MASTER

Design of a Distribution Network in a Disruptive and Dynamic Environment

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Design of a Distribution Network in a Disruptive and Dynamic Environment

Master thesis

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Preface

This Master Thesis Project is the final step in completing my Master's Degree in Operations Management and Logistics at the Eindhoven University of Technology. The project was conducted at the Netherlands Defense Academy for the Department of Defence and was supervised by dr. R.A.C.M. Broekmeulen and dr. C. Fecarotti from the Eindhoven University of Technology and Prof. dr. P.C. van Fenema and Lkol. A.C.M. van Kampen from the Netherlands Defense Academy.

First of all, I would like to thank my first supervisor dr. R.A.C.M. Broekmeulen. When I first mentioned my interest in the military, you were immediately enthusiastic and came up with the idea of looking for a graduation project there. That reaction was greatly appreciated because it is not obvious to carry out a project at the Department of Defence. Throughout the project, I highly appreciated your suggestions and feedback which helped me enormously. Your experience and interest in the subject have brought the research to a higher level. Furthermore, I would like to thank my second supervisor, dr. C. Fecarotti. Her feedback and critical view helped to improve the quality of the research.

Secondly, I would like to thank my supervisors from the Netherlands Defense Academy, Prof. dr. P.C. van Fenema and Lkol. A.C.M. van Kampen for giving me the opportunity to perform my research there. Your feedback, support, and the amount of useful information shared are greatly appreciated. The insights into the organization will hopefully help me in my future (military) career.

Finally, I want to thank my family and friends for their unconditional support during the project. I appreciate the great time I had in Eindhoven, with and thanks to you.

Patrick Ypma,
Eindhoven, May 2022

Abstract

More warfare in urban areas is forcing the Department of Defence to investigate a resilient distribution network to supply soldiers in urban operations. The currently used physical distribution concept is suitable for operations in dispersed areas with low disruptions, however, these characteristics differ in urban operations. In urban operations, the distribution network should be viable to function well in a disruptive and dynamic environment. The adversary could namely disrupt facilities or links between facilities. Moreover, dynamic characteristics such as extreme demand fluctuations, stochastic lead-times, and changing customer locations could affect the design of the distribution network structure. This study examines different distribution network structures to find out what the design of a resilient distribution network should look like in urban operations. The way the maneuver operates and the logistics supply the maneuver are examined by conducting semi-structured in-depth interviews. With the information retrieved from the interviews, the literature study, and corporate documents, a simulation model was designed to acquire an in-depth understanding of the impact of different distribution network structures in urban operations. A full factorial experiment was designed and revealed that the reactive multiple resourcing structure, in which an additional intermediate node may supply to a customer not of its own, if its own customers have no orders, performed best. However, due to the assumptions made, it is suggested that the Department of Defence further investigates distribution networks for urban operations.

Management summary

This research is conducted at the Netherlands Defense Academy (NLDA) for the Department of Defence (DOD). This management summary provides an overview of the most important research outcomes.

Introduction

A trend in warfare is that more wars will take place in urban areas. The traditional method that has been used to fight the enemy in urban areas has been that of massive destruction (heavy bombing). An undesired consequence of these bombings is economic disruptions and usually many civilian casualties. This should be prevented and to do so, armies could siege a city. When sieging a city, all buildings should be cleared from adversaries. However, this method uses many soldiers in the city who should have supplies at any time. Therefore, a resilient distribution network should be used to supply soldiers. The distribution network has to deal with an adversary which can disrupt the network, extreme fluctuations in demand, stochastic lead-times, and changing customer locations. Therefore, the distribution network should be viable to function well in a disruptive and dynamic environment. However, it is unclear whether the currently used physical distribution structure of the Royal Netherlands Army (RNLA) is suitable for urban operations. Therefore, the following main research question was formulated:

What should the design of a resilient distribution network in urban operations look like?

This research only focuses on ammunition supplies.

Research design

To retrieve more information regarding distribution networks in disruptive and dynamic environments, a literature study was performed. Additionally, to retrieve more information regarding urban operations, three semi-structured interviews with experts in maneuver and logistics of the RNLA were held. The interviews were held to examine how the maneuver operates and how the logistics are organized to support the maneuver. It was discussed that supply reliability is extremely important since soldiers should have sufficient ammunition at any time. To have a high supply reliability, a reliable distribution network should be designed. With the use of the literature study and the information retrieved from the interviews, five distribution network structures were found suitable for urban operations. A discrete-event simulation model was designed which aimed to acquire an in-depth understanding of the

impact of different distribution network structures in urban operations. Since little to no data was available regarding urban operations, a full factorial experiment was designed to test different parameter values. These parameter values differed in city size, number of disruptions, number of vehicles, and demand consumption. Additionally, an extensive sensitivity analysis was performed to reflect on other parameters. The distribution network structures were evaluated based on the time it took to conquer the complete city and the time it took to supply the soldiers. These two key performance indicators were used to assess the network structures with the use of a data envelopment analysis. Moreover, indicators and network features such as the ready rate, number of nodes, number of edges, average lead-times, and number of rides were considered when evaluating the structures.

Results

Five different network structures were derived from literature and verified whether suitable for urban operations by the interviewees. A full factorial experiment on these five structures was performed on four demand levels, two vehicle levels, two disruption levels, and two different city size levels. It was found that the structure with an additional intermediate node, the structure that applied reactive multiple resourcing, and the lateral trans-shipment structure, scored relatively similar in all experiments. This was not the case for the current physical distribution structure and the pro-active multiple resourcing structure because they performed worse in most experiments. Additionally, it was found that more vehicles per additional intermediate node increased the performance. Besides, the number of disruptions negatively affected the performance of all network structures. Especially the current physical distribution structure and the pro-active multiple resourcing structure performed much worse with more disruptions. Furthermore, a larger city resulted in worse performance for all structures but especially for the physical distribution structure and pro-active multiple resourcing structure. Besides, the lateral transshipment structure performed in most experiments slightly worse than the structure without lateral trans-shipments. The reactive multiple resourcing structure performed best for all experiments except for the experiments with one vehicle per additional intermediate node and a small city.

Conclusion and recommendations

From the results of the full factorial experiment, it could be concluded that the structure with reactive multiple sourcing performed best. This structure allows an additional intermediate node to supply a customer which is not of its own if its own customers have no orders. This structure had in most experiments the lowest expected conquering time and expected exposed time per grid and thus likely the lowest costs and casualties. However, it is assumed that a lengthy operation increases the number of casualties and resources, this is not investigated. On top of that, the lead-times of this structure were in most experiments the lowest compared to the other structures. This is important as well since if soldiers in the front request supplies, they want those as soon as possible since their lives could depend on them.

Furthermore, it is recommended to the RNLA or NLDA to further investigate this topic. Assumptions made, can be relaxed to get a better model. For example, due to a lack of data and information, ammunition was considered a black box. No distinction was made between the many different types of ammunition. A further research direction could be to dive into these different types of ammunition. If these types are known, specific capacities of vehicles can be examined to see if it affects the results. Moreover, further research could be done on parameter values. The parameter values in this research were only validated by the supervisors, while a more data-driven value could be closer to reality. However, there should be data to come up with a data-driven value. It is therefore recommended that in urban operations exercises, the logistic should actively participate in cooperation with the maneuver. This might lead to more effective cooperation and information and data regarding urban operations.

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List of Abbreviations

AC	Replenishment Center (Aanvulcentrum in Dutch)
BL	Basic Load which is the amount of products a soldier or platoon could carry
DOD	Department of Defence
DEA	Data Envelopment Analysis
FIFO	First In First Out
FLSB	Forward Logistic Support Base
FMW	Faculty of Military Sciences (Faculteit Militaire Wetenschappen in Dutch)
IED	Improvised Explosive Device (bermbom in Dutch)
IOH	Inventory On Hand
IP	Inventory Position
KIM	Royal Navy Institute (Koninklijk Instituut voor de Marine in Dutch)
KMA	Royal Military Academy (Koninklijke Militaire Academie in Dutch)
KPI	Key Performance Indicator
NATO	North Atlantic Treaty Organization
NLDA	Netherlands Defense Academy (Nederlandse Defensie Academy in Dutch)
OTClog	Education and Training Command Logistics (Opleidings en Trainingscommando logistiek in Dutch)
OTCman	Education and Training Command maneuver (Opleidings en Trainingscommando maneuvre in Dutch)
RNLA	Royal Netherlands Army
RQ	Research question
TBT	Team battle train (Teamgevechtstrein in Dutch)
VC	Stock Center (Voorraadcentrum in Dutch)
WLS	Swap loading system (Wissellaadsysteem in Dutch, figures in Appendix A)

Chapter 1

Introduction

In this chapter, an introduction to the research is given. First, some background about the Royal Netherlands Army (RNLA), where this research is conducted, is given. Afterward, the problem is elaborated and the research questions are given. Thereafter, the scope and methodology are presented. Lastly, the outline for the rest of the report is given.

1.1 Royal Netherlands Army

This research is conducted at the Netherlands Defense Academy (NLDA) for the Department of Defence (DOD). The NLDA provides military training, personal training, and academic education for the DOD. The accredited scientific bachelor and master programs for (future) officers of the RNLA and the research underlying them are conducted by the Faculty of Military Sciences (FMW). The FMW is located at two locations: in Breda and Den Helder. The FMW positions itself as a scientific education and research institute that has its unique position compared to civilian universities and the defence organization. The FMW's uniqueness concerns its focus on military education and research and the multidisciplinary nature of its scholarship and its inter-dependence with the Royal Military Academy (KMA) and the Royal Navy Institute (KIM). Training and developing officers comes with great responsibilities. Since the NLDA trains future officers, it is important that the learning paths are future-proof and thus consider trends in warfare.

1.1.1 Supply chain

The research will be about the distribution network of the RNLA. Since the distribution network is part of the supply chain, some background about the RNLA's supply chain is given. The current supply chain of the RNLA is based on the Physical Distribution (FD) concept shown in Figure 1.1. The FD concept was implemented in 2005 and focuses on receiving, storing, and shipping all goods required by the units in the deployment area (Kablau, 2002). The responsibility of FD runs from the 'Point of Debarkation (POD) to the customers, which are in this case the combat units.

Figure 1.1 shows that the POD is the first link that belongs to the supply chain in the area of operations. PODs usually consist of a main location (a harbor for example) and one or

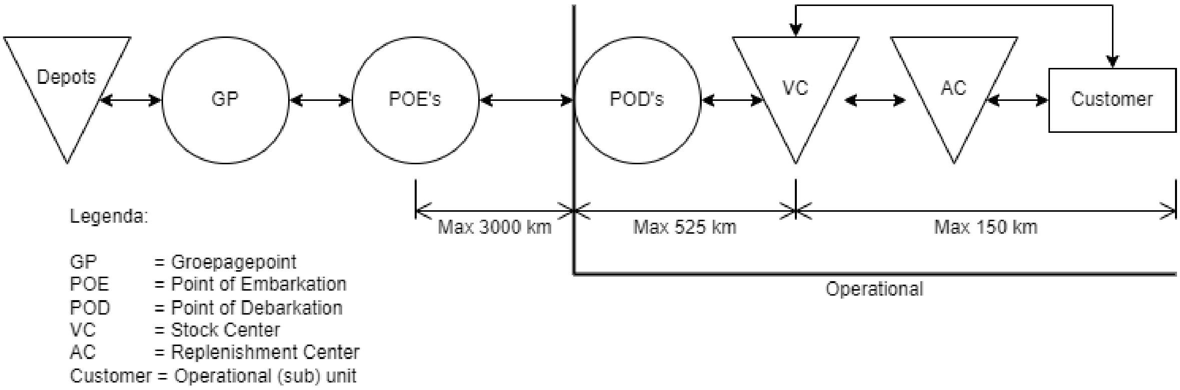


Figure 1.1: FD concept, retrieved from Kablau (2002)

more secondary locations (an airport or station for example) where goods and personnel are transferred. Moreover, there is usually a change of transportation mode at the POD. The next link is the VC, the VC is the main stock center. This is where customer orders arrive and where all goods come in. The VC is located well behind the line where hostilities (may) occur, up to a maximum of 150 kilometers from the customers. The storage capacity of a VC is over 20,000 tons in containers and flatracks and can therefore have a size of many square kilometers. VCs deliver to customers whether or not via a replenishment center (AC). ACs are temporary stock positions that are set up when it becomes clear that the requested delivery time formulated by the customers can no longer be met. The main tasks of an AC are delivering the pushed forward stocks to the customers promptly, coordinating all customer's needs for supplies, coordinating all deliveries to its customers, and acting as the central point of contact. The last link is the customer which is the combat units. Each combat unit has in principle only its Basic Load (BL) at its disposal, which is the stock that is located in or on the system (e.g. tank or vehicle). As soon as the combat unit's BL requires replenishment, an order is made. The combat unit determines the delivery conditions such as the time and location of the delivery 24 hours in advance. When an order is delivered, directly from the VC or via an AC, the combat unit is leading the transfer, whereby various methods of delivery are possible. The combat unit comes to a so-called distribution point where the BL is filled. The FD unit provides loading and unloading equipment. For the transportation of goods flatracks and swap loading systems (WLS) are used from VC to the customer (combat units). Figures A.1 and A.2 in Appendix A illustrate what these systems look like.

