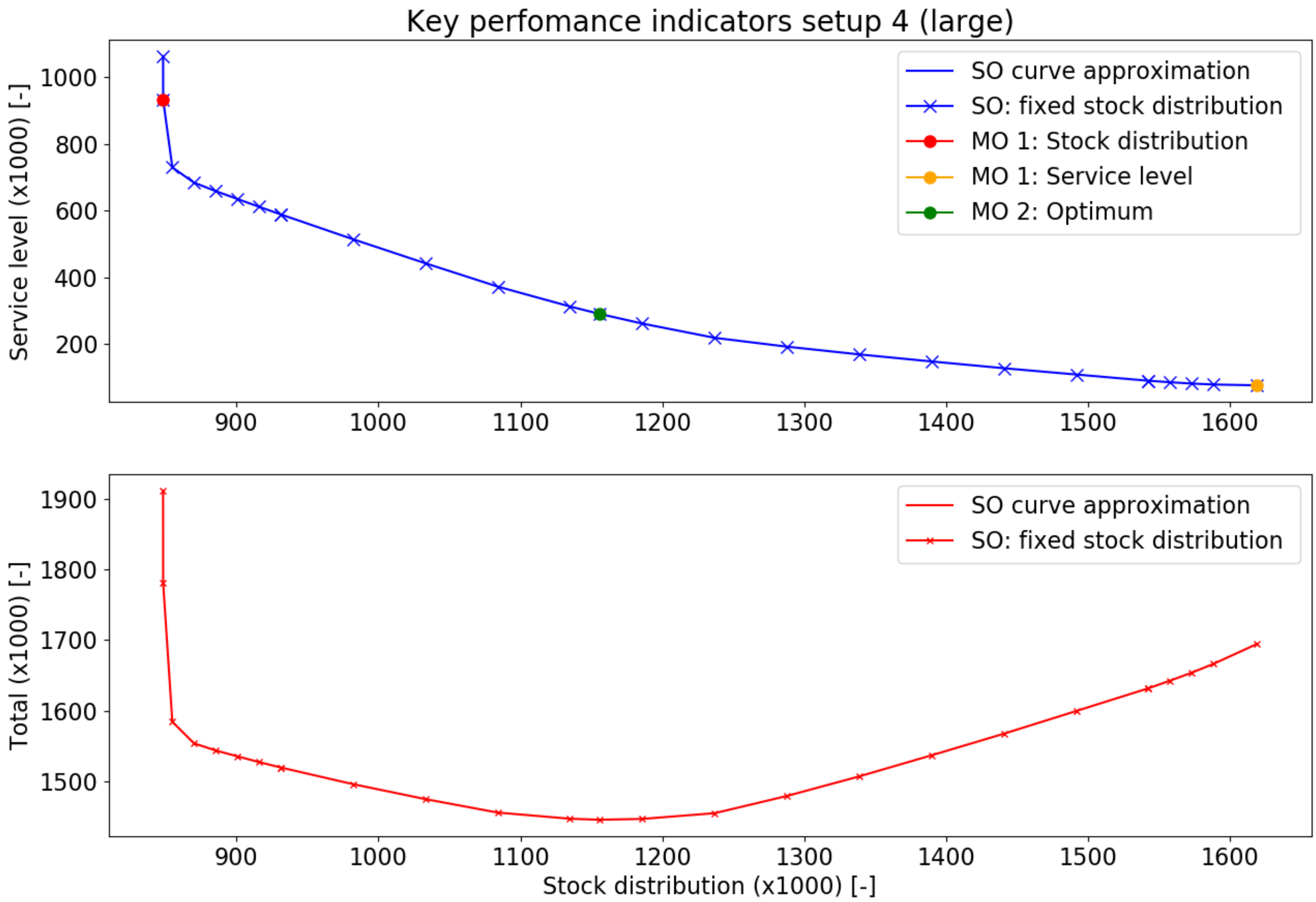

Figure F.12: Service level & Stock distribution KPI objective values - setup 4

F.3.5 Solver gap

	Setup 1	Setup 2	Setup 3	Setup 4
SO	0.0000 / 0.00	0.0050 / 0.00	0.0015 / 0.00	0.0024 / 0.00
MO Ia	0	0	0	0
MO Ib	0	0	0	0
MO II	0	0.0068	0	0.0022
Total	0.0000 / 0.0000	0.0047 / 0.0000	0.0013 / 0.0000	0.0022 / 0.0000

Table F.43: Solver gap large

F.3.6 Solver time

	Setup 1	Setup 2	Setup 3	Setup 4
SO	1.48 / 0.02	3.44 / 7.65	8.97 / 50.72	30.95 / 4018.78
MO Ia	3.56	15.53	16.97	600.26
MO Ib	1.83	9.04	4.36	11.45
MO II	1.74	5.09	4.52	13.33
Total	1.56 / 0.13	4.02 / 11.95	8.93 / 49.17	47.07 / 13228.88

Table F.44: Solver time large