The best part of the FD concept is that with it the RNLA can carry out all its operational tasks (Kablau, 2002). For the transport of large quantities of goods to areas far from the Netherlands, the container is the main loading unit used by civilian carriers. For the handling of this containerized flow to the area of operations, suitable load carriers and handling equipment are used. The FD concept is therefore preeminent useful in a dispersed and dynamic environment. Moreover, the demand is coordinated and due to the centralization of scarce resources, an effective and, if needed, massive and robust deployment is possible.

A characteristic of the military supply chain is that it has to deal with enormous urgency after a disaster or conflict. Hence a focus on effectiveness ("at all costs") over efficiency (Shatzkin, 2017; Vermunt & Thoolen, 2004). The armed forces are a capability organization so they have to be able to do certain things which are not intended to be performed. The organization is primarily focused on effectiveness rather than efficiency (Molana, 2009). Supply success is, therefore, defined by the contribution to the overarching operation goal, not by the usual goal function: meeting demand at the lowest possible cost. A good example of this is transporting water by air, an activity almost unthinkable in a commercial supply chain. Efficiency in a military supply chain, according to Shatzkin (2017), is "an afterthought, and optimization is difficult if not undesired". Yet the available budget is increasingly a limiting factor but it is chosen not to take cost into account for this research.

1.2 Problem definition

In this section, the problem the RNLA is facing is described. The problem statement is given in Section 1.2.1. Then, the research question that corresponds with the discussed problem statement is defined in Section 1.2.2.

1.2.1 Problem statement

A trend in warfare is that more wars will take place in urban areas (Mosul Study Group, 2017). Moreover, it may be the preferred approach of future opponents (Joint Publication, 2013). The traditional method that has been used to fight the enemy in urban areas has been that of massive destruction (heavy bombing) (Joint Publication, 2013), look for examples at the wars in Mosul, Erbil, and more recently in Mariupol. An undesired consequence of these massive bombings is economic disruption and restoring it will take many years (Van Kampen, 2021-05-19). On top of that, a city contains usually many civilians, and these bombings have the side effect that they could result in many civilian casualties, which is something that should be prevented. In line with this, Glenn et al. (2003) stated that it is unlikely that World War II urban combat tactics precipitating the destruction of large swaths of urban terrain and mass civilian casualties will be the norm during future conflicts. This means that armies should change their tactical modus operandi and as a consequence should find a different way to organize their logistical support.

The FD concept assumes that the area of operations has a safe back area, which is not the case in urban operations. The FD concept is suitable for dispersed operations in which there are low disruptions, while in urban operations there are many disruptions as shown in Table 1.1. Furthermore, since in the current method the combat units have to move to a so-called distribution point, where the resupply takes place, the fighting power at the front diminishes temporarily which is undesired. In addition, the WLSs cannot be used in urban operations due to their size. It is, therefore, unknown whether the current supply concept and assets are suitable to replenish combat units in urban operations.

		dynamic environment	
		low	high
Disruptive environment	low		Dispersed operations
	high		Urban operations

Table 1.1: Operations and their environment

A different network design might be more suitable for urban operations. This leads to the following problem for the RNLA:

It is unclear to the RNLA what a resilient distribution network in urban operations to supply combat units should look like.

1.2.2 Research questions

From the problem statement, discussed in Section 1.2.1, can be concluded that it is unclear for the RNLA how to logistically support combat units in urban areas. The following research question (RQ) is, therefore, formulated:

What should the design of a resilient distribution network in urban operations look like?

To answer the main RQ, six sub-research questions are formulated. First of all, it is determined which resilient network structures could be used in urban operations. Literature is studied to find resilient network structures and with experts of the RNLA, it is reflected upon these network structures. The first RQ is, therefore, stated as follows:

RQ1: Which resilient distribution network structures are suitable to support urban operations?

To determine which network structure performs best, relevant Key Performance Indicators (KPIs) are identified. With the use of these KPIs, networks could be evaluated. The second RQ is, therefore, as follows:

RQ2: What are relevant Key Performance Indicators for a resilient distribution network?

The proposed research aimed to model distribution networks through simulation, which is the imitation of a real-world process or system over time. Dynamic problems can be modeled with the use of multi-stage stochastic programs. However, a major difficulty of the stochastic programming approach is dealing with the possibly infinite number of possible scenarios. A network design model is not of much use if it cannot be solved, which is often the case with infinite scenarios. In this research also many scenarios are possible such as differences in the size of the city, the strength of the opponent, and demand distributions. This means that adequate trade-offs must be made between model accuracy and solvability (Klibi & Martel, 2013). Therefore, only several representative plausible future scenarios could be considered. Based on experts of the RNLA, relevant scenarios will be chosen. This leads to the following RQ:

RQ3: What are relevant scenarios for conducting urban operations that should be modeled?

Based on these three sub-questions, a simulation model could be made which evaluates different network structures for different scenarios. After the simulation model is built it will be used to investigate what effect different scenarios or variables have on the KPIs of different structures. This leads to the following RQs:

RQ4: *What is the influence on the KPIs if links or nodes fail?*
RQ5: *What is the influence on the KPIs if demands fluctuate heavily?*
RQ6: *What is the influence of the capacity, reorder level, (re)location, and number of additional intermediate nodes on the KPIs?*

Answering these sub-questions will help to analyze and answer the main research question. The remainder of this thesis is used to answer these research questions.

1.3 Research scope

In this section, the scope of the project is indicated. The focus of the research is on the distribution network. When referring to the FD concept in Figure 1.1, the scope is from the VC to the customer, i.e. the combat units. Furthermore, operations in urban areas require a significant increase in ammunition expenditure, need for personnel replacements, medical personnel and supplies, casualty evacuation, and food and water (Joint Publication, 2013). Ammunition is most likely to be needed on short notice because if a combat unit is under attack, the ammunition level decreases rapidly. Ammunition consumption, therefore, fluctuates more than food or water for example. This research, therefore, only takes ammunition into account. Moreover, ammunition consists of multiple different types. However, since each combat unit could have its own ammunition types, which would make it extremely complex, only the ammunition level, which is denoted by the BL, is taken into account in this research.

1.4 Research methodology

The research model of Mitroff et al. (1974) is used as a guideline for the research project. Figure 1.2 shows a visual representation of this research model. The operational research approach consists of four phases: conceptualization, modeling, model solving, and implementation Bertrand & Fransoo (2002). The implementation phase is, however, outside the scope of this project and is, therefore, not conducted in this research.

In the conceptualization phase, the actual problem is explained by a conceptual model. To go from the reality, problem, situation to the conceptual model, first a literature study is performed. In this literature study, existing literature on resilient distribution networks and urban operations is reviewed. Afterward, interviews with experts that are involved with supply chains in urban operations are conducted. These interviews should gain insights into urban operations and should address the challenges encountered in supply chains in urban operations. These challenges are required to make a more realistic conceptual model. The literature review and the interviews together lead to a conceptual model. The next phase is the modeling phase, in which the conceptual model is translated into a computerized model. The computerized model will be a simulation model that needs to correspond with the actual situation. Validation with experts in supply chains in urban operations is, therefore, important. After defining the computerized model, the model solving phase can take place. The goal of this model is to find relations between variables and network structures. With these relations, solution indications regarding network structures can be given.

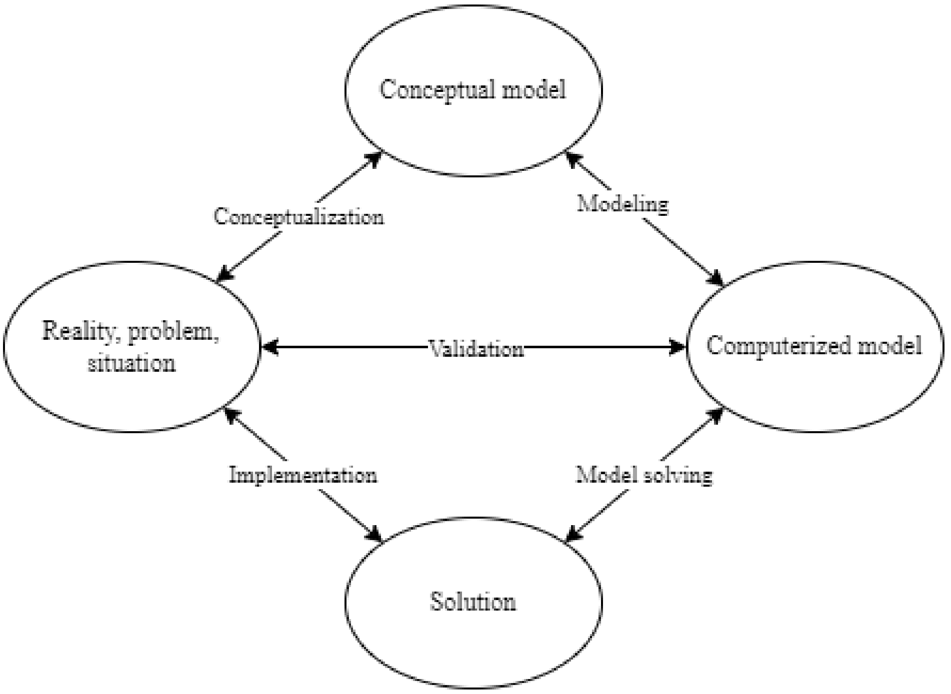


Figure 1.2: Research model adapted from Mitroff et al. (1974)

1.5 Outline of report

The remaining of this report is structured as follows, first, in Chapter 2 relevant literature regarding networks is reviewed. Thereafter, Chapter 3 contains the analysis of the problem in which the knowledge of experts is described. After the analysis, the problem is more identified in the diagnosis in Chapter 4. Findings of the literature review and diagnosis serve as input for the model which is discussed in Chapter 5. The conceptual model will be transformed into a simulation model which is explained in Chapter 6. Afterward, the results of the simulation model are discussed in Chapter 7. Finally, the paper ends with conclusions and recommendations presented in Chapter 8.

Chapter 2

Literature review

The distribution network in urban operations should be resistant to disruptions as there are adversaries in urban warfare areas. Moreover, as the siege continues, combat units are moving through the area, which means that the distribution network should deal with a dynamic environment. Another uncertainty is that in a short time, ammunition demand could be enormous if combat units are attacked. The distribution network in urban operations thus should be resistant to both a disruptive and dynamic environment.

2.1 Disruptive environment

The existing research on network design problems assumes that facilities in a network are always available to serve their customers. Carefully constructed plans from models with this assumption can be severely ruined if they fail to consider disruptions in the design phase and therefore lack countermeasures when disruptions do strike. The popularization of the "lean" concept, which allows minimum redundancy, exacerbated the problem because there tends to be very little inventory to "buffer" any disruptions. As a result, any disruption can have a dramatic impact on the entire logistics system (Blackhurst et al., 2005; Peng et al., 2011). Many potential threats can lead to facility or link disruptions, e.g., operational contingencies such as equipment failures, natural disasters, industrial accidents, power outages, labor strikes, and terrorism. The functionality of facilities and transportation links in networks can be affected by these disruption events, either partially or completely over an undefined time (Snyder et al., 2016). Although these disruption events may only lead to short-term facility contingencies, they can also cause not only serious operational consequences, such as higher transportation costs, order delays, inventory shortages, loss of market shares, and so on but also extended negative financial effects. An empirical study by Hendricks & Singhal (2005) has shown that between 1989 and 2000, the abnormal stock returns of firms that have been affected by disruptions were nearly 40%. Evidence has also shown that these firms had a hard time recovering from the negative effects of disruptions and that their equity risk increased significantly around the announcement date. Similar findings are described by Hicks (2002).

There are two groups of strategies that countermeasure disruption risks and obtain a resilient network: mitigation strategies and contingency strategies (Fattahi et al., 2017). Mitigation strategies are those in which a network takes some preventive actions in advance of a disruption and also pays their related costs regardless of whether a disruption occurs, while contingency strategies are those where a network takes several actions merely when a disruption happens intending to return the network to its original condition (Tomlin, 2006). The most popular mitigation strategies in the related literature are facility fortification, strategic stock, and sourcing strategy (Govindan et al., 2017). Firstly, the fortification strategy is implemented through efficient investments in fortifying key facilities in existing logistics systems. Secondly, in the strategic stock strategy, a network can hold emergency inventory for products in its facilities within different layers of the network. Thirdly, in the sourcing strategy, sourcing is carried out by using multiple facilities simultaneously before disruption occurrence. Contingency strategies are reactive to disruptions in a network. This implies that allocation decisions of customers to facilities can be modified after a disruption occurred such that the responsiveness of a network is maintained. The contingent-rerouting strategy is a strategy that modifies the allocation decisions of customers after a disruption. The literature stated that a combination of both mitigation and contingency strategies might be the appropriate tactic to manage disruptions.

To design a responsive network, most models defined some objective function or value creation outcomes that could be economically related, such as cost or profit, or could be related to the responsiveness of the network. Examples of network responsive objectives are minimizing lateness of products' delivery, minimizing customers' service time, and maximizing the fill rate of customers' demands. The studies of Peng et al. (2011) and Qi et al. (2010) argued that substantial improvements in responsiveness are often obtainable with minor increases in costs. The design of a distribution network requires solving two hard combinatorial optimization problems including determining the facilities' locations and vehicle routes to serve customers (Govindan et al., 2017). Regarding the facility location problem, Fattahi et al. (2017) stated that as the customers' sensitivity to the delivery lead-time of products increases, the facilities that supply these customers should be located closer to them, and hence, the design costs of the network increase. In terms of vehicle routes, there is a possibility to use single-sourcing, multiple-sourcing, lateral transshipments, or direct flows from upper layers. All in all, several decisions regarding the disruption risks, counter-measurements, objectives, and network structure should be made by decision-makers. These decisions could, however, be quite different because decision-makers could have different viewpoints on these decisions.

2.2 Dynamic environment

The previous section argued that disruptions in distribution networks could have serious consequences. However, Schmitt & Singh (2012) showed that the impact of demand spikes can be even greater than the impact of facility failures. It is, therefore, important to consider variations in demand, prices, interest rates, and exchange rates among others when designing the network (Klibi & Martel, 2013). Moreover, other factors that influence the dynamic environment are technology development, globalization of the economy, and the unpredictable behavior of customers (Rezapour et al., 2011). During the facility's lifetime, changing trends in the above-mentioned parameters can turn today's optimal location into an investment blunder in the future (Nasiri & Jolai, 2018). Thus, determining the proper facility location is an important strategic challenge for the design of the network. Another source of uncertainty is if a company wants to extend its activities to new geographical areas and therefore has to locate facilities and design a new part of its network. Furthermore, a source of uncertainty can come from unstable or competitive markets. When faced with uncertainty, response policies must be adapted to cope with unforeseen events and distribution networks must be structured to be resilient.

The objectives of network design for distribution networks in dynamic environments are the same as the objectives in disruptive environments. Meaning that a large proportion of the network design in the literature aims to minimize costs or maximize profit or sales (Klibi & Martel, 2013; Nasiri & Jolai, 2018). Dynamic problems can be modeled with the use of multi-stage stochastic programs. However, a major difficulty of the stochastic programming approach is dealing with the possibly infinite number of possible scenarios. A network design model is not of much use if it cannot be solved, which is often the case with infinite scenarios. This means that adequate trade-offs must be made between model accuracy and solvability (Klibi & Martel, 2013). Therefore, only several representative plausible future scenarios could be considered. Different scenario samples may, however, lead to alternative network designs. The min-max regret model minimizes the objective function concerning a selected subset of scenarios whose occurrence probability is greater than the user-specified value α (Daskin et al., 1997). Another approach is called lexicographic α-robustness that, instead of considering the worst case, considers all scenarios in lexicographic order from worst to best and also incorporates a tolerance threshold α to not allow a difference among solutions with similar values (Kalai et al., 2005). Lastly, the fuzzy set theory can be used to model the uncertain parameters based on managerial judgments and experimental data (Pishvaee & Torabi, 2010). Next to stochastic models, deterministic models could be used to design a network as well. Klibi & Martel (2013) argued that the predominant approach to solving a network design problem has been the use of deterministic mathematical programming models with appropriate sensitivity and scenario analysis.

2.3 Reflection

Disruptions such as equipment failures, natural disasters, industrial accidents, power outages, labor strikes, terrorism among others, and uncertainties in for example demand could affect the performance of networks. It was found that there are numerous disruptions and also numerous uncertainties. It is, therefore, impossible to model all possible scenarios. Appropriate sensitivity and scenario analysis are, therefore important. Scenario selection is a key aspect when designing the network. Scenario selection is especially complicated because decision-makers could have different viewpoints on risks and uncertainties. For this project, it is thus important to discuss scenarios with various experts of the RNLA. The design of the network depends on decisions such as where facilities should be located and if multiple-sourcing and lateral trans-shipments are allowed. On top of that, a combination of preventive and reactive strategies to countermeasure disruptions and uncertainties is advised. These network design decisions are discussed in the next section.

Chapter 3

Analysis

The previous chapter described the current literature related to distribution networks in disruptive and dynamic environments. In this chapter, insights into urban operations gained by the interviews held with experts of the RNLA that are involved with urban operations are elaborated to make a diagnosis of the problem. First, in Section 3.1, the method of the analysis is defined. Thereafter, the results from the interviews will be presented in Section 3.2. The chapter ends with a summary in Section 3.3

3.1 Method

The objective of this analysis is to gain insights into how units in the front operate and how the supply chain is aligned with these units. An appropriate research method to gain concrete, contextual and in-depth knowledge about a specific topic (or case) is through a case study (Yin, 2011). Given the exploratory nature of the objective, a qualitative research approach is selected. Qualitative research is appropriate to explore a phenomenon within some particular context. This is done through various data sources, and it undertakes the exploration through a variety of lenses to reveal multiple facets of the phenomenon (Rashid et al., 2019). Data is collected through in-depth interviews with experts of the RNLA that are involved with urban operations. To reveal multiple facets, both experts in maneuver and logistics are interviewed. In order to guide and structure discussions of specific topics, a semi-structured interview guide is used. An interview guide is a list of topics to be covered during the interview, with questions for each topic. The interview guide is discussed beforehand with both supervisors of the NLDA. With semi-structured interviews, the interviewer asks predetermined questions but could also ask follow-up questions on the answers given. The interviewee, therefore, gets the opportunity to elaborate end explain particular issues (Alsaawi, 2014). The unstructured part, therefore, provides the necessary flexibility to gain new insights during the interview. Although, the structured part of semi-structured interviews ensures that the qualitative data is reliable and comparable (Hennink et al., 2020).

To obtain valuable information and ultimately draw valid conclusions, representative experts must be selected. To obtain a level of anonymity only the interviewers' job description is given. As the topic is related to both the maneuver and logistics in urban operations, experts in both topics should be questioned. This resulted in three interviews since there is a limited number of experts in urban operations. One with a Lkol who is a lecturer in ground operations, thus with expertise in the maneuver aspect. One with a Major and a Warrant Officer Class I of the Education and Training Command maneuver (OTCman) department, who have expertise in the maneuver aspect in urban operations. The last one is with a Major of the Education and Training Command Logistics (OTClog) department, who has expertise in the logistics topic.

Concrete information regarding the topics was shared with the interviewees beforehand. By sharing this information in advance, interviewees were given the opportunity to prepare themselves to achieve the desired depth during the interviews. On top of that, before the interview took place a short presentation regarding the project was given to further elaborate on the research. Besides, all interviews are recorded which allows the interviewer to concentrate on the interview rather than writing nodes to make a retrospective evaluation (Creswell & Creswell, 2018).

Next to the research design and the data collection method, there is the analysis method. The data analysis method is based on the data analysis process in qualitative research by Creswell & Creswell (2018), consisting of five iterative steps. The first step contains data organization and preparation, in which the data is transcribed based on the recordings and notes of the interviews. The transcripts are shared with the interviewees to verify findings and to revise incorrectly interpreted answers. The second step is to get a general feeling and first impression of the data by reading all the data and re-listening to the recordings. The next step is to code all the data. Coding implies organizing and labeling the data by using brackets and words representing a category. In the fourth step, these codes are used to identify themes and descriptions. Lastly, in the fifth step, the underlying relationships between the themes and descriptions are identified. This step is performed by comparing answers given on the topics that were elaborated.

3.2 Results

This section presents the results of the qualitative research obtained by the method discussed above. The average duration of the interviews was about 1 hour and 40 minutes. Moreover, all participants expressed their appreciation for investigating this ”new” and complicated topic. All interview transcripts, in Dutch, are classified but can be requested from the author or organization. In this section first, the deployment readiness is discussed. Then, the logistical independence of the soldiers is elaborated. Thereafter, the processes of resupplying are discussed. Lastly, the tactic of the maneuver is discussed.

3.2.1 Deployment readiness

In the current situation, there is at most one brigade ready at a time. One brigade exists of two battalions, one battalion exists of three companies, one company exists of three platoons, one platoon exists of four groups, and a group exists of 8 to 10 soldiers (Militaire eenheid, 2022). However, the RNLA is (almost) always linked to an international ally. In the future, it is aimed to have three brigades ready, which is necessary because cities are growing.

3.2.2 Logistical independence

Every group of soldiers should be able to be logistically independent for about 48hours. The team battle train (TBT) which is at the company's level has an additional stock for the platoons such that they could have logistical independence for up to 72hours. This is following the North Atlantic Treaty Organization (NATO) requirements. A group has a vehicle that carries products for soldiers as well. However, if units have to force a break-in, the ammunition inventory could be insufficient for 48hours but might last for only a couple of hours since the ammunition level could shrink tremendously, especially in urban operations. Demand namely could fluctuate extremely. The regular open terrain combat ratio is 3:1, in urban operations, it is 10:1. This means that for open terrain about 3 soldiers are required to eliminate 1 adversary and for urban terrain, it requires 10 soldiers to eliminate 1 adversary. This implies that with relatively little opposition already a lot of combat power is needed and therefore probably also a high ammunition consumption. The logistical process thus should be organized beforehand to supply as soon as possible.

3.2.3 Resupply

All interviewees indicated that supply reliability is most important. The most urgent need at the time, especially for ammunition, there cannot be a shortage. From a commander's view, it is irrelevant how the logistics are designed, as long as the products are delivered. Logistics should not be the limiting factor, soldiers should be able to fight at any time. However, the logistics have boundaries, but within the boundaries, the challenge is to create possibilities such that the commander can make decisions. Logistics looks at what are the resources, what the commander wants to achieve, and how can that be achieved with the resources available. If it is unfeasible there might be an alternative and otherwise, options should be created from which the commander can choose.

3.2.3.1 Request

Soldiers in a group constantly monitor the ammunition level. After a battle, a consolidation among a group is performed such that everyone has the same level of ammunition. It is assumed that if there is less than 50% of ammunition, a request to the TBT is made and the resupply process is started. Moreover, there is a minimum limit of 25%, so if the ammunition level is below 25% the group is unable to move forward because they are too short on ammunition. The company commander responsible for logistics then assesses when to supply. In urban operations, this sometimes has to be performed earlier because it is very difficult to supply in a city due to places that are difficult to reach. Then a resupply may be planned earlier. Depending on the tactical situation, groups could withdraw or wait for a resupply if they are out of ammunition. If the commander thinks that staying put without ammunition is infeasible, they will pull back. However, groups worked hard to get there for a reason so the position will not be just given away. In these situations, there is also indirect support such as close air support or from mortars or armored howitzers. But that is a decision the commander needs to make, how urgent is it to stay put. What is the importance of staying there versus the potential cost/damage that it could entail. The operational theme is also important, is it warfighting, in which national state interests are at stake, or is it a peace operation, in which there are also such missions. Then there are very different considerations.

3.2.3.2 Team battle train (TBT)

The TBT which is on the company's level has a sergeant distribution who is the point of contact for the logistics. This sergeant has a transport vehicle and is therefore the last logistics link in the chain. If the platoon has achieved its goal they consolidate and prepare for the next battle which takes time that is used for resupplying. If there is a request for a resupply, the sergeant delivers the products to a certain distribution point where the transition from the TBT to the platoon(s) is made. It can also occur that the TBT dumps the products at a location and the platoon visits the dump point when possible. Synchronization with the battle is extremely important because the platoon determines when the resupply takes place.

The distribution points are close to the platoons such that they do not have to give up their position. Also, injured are often taken at these points. The location of these points is often determined before the battle but if changes occur they could be exchanged during the battle. A disadvantage of the distribution point strategy is that a physical link-up with the TBT and platoon(s) is required.

An advantage of dumping products is that platoons can resupply any time it suits them which is not the case with distribution points. Besides, it is also possible to drop ammunition in a "safe" area before a request has been received such that platoons move forward but if a problem occurs supplies are close. In addition, when looking at dumping products, the air force also engages in airdrops, but then it still is always brought from the drop zone by a TBT or reserve platoon to the platoon(s). However, in the case of airdrops, air threats among others must be considered.

The echelon above the TBT is the VC/AC. This means that the resupply of the TBTs is done by the VC/AC. The distance is quite large because those stock points are out of the city and it thus takes some time to deliver the products.

3.2.3.3 Ammunition

VCs work with ammunition boxes while soldiers need sorted ammunition in magazines. This means that there needs to be a transition somewhere which is a manual process. The reserve platoon could do this, however, in a battle, it may be that all platoons must fight. It often does happen amid a platoon, but the time might be limited. Besides, to shorten the reaction time between a request and delivery, standard ammunition packages could be used.

3.2.3.4 Vehicles

The products are delivered from the VC via the TBT to the groups. The WLSs that are used between the VC and TBTs cannot be used to supply groups because they are too large. Moreover, a TBT has to supply three platoons and thus drives a lot. In the past, a TBT had two vehicles, this is no longer the case everywhere. In urban operations, it might be required to have multiple vehicles to properly support platoons.

3.2.4 Maneuver

Phase difference in operating, that is, that one platoon is further along than another platoon, can be enormously dangerous. A platoon can get cut off because they go too far and therefore, it can be impossible to be supported which leads to big problems. In addition, it may allow the adversary to slip through the line of attack and launch attacks in the ”safe” back area. On the other hand, if there is a phase difference, it is possible to create a momentum that may cause the enemy’s system to implode due to the unexpectedness. They may be expecting that linear line of attack, but it is the task of the commander to act unexpectedly. Moreover, sometimes it is chosen to immediately take a strategic point with, for example, the airmobile unit. Then it remains narrow and they want to go to, for example, an intersection or object that has to be held to further expand the area. Intersections and supply lines are namely important to be kept clear for logistics. Different maneuver strategies thus could be used in urban operations.

3.3 Summary

This analysis aims to gain insights into how urban operations and the logistic of these operations are executed. In this conclusion, the main findings are discussed. The next chapter contains a reflection of the results.

The deployment readiness is currently one brigade, however, in the future, it is aimed to have three brigades operational. Every soldier has a logistical independence of 48hours. The TBT has an additional stock so that soldiers could have a logistical independence of 72hours. The 48 and 72hours of independence can decrease rapidly due to the battles which means that resupplying should be executed sooner to prevent ammunition shortages. The resupplying process is, however, complicated because demand fluctuates extremely. Supply reliability is therefore most important, especially for ammunition. Groups constantly monitor their ammunition level and it is assumed that as soon as their ammunition level drops below 50% a request to the TBT is made. On top of that, if the ammunition level drops below 25%, groups are unable to move forward. Moreover, groups could withdraw or wait for resupplies if they are out of ammunition, depending on the tactical situation. When a TBT resupply platoons they could either dump products such that platoons can resupply any time it suits them or a TBT and platoon(s) meet at a distribution point in which a physical link-up takes place. The distribution points are close to the platoons such that no position is given up. Besides, groups need ammunition in magazines, while they receive ammunition boxes. A manual transition is thus required which takes time. Platoons often take care of this amid them, however, in a battle, it may be that everyone needs to fight. To shorten the reaction time between a request and delivery, standard ammunition packages could be used. However, a requirement is that there has to be standardization among groups. Based on sufficient information and data, packages could be adjusted properly. Moreover, since a TBT has to supply three platoons it travels a lot, meaning that they need sufficient vehicles. Lastly, phase differences in operating can be extremely dangerous. If one platoon goes further than the others it could be cut off by the adversary making it impossible to resupply. Moreover, the adversary could slip through the line of attack and could launch attacks in the ”safe” area. On the other hand, phase difference does give an unpredictability that can disorder the opponent.

Chapter 4

Diagnosis

Chapter 3 discussed the findings of the qualitative research. This chapter contains a reflection on those results, serving as input for a conceptual and simulation model.

The key conclusion from the interviews is that supply reliability is extremely important. Soldiers should have ammunition to be able to battle at any time, therefore, products should be delivered promptly to them when needed. However, delivering products promptly in urban operations is complex due to the disruptive and dynamic environment. In the literature review in Chapter 2, it was argued that existing research assumes that facilities are always available to serve customers. However, in this research disruptions to facilities or links between facilities are considered. Moreover, the dynamic characteristics that are considered in this research are extreme fluctuations in demand, stochastic lead-times, and changing customer locations. Therefore, the supply network should be viable to function well in a complex and uncertain environment. The network structure is crucial because it determines the infrastructure and physical structure of the supply network (Govindan et al., 2017). Fattahi et al. (2017) stated that as the customers' sensitivity to the delivery lead time of products increases, the facilities that supply these customers should be located close to them. This means that if customers want products quickly, supply facilities should be close to the customer. Thus, since lead times between combat units and TBTs should be minimized, supply facilities for combat units, TBTs, should be close to them. This is the case in the current FD concept. However, TBTs have limited capacity and in combination with heavily fluctuating demand, stock-outs could occur. When the lead time between the VC/AC and TBTs is large, reacting to stock-outs could take time which might affect the supply reliability. Moreover, lead times between TBTs and soldiers further increases due to the transition from ammunition boxes to magazines. Currently, someone from the platoon must make that transition but that person may also be needed to fight. Transitioning at a higher echelon might thus save time for platoons. Besides, another conclusion that could be drawn from the interviews is that the amount of vehicles TBTs have, is limited. Therefore, TBTs may be unable to supply all platoons quickly affecting the supply reliability.

Moreover, it could be concluded that combat units have a continuous review policy. Combat units constantly keep track of their ammunition level and when it drops below 50%, a resupply is requested. Additionally, TBTs have a continuous review policy as well. Furthermore, both combat units and TBTs could order a variable quantity.

Chapter 5

Modeling

Based on the literature study, interviews, and diagnosis, a model could be designed. It was found that supply reliability is extremely important because soldiers should have sufficient ammunition at any time. Increasing supply reliability could be done by reducing the lead time between customers and supply facilities. Possible ways that could reduce the lead time are decreasing the reaction time, decreasing the delivery time, or reducing the delivery distance. Another way to increase supply reliability is to design a reliable supply network.

First, decreasing the reaction time could be done through the use of standard ammunition packages. A requirement is that there has to be standardization among groups. In addition, there has to be coordination with groups, what do they want and do not want. Moreover, a customer order decoupling point should be determined from which the packages are designed and determined for a certain group. However, when the transition is made at a higher echelon, the volume of ammunition supplies increases. Since the capacity of the vehicles is already limited, this might not be suitable. On top of that, at some point the products that have not been used pile up which makes it harder to keep track of these products. Although, with sufficient information and data, these packages could be adjusted properly. Since there is little to no data on ammunition consumption in urban operations, this option does not seem feasible for this study. Second, reducing the delivery time depends on the resources available. Vehicles that are used should be cautious in urban operations and increasing their speed is therefore complicated. However, drones will likely be used for resupplying in the future which might decrease the delivery time (Hambling, 2021). Since this seems to be possible only in the future and therefore there is no data on it yet, it is also not included in this study. Nonetheless, reducing the distance between customers and supply facilities is something that could be considered. This namely has to do with the design of the network structure. Therefore, the main goal is to design a network with high supply reliability, such that soldiers have ammunition at any time. First, the conceptual model is determined in Section 5.1. Thereafter, a detailed design of the model is discussed in Section 5.2

5.1 Conceptual model

In the conceptual model, the decision variable is explained. The variable that could be adjusted is the design of the supply network structure. Therefore, Section 5.1.1 elaborates on the elements of a supply network and different network structures that could increase the reliability. Thereafter, the KPIs are discussed in Section 5.1.2.

5.1.1 Supply network

This section discusses different resilient network structures to answer RQ1. Section 5.1.1.1, explains the elements of a logistic network model. Afterward, different logistic network structures are elaborated in Section 5.1.1.2. Moreover, Section 5.1.1.2 also discusses whether these structures are suitable for urban operations. The suitability of networks is discussed during the interviews with experts.

5.1.1.1 Logistic network model

A logistic network is an ordered set of logistic nodes and edges (Kress et al., 2002).

Nodes of a logistic network model

A logistic node is a location where any logistic activity may take place. Examples of logistic nodes are forward area rearm/refuel points, brigade support areas, ammunition supply points, ports of debarkation, airfields, ammunition depots, and home bases. The set of nodes is usually divided into three subsets: supply nodes, demand nodes, and intermediate nodes. Supply nodes generate the flow that is distributed through the edges, demand nodes are the end-points of the network, and nodes that are neither supply nodes nor demand nodes are called intermediate nodes. Each node in a logistic network model possesses three properties: capacity, survivability, and dynamics (Kress et al., 2002).

- Capacity: Nodes in a logistic network model may represent storage facilities that are capacitated. The larger the capacity of a node, the less constrained the flow that runs through it because there is more space to store flow. In urban operations, the capacity of facilities is restricted. Soldiers can only take as much ammunition as they could carry. In addition, the capacity of logistic facilities is limited due to mobility requirements. The capacity of a VC is large because it is located outside of the urban area.

- Survivability: Logistic facilities operate in urban operations and are therefore subjected to battlefield attrition. A node may be damaged or even destroyed by the enemy's actions in which case it is removed from the logistic network. Such a possible predicament must be explicitly represented in a logistic network model by a parameter that indicates the vulnerability of the node and its survivability. The survivability of a node also depends on the mobility of a node as explained in the interviews.

- Dynamics: A general network is typically stationary. The relative positions of the nodes remain constant over time as they usually represent entities such as warehouses and stations in distribution or transportation models. Since many of the logistic nodes in the model are units that may occasionally change their positions - as the operation evolves - it follows that the corresponding nodes in the logistic network model may change their relative position too. Meaning that the model has a dynamic geometry - it may change its shape over time. However, to be dynamic, the capacity is limited.

Edges of a logistic network model

A logistic edge connects two logistic nodes. Examples of logistic edges are roads connecting rear supply depots with forward supply points, railways connecting maintenance depots with ports of embarkation, and air routes between airfields. Each edge in a logistic network model possesses three properties: capacity, duration, and survivability.

- Capacity: Edges in a logistic network model correspond to roads, railways, air routes, and sea lanes. Similar to the nodes in the model, edges are capacitated. The capacity of an edge depends on the type, width, and topography of the unit, and on the number, capacity, and speed of means of transport that are assigned to that edge. Therefore, narrow alleys are for example not suitable for WLSs. The somewhat larger streets in urban areas are easier to use for transportation. However, if only the larger streets could be used, it may not be possible to come close to the soldiers which increases the delivery time.

- Duration: The duration indicates the nominal time it takes a unit of flow (e.g., a truck) to travel from the source node of an edge to its destination node. The duration of the edge determines the time each quantum of flow spends on the route. In this model, factors that can increase the delivery time are roadblocks, Improvised Exploding Devices (IEDs), and suicide bombings. The adversary can use these to cross the opponent and to create chaos which increases the duration of the transport.

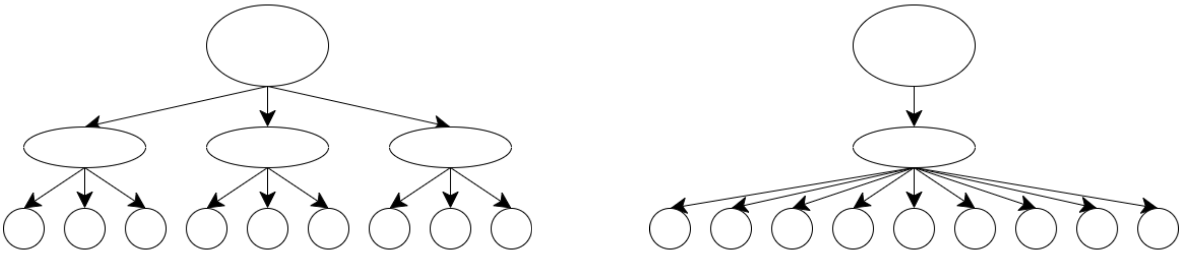
- Survivability: The everlasting friction on the battlefield, and in particular hostile actions by the enemy, may degrade the capacity of an edge and increase its duration. An artillery barrage or an IED may hit a convoy on the road, and a commando unit may block a crucial passage. Thus, similarly to nodes, survivability is an important property of edges. Survivability may be measured by various probability parameters such as the probability of reaching the destination within a specified time window. Besides, the dynamic property of the nodes affects the edges too. When nodes change their position, the edges that connect them may alter too. The survivability of an edge in urban operations is high up to a certain extent. If some road can not be used due to for example a roadblock, another road could be used or mobility equipment that clears the roadblock could be used as discussed in the interviews.

5.1.1.2 Logistic network structures

Nodes and edges together form a network structure. A hierarchical network structure is where a logistic node at a given echelon feeds resources to subordinate units at lower echelons Kress et al. (2002). This network structure has the form of a tree and although the main structure of a tree network is clear, there are many possibilities to increase the resilience of a tree network. Tree network structures may be different in width, simplicity, sourcing policy, and the acceptance of lateral trans-shipments or direct shipments of the system. With these possibilities the distances between nodes could decrease which likely decreases the delivery time. Each variation on the tree structure is explained below to answer RQ1. Additionally, per structure, it is discussed whether the structure is suitable for urban operations or not.

Width

The "width" of a tree indicates the dimensions of the system concerning the number of logistic entities (Kress et al., 2002). A richer and wider system is more robust because it contains built-in redundancies. Such planned redundancies may facilitate effective backups among facilities. However, a wide deployment may result in inefficient utilization of transportation resources. If transport vehicles are scattered over a large number of disjoint locations, their employment may be less flexible and hence less efficient. On the other hand, narrow systems enhance the negative effect of bottlenecks or cuts in the logistic flow. In the absence of mutual backups, the system is more vulnerable to congestion and hostile actions. Figure 5.1a presents a wide system while Figure 5.1b presents a narrow system.



(a) Wide (b) Narrow

Figure 5.1: The "width" of a tree

The width of the RNLA supply network is fixed as discussed in the interviews. A battalion is divided into three companies, a company is divided into three platoons and a platoon is divided into four groups. In the current organization, no adjustments to the structure could be made. Therefore, the network is quite wide which facilitates effective backups.

Simplicity

One aspect of simplicity is embodied in the number of stock points along the supply chain (Kress et al., 2002). Stock points are logistic intermediate nodes in which logistic flow can be transferred from one means of transportation to another. Operating and controlling such a stock point is a difficult task - especially in the presence of battlefield uncertainty and friction. It involves loading, unloading, storing, and traffic control - all of which require careful scheduling and coordination among interdependent entities. Consequently, each stock point adds considerable complexity to the execution of the logistic support chain. On the other hand, more stock points can also provide more flexibility. Stocks can be redistributed over lower echelons at a later stage. Moreover, the distance between stock points reduces. Figure 5.2a presents a complex system while Figure 5.2b presents a simple system.

In the simple variant, Figure 5.2b, the lead times might be larger due to the larger distances between the nodes. As explained in Chapter 4, the distance between TBTs and the VC is large. To shorten the distance and thus lead-time, an additional intermediate stock point might be suitable as in the more complex variant (Figure 5.2a). However, an additional stock point such as an AC is unsuitable in a city because of its size. Therefore, a smaller intermediate stock point a so-called Forward Logistic Support Base (FLSB), might be more suitable. These FLSBs ensure that the lead time to resupply TBTs will diminish. Therefore,

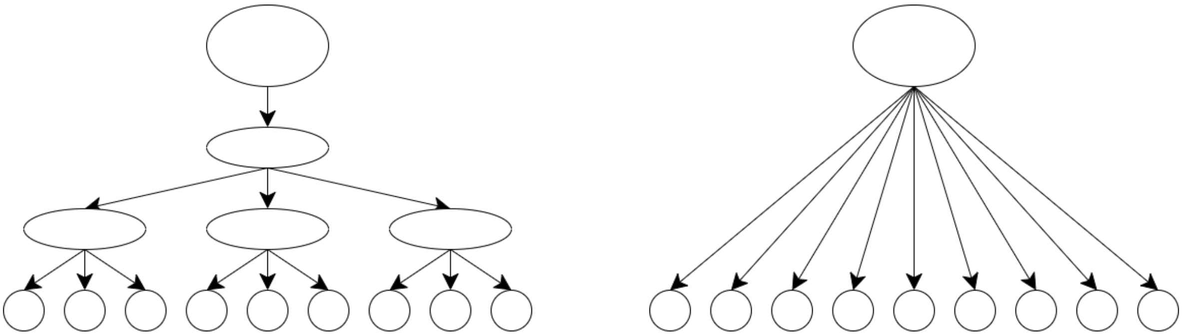

(a) Complex (b) Simple

Figure 5.2: The simplicity of a tree

it might increase the supply reliability because TBTs could be resupplied sooner. Moreover, since the VC uses WLSs, that are unsuitable for urban operations, FLSBs could be used to transfer from transportation means.

Multiple-sourcing

A multiple-sourcing strategy is a policy that can significantly increase the performance of a network. With multiple sourcing, sourcing is carried out by multiple facilities. This policy can either be proactive or reactive. The pro-active policy is shown in Figure 5.3a. The figure shows that each customer is connected to at least two facilities in a higher echelon. This means that a customer receives some products from one facility and other products from another facility. It can also mean that at one moment the customer is served by one facility and that at another moment the other facility serves the customer. In the reactive policy, sourcing from another facility is only done if, for example, a facility breaks down as shown in Figure 5.3b. In this case, the dashed lines are only active if the most left facility breaks down.

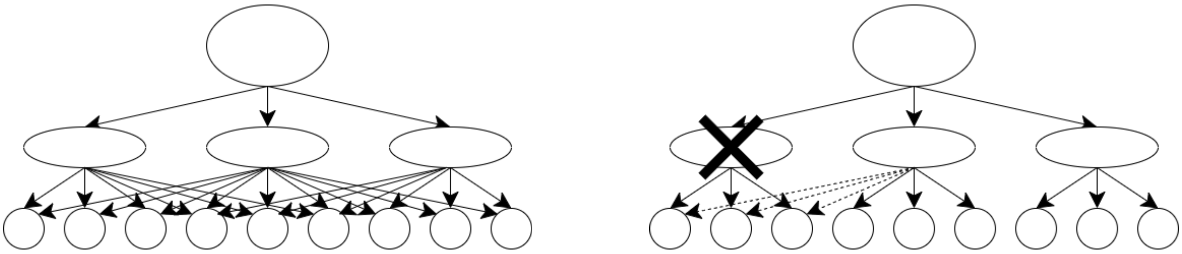

(a) Pro-active (b) Reactive

Figure 5.3: Multiple-sourcing strategy

With multiple sourcing strategies, intermediate nodes could supply to any subordinate node in a lower echelon. However, according to the doctrine TBTs can only supply their own three platoons. They are extremely trained in routines. It limits their flexibility, but it allows them to have an extremely efficient performance, which is very important in high-risk situations such as urban operations. This means that the multiple-sourcing strategies could only be used in combination with FLSBs. Meaning that with pro-active multiple sourcing FLSBs could supply any TBT. When looking at the multiple-sourcing model with a reactive policy it must be stated that there is no upfront relation between multiple supply facilities and customers. This means that there is some level of improvisation required, which could take extra time. New areas or roads that have not been used before might decrease the delivery reliability. However, both strategies could increase supply reliability and are, therefore, relevant to model.

Lateral trans-shipments

Lateral trans-shipment has been studied lately as a promising policy for increasing the performance of a network. By lateral trans-shipment, products can be moved from one location with excess inventory to another location, at the same echelon, in shortage, to reduce supply delays of spare parts (Tiacci & Saetta, 2011). A network with lateral transshipment has more edges and might therefore be more complex than without due to for example extra communication lines between nodes. Figure 5.4 shows the network structure of a wide tree structure which allows lateral trans-shipments.

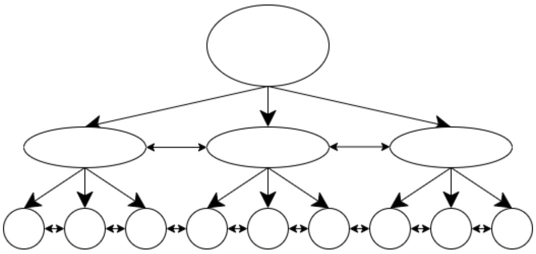


Figure 5.4: Lateral trans-shipments

Lateral trans-shipments between points in the same echelon might result in a more resilient network. However, lateral trans-shipments between platoons are not always possible. A reserve platoon could relinquish its ammunition to a platoon in need or it could even support a platoon but already distributed ammunition is hard to exchange among platoons. It is not impossible, if there are real problems every option is possible, it is even possible if necessary to throw a magazine over a fence for example. Nonetheless, since it is not always the case that platoons could exchange ammunition, it is not modeled. Moreover, as explained in the multiple-sourcing strategy, TBTs can only supply their platoons. Therefore, lateral trans-shipments between TBTs do not occur. This means that the lateral trans-shipment structure could only be used in combination with FLSBs. Lateral trans-shipments could take place among FLSBs.

Direct shipments

With direct shipments, products can be moved from a higher echelon directly to the customer, without using the echelon between these facilities. An example is shown in Figure 5.5. This figure shows that it is possible to move products from the highest echelon to the customers in the lowest echelon. According to Chopra et al. (2013), this structure is especially suitable for low-demand products which do not need to have a low lead time. So applying only this structure to the network for ammunition might not be suitable since ammunition has a high demand and requires a short lead-time. This structure is, however, also suitable for high-value products and products with a high variety (Chopra et al., 2013).

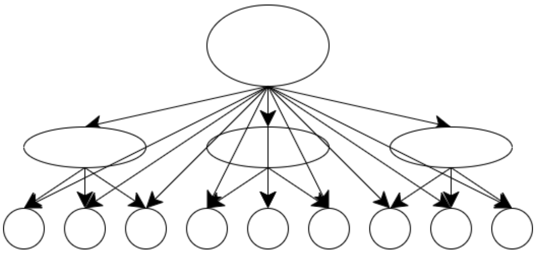


Figure 5.5: Direct shipments

With direct shipments, the line of communication is long which could make the physical link-up with combat units more complex. Moreover, the WLSs used at the VC are useless to supply combat units in the front. Direct shipments are therefore infeasible. Another direct shipment could be with the use of airdrops, however, that type of supplying is unconsidered in this research because air dominance is not a certainty. Therefore, it is chosen that direct shipments are not suitable for urban operations and are thus not considered.

5.1.1.3 Overview

As explained, several different structures could increase the supply reliability of a network. Based on the network structures discussed in Section 5.1.1.2, five models could be designed. The network structures are explained below, Figures of the visualization of the structures could be found in Appendix C.

1. FD-concept (FD): In the current FD-concept the VC delivers ammunition to the TBTs and the TBTs deliver ammunition to the platoons.

2. Additional intermediate node (AIN): In this structure the FD-concept is used as a base but an additional intermediate node between the VC and TBT is used, a so-called FLSB. With FLSBs, the lead time to supply TBTs is shorter. Moreover, an additional intermediate node could increase the redundancy and could thus increase the ability to anticipate on disruptions. Furthermore, a change from transportation means could be provided. The FLSB is at the battalion level which means that it serves three TBTs.

3. Pro-active multiple sourcing (PRO): This structure could only be used in combination with FLSBs. The AIN-structure is used as the base. In this model, FLSBs could deliver ammunition to any subordinate node in a lower echelon, TBT. Every TBT could be resupplied by any FLSB which means that the distance is unconsidered in this structure.

4. Reactive multiple sourcing (REA): This structure could also only be used in combination with FLSBs. Again, the AIN-structure is used as the base. In this structure, a FLSB only supplies TBTs from another FLSB if it has no outstanding orders.

5. Lateral transshipment (LAT): Again, this structure could only be used in combination with FLSBs and thus the AIN-structure is used as the base. In the lateral transshipment structure, ammunition can be exchanged between FLSBs.

5.1.2 Performance measures

In this section, relevant KPIs are discussed to evaluate network structures and simultaneously answer RQ2. As explained in Chapter 1, a characteristic of military distribution networks is that it has a focus on effectiveness (”at all costs”) over efficiency (Shatzkin, 2017; Vermunt & Thoolen, 2004). Yet the available budget is increasingly a limiting factor but it is chosen not to take cost into account for this research. An indicator that is relevant for urban operations is the time it takes to conquer a city. Moreover, the time logistics need to supply the platoons is also important.

- Expected conquering time: The expected conquering time is used as KPI because it is desired that the operation is over quickly. A lengthy operation may cost many resources and possibly more casualties and should therefore not take long. Note that it is assumed that a lengthy operation may increase the number of casualties and resources, this is not investigated. The expected conquering time denotes the expected total time it takes to conquer a city.
- Expected exposed time per grid: Since there should be as little movement as possible in urban operations because that increases the risks of danger and therefore probably more casualties, the exposed time is a KPI. However, note that it is assumed that a higher exposed time may increase the number of casualties, this is not investigated. The exposed time per grid is calculated with the use of Equation 5.1. In this equation GL denotes the grid length per platoon (explained in Section 5.2.2.1), NP denotes the number of platoons, CT denotes the conquering time, E denotes the echelons in the network structure, $L_{e,t}$ denotes the lead time of echelon e at time t, and $D_{e,t}$ denotes a binary variable if an order departures in echelon e at time t. The expected exposed time per grid thus shows the average time vehicles are shipping to supply platoons such that they could conquer a grid. Note that only the outbound lead-time is taken into account. This measurement is used because it can compare all models. The difference between the FD and AIN model is that the AIN model entails a higher lead-time because the distance of traveling from point A to point C is shorter than traveling from point A to point C via point B. Moreover, with the multiple sourcing structures the distances between nodes in different echelons increase which affects the lead-times. Lastly, with lateral trans-shipment, the lead-times between the FLSBs are taken into account as well. The expected time exposed per grid is, therefore, a useful KPI to evaluate all structures.

$$E[ETPG] = \frac{1}{GL * NP} \sum_{t=0}^{CT} \sum_{e}^{E} L_{e,t} * D_{e,t} \tag{5.1}$$

5.1.2.1 Data Envelopment Analysis (DEA)

Operations should be finished quickly. Therefore, it is intended that the expected conquering time should be low. However, this means that platoons should be resupplied promptly, which might result in a network with a high expected exposed time per grid. A high expected exposed time per grid is unfavorable because it might increase the risk of danger. For assessing these KPIs and thus the networks, this research applies a data envelopment analysis (DEA). With DEA, a set of measures is selected to benchmark the performance of in this case network structures. It is believed that when applying DEA to study network structure performances, it can generate useful information to support strategic decision-making. Figure 5.6, shows the basic concept of DEA with a theoretical and best practice frontier (Hui & Wan, 2013). The theoretical frontier is the ideal situation. In this set of points, points A, B, C, and D are identified as the most efficient and they provide an envelope (best practice frontier) around the entire data set. Other points are inefficient but might be improved with suggested directions for improvement. The distance to the theoreticcal frontier provides a measure of the efficiency or its lack thereof. However, in this research the theoretical frontier is unknown. Therefore, the distance to the origin of the diagram provides a measure of efficiency.

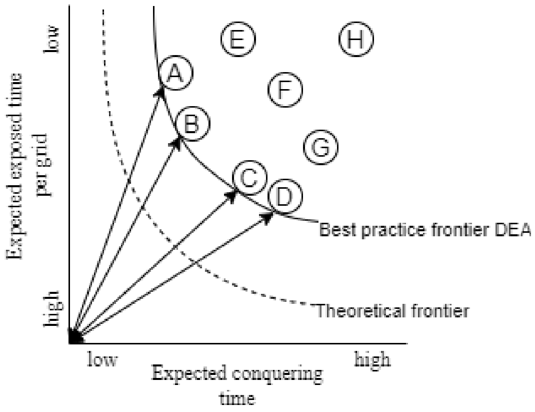


Figure 5.6: Basic concept of data envelopment analysis (DEA), based on Hui & Wan (2013)

5.1.2.2 Other performance indicators/features

Next to the expected conquering time and expected exposed time per grid, other performance measures could be used to interpret the results of the simulation model. Therefore, other indicators and features are explained below.

The ready rate is an important indicator as well. The ready rate denotes the fraction of time the inventory on hand is positive (Van Donselaar & Broekmeulen, 2014). Since platoons should have supplies at any time, the ready rate should be high. However, since platoons cannot move forward if their inventory on hand is below 25%, it is chosen to denote the ready rate as the fraction of time the inventory on hand is greater than 25%.

The multiple sourcing models stand out from the other models when looking at the minimal paths of the models. The minimum path set denotes the minimum set of components, nodes, and edges, which cannot be reduced such that the network can still supply every customer. For the FD and AIN models, each node and link is in the minimum path set since if a node or link fails, at least one customer could not be supplied. The LAT model has the same minimum path set as the AIN-structure because the lateral transshipment edges are not crucial for an operating network. However, for the PRO and REA model, fewer nodes and edges are in the minimum path set to supply all customers. If for example a node is disrupted, another node could compensate for the disruption. The same holds for the edges. Therefore, disruptions might affect the reliability of multiple sourcing models less than in other networks. However, because the minimal path is not distinctive in these structures it is not considered as KPI.

The more nodes and edges between them in a network, the more complex the network. Choi & Hong (2002) depicted complexity as both the number of nodes and the average distance of rides in a network. Moreover, the amount of different edges used is also an indicator of complexity. On top of that, the amount of rides is used as an indicator as well since then many lateral trans-shipments for example are unfavorable.

5.2 Detailed design

A full factorial experiment will be performed in which several levels for different input parameters will be tested. Section 5.2.1 describes the different simulation experiments. In Section 5.2.2, the modeling decisions are explained.

5.2.1 Simulation experiments

This section describes the different simulation experiments that are tested to answer RQ3. Every urban operation has characteristics such as the infrastructure of the city, the population, and the adversary. These characteristics affect the demand for platoons. The demand levels are elaborated in more detail in Section 5.2.1.1. Moreover, a characteristic of urban warfare is the usage of IEDs among others. The IEDs disrupt supplies, moreover, supply nodes could be attacked. Therefore, different levels regarding the number of disruptions are tested. Additionally, it is unknown what the vehicle capacity could be for a FLSB. It is expected that the number of vehicles affects the performance of structures. Therefore, different levels with different numbers of vehicles per FLSB are tested. The number of vehicle levels is explained in Section 5.2.1.3. Table 5.1 shows per input parameter the different levels that are tested. Each input parameter is elaborated in more detail below, however, the levels of the ”structures” input parameter are already described in Section 5.1.1.3.

Table 5.1: Input parameters for the simulation experiment

Input parameter	Levels
Structures	{FD, AIN, PRO, REA, LAT}
Demand	{Low, High, Wavy, Peak}
Vehicle	{1,2}
Disruptions	{Low, High}

5.2.1.1 Demand levels

Factors such as the amount, size, and heights of buildings in an urban area affect the infrastructure of a city. In dense urban terrain, buildings are not just buildings, they are fighting positions - defensible locations (Mosul Study Group, 2017; King, 2021). The many windows, doors, and other openings from these buildings comprise possible firing positions (Glenn et al., 2003). The adversary can use these buildings not just for firing positions, but buildings can be used for cover and concealment as well. To siege a city, all buildings have to be cleared. Next to buildings, the adversary can utilize tunnels and sewers (subterranean constructions), which further complicates urban warfare. Different buildings and terrain affect the ammunition types needed. Moreover, since buildings and sewers block radio signals, communication is much harder, which makes it difficult to control soldiers' efforts and to keep track of their physical positions (Glenn et al., 2003). The infrastructure, therefore, affects urban operations.

Next to infrastructure, there is the population aspect. The urban environment is like a living organism, many civilians move through the city (King, 2021). The adversary can hide among the population (Mosul Study Group, 2017), which makes it difficult for soldiers to distinguish adversaries from civilians. Furthermore, goods intended for soldiers are also wanted by the civilians. When soldiers are resupplied, civilians could perform unexpected acts or actions which complicate the logistical operations.

Lastly, there is the adversary. As discussed during the interviews, the regular open terrain combat ratio is 3:1, in urban operations, it is 10:1. This means that for open terrain about 3 soldiers are required to eliminate 1 adversary and that in urban terrain it requires 10 soldiers to eliminate 1 adversary. This implies that with relatively little opposition already a lot of combat power is needed and thus probably also a high ammunition consumption.

Infrastructure, population, and adversary thus affect urban operations. These factors affect the amount of ammunition needed. Since there is no data on ammunition demand in urban operations, different levels are designed that will be tested on the five structures. The results of these tests will answer RQ5. It is hypothesized that higher demand, negatively affects the results of the structures. However, it is expected that the REA-, PRO-, and LAT-structure could better handle different demand levels since these structures have more flexibility.

- Low demand: In the low demand level, the demand in the urban area is everywhere quite low.
- High demand: In the high demand level, the demand in the urban area is everywhere high.
- Wavy demand: In this level, the demand follows a wavy distribution. Thus, areas of high and low demand alternate.
- Peak demand: In the peak demand level, there are high peaks at certain areas in the urban area. In the rest of the area, the demand is relatively low.

5.2.1.2 Disruption levels

The results of different disruption levels will be used to answer RQ4. It is hypothesized that the number of disruptions negatively affects the performance of structures. However, it is expected that the PRO-, REA-, and LAT-structures could better anticipate to those disruptions. Therefore, two levels are tested to find out if and in what way the number of disruptions affects the results.

- Low disruption: In this level few node and edge disruptions are expected.
- High disruption: In this level many node and edge disruptions are expected.

5.2.1.3 Number of vehicles levels

It is expected that more vehicles per FLSB positively affect the performances of structures with FLSBs. Especially for the multiple sourcing and lateral transshipment models.

Therefore, two levels are tested to find out if and in what way the number of vehicles per FLSB affects the results.

- 1 vehicle: In this level each FLSB has 1 vehicle at its disposal.
- 2 vehicles: In this level each FLSB has 2 vehicles at its disposal.

5.2.2 Modeling decisions

In this section, modeling decisions are discussed. Section 5.2.2.1, explains why a grid system is used for modeling. Section 5.2.2.2 discusses the inventory control systems of the nodes. Lastly, the assumptions made for modeling are explained in Section 5.2.2.3.

5.2.2.1 Grid system

When sieging a city, platoons start from the border and move towards the center or towards the other side of the city, depending on the operation. If the goal of the operation is to eliminate the adversary, the intention could be to circle the city and move inwards. If the goal is to drive out the adversary the platoons could move from one side to the other side of the city. To have some structure in sieging a city, a grid system is used. Consider a city that is divided into multiple grids such as in Figures B.1a and B.1b in Appendix B. To siege a city, all grids should be conquered independently whether the goal is to eliminate or drive out the adversary. Either way, soldiers have to conquer a certain amount of grids in a lane.

5.2.2.2 Inventory control system

According to Van Donselaar & Broekmeulen (2014), there are four basic inventory control systems namely (R,s,nQ), (R,s,S), (s,nQ), and (s,S)-systems. In these systems R denotes the review period, s denotes the reorder level, S denotes the order-up-to level, and n denotes the integer of the fixed replenishment quantity Q. The four basic inventory control systems with their characteristics are shown in Table 5.2

	Periodic review	Continuous review
Fixed replenishment quantity	(R,s,nQ)	(s,nQ)
Variable replenishment quantity	(R,s,S)	(s,S)

Table 5.2: Classification of inventory control systems

The models show that the platoons are in the lowest echelon. The VC is the highest echelon and the FLSBs and TBTs are between the VC and platoons. Because each echelon has different characteristics, they could have different inventory control systems.

- Platoon: Since platoons can request supplies at any time, there is a continuous review policy. Moreover, platoons can request a variable replenishment quantity meaning that the (s,S) inventory control system is used. Van Donselaar & Broekmeulen (2014) stated that "the replenishment logic used in the (s,S) system is as follows: As soon as the inventory position drops below the reorder level s the number of units is ordered which is needed to bring the inventory position after ordering back to the order-up-to level S".

- TBT: TBTs have a continuous review policy and have a variable replenishment quantity. Based on Table 5.2, the TBTs thus apply an (*s*,*S*) policy.
- FLSB: FLSBs also have a continuous review policy. The same as for the platoons and TBTs the FLSBs have a variable replenishment quantity. Based on Table 5.2, the FLSBs thus apply an (*s*,*S*) policy. Moreover, since $S_{FLSB} - s_{FLSB}$ is likely higher than $S_{TBT} - s_{TBT}$, higher order sizes are shipped from the VC towards the FLSBs than from the VC towards the TBT in the FD-structure. This will thus likely affect the expected exposed time of structures with FLSBs.
- VC: Since it is assumed that the VC has unlimited supplies, no policy is required. Unlimited supplies also mean that the VC could always deliver to the TBTs (in the FD-structure) or FLSBs (in the other structures).

Additionally, back-ordering is assumed so if a supply node cannot deliver the products to a subordinate node, a back-order is made.

5.2.2.3 Assumptions

Urban operations are complex, especially since the maneuver aims to be unpredictable to surprise the adversary. This research focuses on the logistics part to support the actions of the maneuver. It is, therefore, important to consider the maneuver aspect, but assumptions are required to design a model. The first assumption is that platoons operate on the same attacking line. This means that platoons have to wait on each other when they have conquered a grid. Although platoons could exploit success, it is assumed that platoons stay on the same attacking line because otherwise the field could become dispersed which is extremely dangerous as discussed during the interviews. Moreover, platoons only conquer grids in their grid line, they do not conquer grids in the line of another platoon. Additionally, it is assumed that platoons do not withdraw, they could always conquer a grid. Another assumption is that there is transparency at all stock points. This means that it is known how much stock each node has at any time. Moreover, all orders arrive, there are no communication failures for example. Furthermore, it is assumed that there is no order pick time, meaning that the lead time only exists of the waiting time and delivery time. The waiting time denotes the time it takes between the order arrival and the time the order supplies leave the supplying node. The delivery time denotes the time it takes to deliver the supplies from one node to another node. Additionally, TBTs can adjust the orders up to and until the FLSB has shipped the order. Furthermore, it is assumed that the VC has unlimited supplies and vehicles. Lastly, it is assumed that when TBTs or FLSBs are moving forward, they are not able to deliver products. These nodes could receive products and products that have already been sent will continue but no new orders could be delivered while moving.

Chapter 6

Simulation model

In this chapter, the discrete-event simulation model using Future Event Scheduling based on Boon et al. (2019) is explained. First, the ammunition measuring unit is explained in Section 6.1. Thereafter, in Section 6.2, the dual order policy for platoons is discussed. Afterward, a schematic overview of the simulation model is described in Section 6.3.

6.1 Measuring unit

As described in Chapter 3, platoons have inventory for about 48hours and TBTs have additional inventory such that platoons could be logistically independent for 72hours. When it is assumed that a BL denotes the amount a soldier could carry they have 1BL on them and 1BL in the vehicle meaning a soldier has 2BL in total. Every platoon contains four groups and each infantry group contains about ten soldiers. This means that a platoon has a BL of $2 * 10 * 4 = 80$. Because TBTs have the additional stock for 24hours, half of the platoons stock, this means that every TBT has $0.5 * 80 = 40$BL per platoon on stock. Since TBTs supply three platoons their inventory is $40 * 3 = 120$BL. Moreover, BL is a continuous variable because it denotes the overall ammunition quantity.

6.2 Dual order policy platoons

Chapter 3 stated that if the inventory level of platoons drops below 50% while they are attacking, they request supplies. Because platoons are still attacking, they need these supplies immediately and are therefore called priority requests. In literature, this is called expediting orders in which decision-makers are willing to pay higher replenishment costs for speeding up orders by reducing their lead times to avoid shortages (Yao & Minner, 2017). In this research, costs are not considered but lead-time reductions are used by prioritizing these orders. In addition to the priority supplies, there is another stream of supplies. When a platoon has conquered a grid but has to wait for the other platoons and their inventory drops below s an order is requested. These requests are called regular requests. Thus, there are two types of resupply streams, priority and regular resupplies. Priority orders are requested when the platoon is still attacking while regular orders are requested when the platoon has to wait for the other platoons to conquer a grid. The reorder levels of both the priority and regular resupply are the same. TBTs use the First In First Out (FIFO) policy for priority and regular resupplies. Meaning that orders are shipped in the same order as they arrived. Thus, first, priority orders are FIFO shipped and then regular orders are FIFO shipped. Additionally, there could be only one outstanding order, meaning that first, an order needs to be received before another order could be placed. The order size (OS) is calculated based on Equation 6.1. S denotes the capacity and s denotes the reorder level. The Minimum Order Quantity (MOQ) is thus $S - s$. The MOQ ensures that extremely small amounts are not shipped because those amounts do not help platoons that much but increase the risk of disruptions. For the intermediate nodes, Equation 6.1 is also used to determine the order size. However, they have different parameter values.

$$OS = S - s \tag{6.1}$$

6.3 Schematic design

Figure 6.1, shows a schematic design of which processes take place in urban operations. This schematic design is based on the second model (AIN-structure), it thus contains FLSBs. In the FD-structure, TBTs request supplies directly from the VC.

Platoons start at the front of the city, close behind the platoons are the TBTs, two grids behind the TBTs are the FLSBs, and five grids behind the FLSB is the VC. An overview of the starting grid is shown in Table B.1 in Appendix B. When platoons start conquering a grid, they move one grid forward. The time it takes to conquer a grid is stochastic. The demand per grid is also stochastic and depends on the demand level. While platoons are conquering grids, they place a priority order if their Inventory Position (IP) drops below 50%. The IP of a node is the node's Inventory On Hand (IOH) plus the inventories in transit to the node minus the backorders. The IOH denotes the inventory a node has in its stock. Backorders are customer orders which could not be delivered from the IOH and which will be delivered as soon as new IOH becomes available (Van Donselaar & Broekmeulen, 2014). The order size of the priority request is based on Equation 6.1. The IP of the TBT decreases by the order size and the TBT adds the platoon to its priority shipping list. While the platoon waits on the priority shipment, they continue conquering the grid. However, as soon as the platoon's IOH is below 25%, they stay put such that their IOH decreases less since the defending demand is less than the attacking demand as explained in Chapter 3. The defending demand is calculated with the use of Equation 6.6. When a platoon receives supplies and has not yet conquered the grid, they will continue conquering the remaining part of the grid. If the IP again drops below 50%, there will be another priority request. When the grid is conquered, platoons must wait for other platoons to conquer a grid. While waiting for the other platoons they defend their grid, the inventory thus decreases according to the defending demand. Since platoons could wait a while on the other platoons it could be that their IP drops below 50%, then a regular resupply is requested. The TBT adds the platoon to its regular shipping list and the IP of the TBT decreases by the order size. When the priority shipping list is empty, regular resupplies are shipped by the TBTs.

When an order arrives at a TBT, the TBT waits until it has an available vehicle. If there is a vehicle, it is checked if the priority shipping list is empty. If not, it is checked if the TBT has sufficient supplies to complete the order. Then, the TBT supply the platoon. TBTs apply a continuous review policy, thus as soon as the IP of a TBT drops below the reorder level, a request is sent to the FLSB. If the FLSB has an available vehicle and sufficient supplies the FLSB ships the order to the TBT. If the FLSB cannot ship the order due to for example insufficient IOH or no available vehicle, the TBT can still increase the order if the TBT's IP further decreases while the FLSB has not shipped the order. Order adjustment is thus allowed until the order is shipped from the FLSB. Additionally, FLSBs also use the FIFO policy. FLSBs also apply a continuous review policy thus when the IP of a FLSB drops below its reorder level, a request is sent to the VC and the VC immediately ships the products to the FLSB.

When all platoons have conquered a grid, TBTs move one grid forward. Moreover, it is checked if FLSBs should move forward as well such that the distance and thus delivery time will be limited. FLSBs move forward if the maximum distance between the FLSB and TBT is reached. FLSBs then move forward but there is a minimum distance between the TBTs and FLSBs. FLSBs are mobile and can move quite easily but they do not move every grid. The VC will always be located outside the city and will thus not move. When all platoons have an IOH greater than the reorder level (s) and all TBTs have moved a grid, all platoons start conquering the next grid and the process starts all over again.

Additionally, disruptions occur in the model. A disruption could be on an edge or a node. It is assumed that multiple routes could be used on an edge. So if there is for example a blockade on a route, another route is chosen. This kind of disruption on an edge is included with the stochastic lead-times. However, if there is a disruption specifically on the supplying vehicle, an IED for example, the total order could not be delivered. Therefore, the same order becomes the first order in the list. Moreover, a new vehicle from the VC should be sent to the supply node of the edge at the speed of a VC vehicle. Equation 6.2 is used to determine if a disruption occurs on an edge. In this equation, 1 denotes a disruption, 0 denotes no disruption, P_e denotes the probability of an edge disruption per time unit and L_e denotes the lead time of the edge. The probability of edge disruption per time unit is an input parameter that is elaborated in Section 6.4. The time the edge disruption occurs is calculated with Equation 6.3. In this equation $t_{departure}$ denotes the time the vehicle started driving from the supplying node; the departure time. L_e denotes the lead-time of the order on the edge. To determine if a disruption occurred on a node, Equation 6.4 is used every time before an order could be shipped. In this equation, P_n denotes the probability of a node disruption. When there is a disruption on a node, it is assumed that not the complete node is disrupted. Equation 6.5 is used to determine the IOH of the node after a disruption. The IP simultaneously decreases as well which may lead to an order being placed.

$$\textit{Edge disruption}\begin{cases}1, & \text{if } P[U(0,1) \geq P_e * L_e] \\ 0, & \text{otherwise}\end{cases} \tag{6.2}$$

$$\textit{Time of edge disruption} = U(t_{departure}, t_{departure} + L_e) \tag{6.3}$$

$$\textit{Node disruption}\begin{cases}1, & \text{if } P[U(0,1) \geq P_n] \\ 0, & \text{otherwise}\end{cases} \tag{6.4}$$

$$\textit{IOH after a node disruption} = U(0, IOH) \tag{6.5}$$

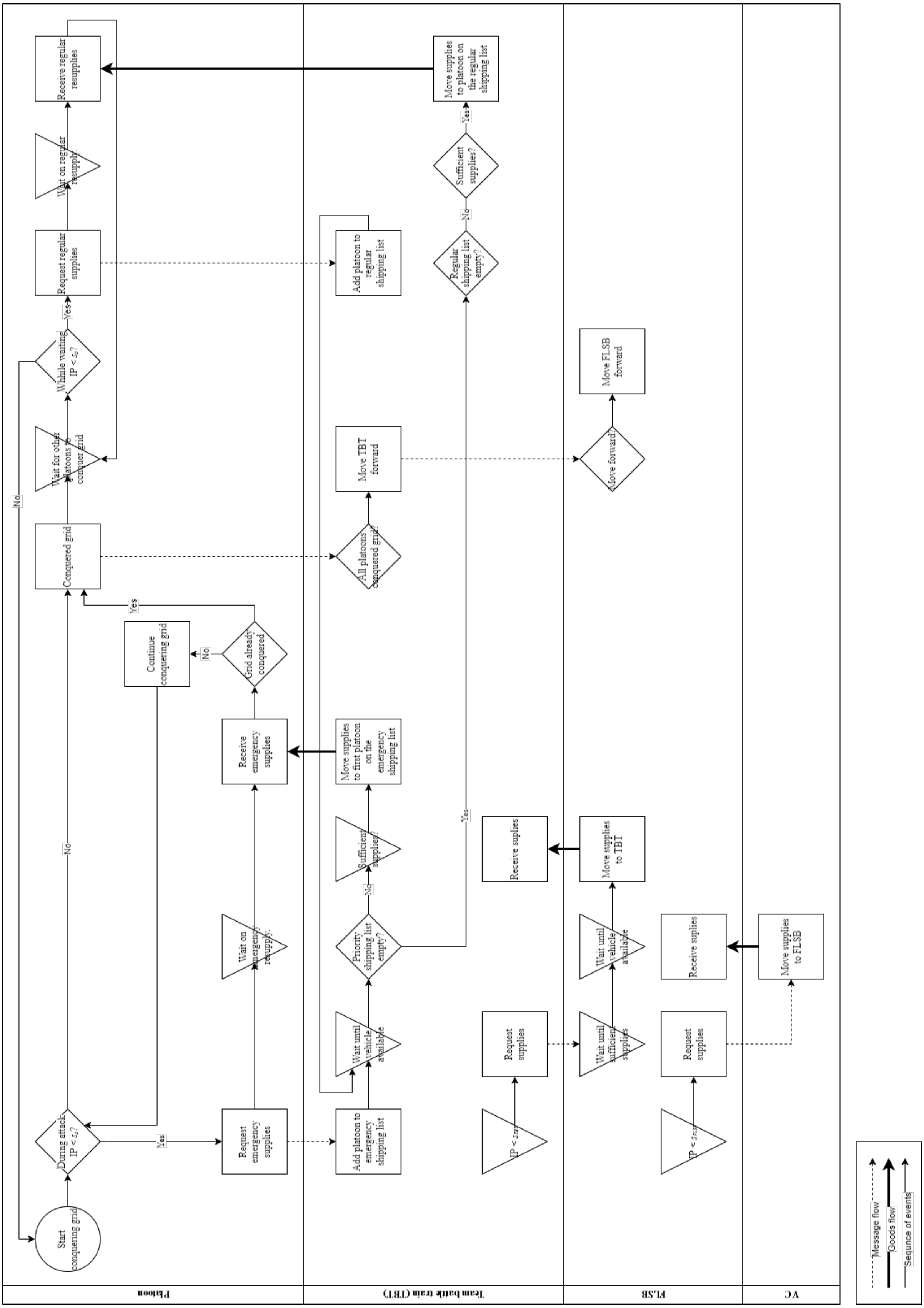


Figure 6.1: Schematic design of the model

The difference between the FD-structure and AIN-structure is that in the FD-structure the TBT directly orders from the VC. The main difference between the PRO- and AIN-structure is that in the PRO-structure, all orders from the TBTs are stored in one list. Thus, an order is shipped as soon as a FLSB has sufficient stock and an available vehicle. The IP of a FLSB decreases as soon as the order is shipped in this structure. The supplying node could, therefore, be any FLSB which means that the distance is unconsidered. In the REA-structure a FLSB only supplies TBTs from another FLSB if its own TBTs have not requested resupplies, if it has an available vehicle, and if it has sufficient supplies to complete the order. In the LAT-structure a lateral transshipment could be sent if the distance between the supplying FLSB and receiving FLSB is smaller than the distance between the receiving FLSB and the VC, if the supplying FLSB has no requests from its TBTs, and if the supplying FLSB has an IOH greater than its reorder level plus the minimum lateral transshipment amount.

6.4 Input parameters

The input parameters are categorized into demand, general, platoon, TBT, FLSB, VC, and disruption parameters. The values of the parameters are discussed with the supervisors. Due to the time limit, no further discussion with other experts could be held. Therefore, an extensive sensitivity analysis will be done to reflect on different parameter settings. Furthermore, it is chosen to use uniform distributions because no data is available on these parameters. With a uniform distribution, each outcome possibility has the same probability which results in dispersion.

6.4.1 Demand parameters

For each of the four demand levels, different demand distributions are chosen. Table 6.1 shows the values of the parameters. These values show the demand per time unit for the whole grid. In the wavy demand level, demand changes every 3 grids from high to low, the location of the platoons thus determines which demand distribution is used. So after each platoon has conquered three low demand grids, every platoon has to conquer three high demand grids and vice versa. For the peak demand level, there is a probability of 20% that a grid has an extremely high demand while there is a probability of 80% that a grid has a low demand. Moreover, the input parameter Defend_factor is used to determine the defending demand which is calculated based on Equation 6.6. In this equation, the "*demand*" denotes the demand dependent on the level which has been assigned to the grid.

$$\text{Defending demand} = \frac{demand}{Defend\_factor} \tag{6.6}$$

6.4.2 General parameters

The general input parameters are shown in Table 6.2. Two battalions operate simultaneously which results in at most 18 'lanes' and no platoons in reserve. Each TBT always supplies three platoons. The parameter "#TBT_per_FLSB" is changed in the sensitivity analysis. The general parameters "number of columns" and "number of runs" are elaborated in Section 6.5.

Table 6.1: Demand input parameters

Demand parameters		
Low demand	U(5,30)	Demand per time-unit
High demand	U(30, 60)	Demand per time-unit
Wavy demand	3 grids U(30, 60) followed by 3 grids U(5, 30)	Demand per time-unit
Peak demand	U(5,30), if $P[U(0,1) \geq 0.20]$ U(40,80), otherwise	Demand per time-unit
Defend_factor	10	Defending demand is lower than attacking demand (see Equation 6.6)

Table 6.2: General input parameters

General parameters		
#Platoons	18	Determines the width of the grid since each platoon has its own grid lane
#P_per_TBT	3	Amount of platoons a TBT serves
#TBT_per_FLSB	3	Amount of TBTs a FLSB serves
#Columns*		Number of grids each platoon should conquer
#Runs*		Number of runs to have the desired confidence interval

*These simulation properties are elaborated in Appendix D.

6.4.3 Platoon parameters

Table 6.3 shows the parameters related to the platoons.

Table 6.3: Platoon input parameters

Platoon input parameters		
P_attackTimeDist	U(0.5, 1.5)	Attack time per grid is uniform distributed
S_p	80	Basic Load/maximum capacity/Order-up-to level of a platoon
s_p	40	Reorder level of a platoon
s_p^{min}	25	Percentage at which a platoon stays put and from which the ready rate is affected.

6.4.4 TBT parameters

The parameters of the TBT are shown in Table 6.4.

Table 6.4: TBT input parameters

TBT input parameters		
TBT_movingTimeDist	U(0.1, 0.2)	Total moving time is uniform distributed
S_{TBT}	120	Basic Load/maximum capacity/Order-up-to level of a TBT
s_{TBT}	60	Reorder level of a TBT
#TBT_vehicles	1	Number of vehicles a TBT has
TBT_V_speedDist	U(0.05, 0.15)	Time per grid is uniform distributed

6.4.5 FLSB parameters

Table 6.5 shows the FLSB parameters. The values "S_{FLSB}", "s_{FLSB}", "FLSB_TBT_minDist", and "FLSB_TBT_maxDist" are also tested in the sensitivity analysis. The number of vehicles per FLSB depends on the level that is used.

Table 6.5: FLSB input parameters

FLSB input parameters		
FLSB_LatTransAmount	120	Minimum and maximum amount that could be shipped between FLSBs
FLSB_movingTimeDist	U(0.3, 0.5)	Total moving time is uniform distributed
S_{FLSB}	360	Basic Load/maximum capacity/Order-up-to level of a FLSB
s_{FLSB}	180	Reorder level of a FLSB
FLSB_TBT_minDist	2	Minimum amount of grids between a FLSB and TBT in the same line
FLSB_TBT_maxDist	5	Maximum amount of grids between a FLSB and TBT in the same line
#FLSB_vehicles	{1, 2}*	Number of vehicles a FLSB has
FLSB_V_speedDist	U(0.05, 0.15)	Time per grid is uniform distributed

*Dependent on the number of vehicles per FLSB level.

6.4.6 VC parameters

Table 6.6 shows the parameters related to the VC.

Table 6.6: VC input parameters

VC input parameters		
VC_V_speedDist	U(0.05, 0.10)	Time per grid is uniform distributed
VC_loc	5	VC is located 5 grids behind the FLSB at the start

6.4.7 Disruption parameters

The disruption parameters are divided into two levels the low and high disruption levels. The parameter values per level and can be found in Table 6.7.

Table 6.7: Disruption input parameters

Disruption input parameters			
	Low	High	
$P_{priorityEdgeDisruption}$	0.10	0.20	Probability a priority resupply is disrupted per time-unit
$P_{regularEdgeDisruption}$	0.10	0.20	Probability a regular resupply is disrupted per time-unit
$TBT_{edgeDisruption}$	0.08	0.16	Probability a TBT resupply is disrupted per time-unit
$TBT_{nodeDisruption}$	0.08	0.16	Probability a TBT is disrupted
$FLSB_{edgeDisruption}$	0.05	0.10	Probability a FLSB resupply is disrupted per time-unit
$FLSB_{nodeDisruption}$	0.05	0.10	Probability a FLSB is disrupted

6.5 Simulation properties

Since the simulation study aims to retrieve the expected conquering time, this variable is most important when defining the warm-up period, simulation length, and the number of runs.

1. Warm-up time: The warm-up period is the period that the simulation will run before starting to collect results. This period allows simulation aspects to get into conditions that are typical of normal running conditions in the considered environment (Boon et al., 2019). In this case, the expected conquering time of the operation is considered. Meaning that the start is important as well. Therefore, the simulation model does not have a warm-up time meaning that the complete operation from the start to the end is considered when determining the performance of a network. Although, as the figures in Appendix D show, there is some transient behavior in the figures until about 30 grids per platoon. Therefore, there is no warm-up since all grids are considered, but at least 30 grids should be tested to have a clear difference in performance for each structure.

2. Length of a run: Urban operations often take a long time. Mosul for example took about nine months. However, to limit the computation time, the minimum required run time is the time until the expected conquering time is stable. If a maximum run time is used it could be that a model conquers for example 10 grids per platoon while another model conquers 20 grids per platoon at the same time. Therefore, to ensure that the results of the different models and levels could be compared, not the run time but the number of grids per platoon is used as the length of a run. Appendix D shows the analysis to find the length of a run. It shows that until 30 grids per platoon the expected time to conquer is about the same for all structures. After 30 grids per platoon, there are some major fluctuations. Therefore, it is chosen to expand the analysis, so that two run-length levels are added to the simulation experiments. One level with 30

grids per platoon, thus $18 * 30 = 540$grids, and one level with 60 grids per platoon, thus $18 * 60 = 1080$grids.

3. Number of runs: The number of runs is determined with the use of Equation 6.7 which calculates the confidence interval. $z_{\alpha/2}\sqrt{\frac{S^2}{n}}$ denotes how much is off the mean. In this equation $z_{\alpha/2}$ is 1.96 based on a 95% confidence interval, S is the standard deviation of the expected conquering time, and n is the number of runs. To ensure that there is not too much from the mean, it is chosen to use a 95% confidence interval and to set the maximum of $z_{\alpha/2}\sqrt{\frac{S^2}{n}}$ to 1. The number of runs could thus differ for every level. Moreover, at least 100 runs are simulated and after that, every 10 runs it is checked if the desired value is achieved. Additionally, a maximum of 1,000 runs is set to limit the computational time. If the maximum is reached, the confidence interval of the expected conquering time is shown.

$$\left(\bar{Z} - z_{\alpha/2}\sqrt{\frac{S^2}{n}}, \bar{Z} + z_{\alpha/2}\sqrt{\frac{S^2}{n}}\right) \tag{6.7}$$

6.6 Model validation

Since there is no verified analytical model for urban operations, the complete model is validated via the face validation method as described by (Sargent, 2010). This validation method evaluates whether the model's behavior is reasonable and possesses sufficient accuracy for the levels and various input parameters. First, the sequence of simulation events is checked. Second, the behavior and primary requirements of the model under different parameters are numerically and visually assessed. For example, the ready rate could never be higher than one, lead-times could never be negative, and the relationship between the number of grids and lead-times is as expected. On top of that, the model was tested under extremely high demand parameters which revealed that no grids could be conquered. When the model was tested under extremely low demand, the expected conquering time was the lowest. Lastly, the different levels that were modeled were validated by comparing the behavior and results with each other.

Chapter 7

Results

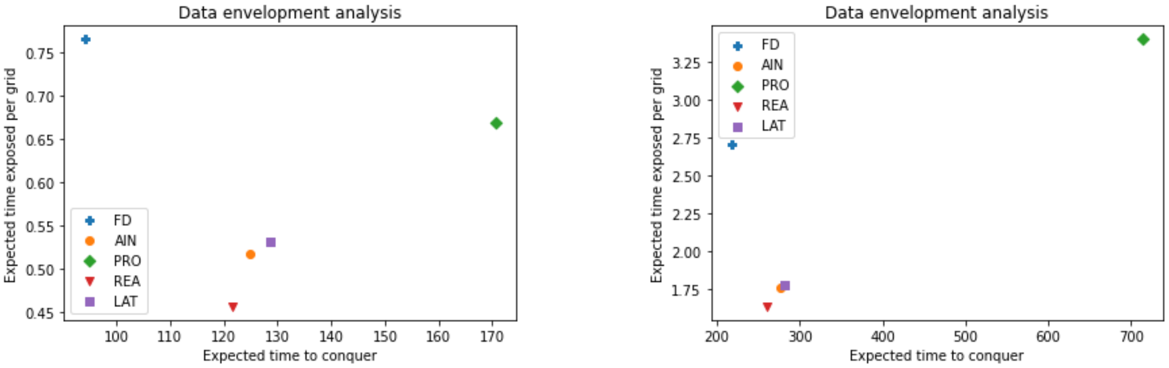
In this chapter, the performances of the network structures are discussed. The simulation model as described in Chapter 6 is used to test different input parameter levels on the network structures. Five structures are each tested on 4 demand levels, 2 disruption levels, 2 number of vehicle levels, and 2 run length levels resulting in 160 combinations. First, the experiments with 30 grids per platoon are elaborated. Afterward, the experiments with 60 grids per platoon are elaborated. For 30 grids per platoon, first, the low disruption level is described, afterward, the high disruption level is described. For the low disruption level, first, 1 vehicle per FLSB is described, afterward with 2 vehicles. The same structure is used for 60 grids per platoon. Moreover, to have a comprehensive results chapter, the Tables with the performance indicator values and features are shown in Appendix E. Additionally, the full factorial table with heatmaps could be found in Appendix F. The DEA figures are shown in this chapter to see the differences in KPIs.

7.1 30 grids per platoon level

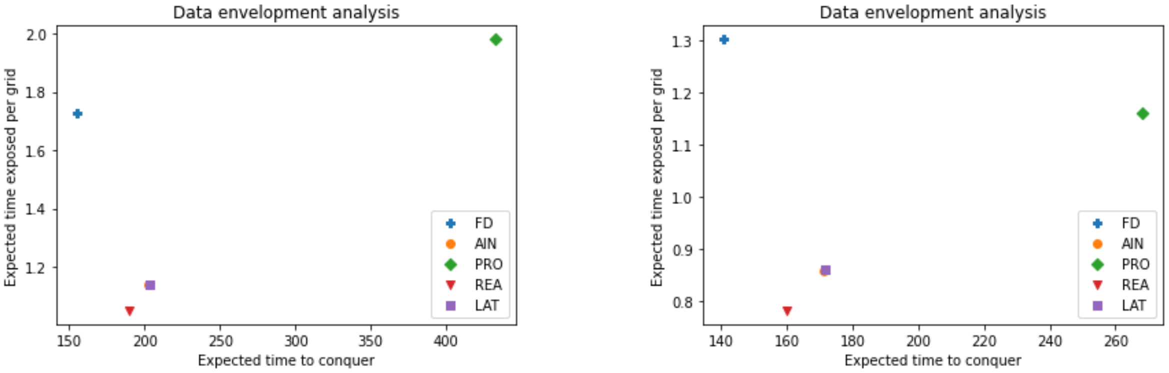
7.1.1 Low disruption level

7.1.1.1 1 vehicle level

The results of the network structures tested on 30 grids per platoon with the low disruption level and 1 vehicle per FLSB are discussed in this section. It was found that the LAT-structure performs slightly worse than the AIN-structure in all demand levels. Moreover, the PRO-structure performs worst on most indicators. The expected time to conquer is always by far the highest for the PRO-structure, which could be due to the much higher lead-times which are caused by the allocation policy of the PRO-structure. This allocation policy does not take the distance into account which likely affects the lead time and therefore the expected time to conquer and expected exposed time per grid. Additionally, since the expected time to conquer is so large, more resupplies are requested which also results in more rides. However, the PRO-structure has a lower expected exposed time per grid in the low and peak demand level compared to the FD-structure.



(a) Low (b) High



(c) Wavy (d) Peak

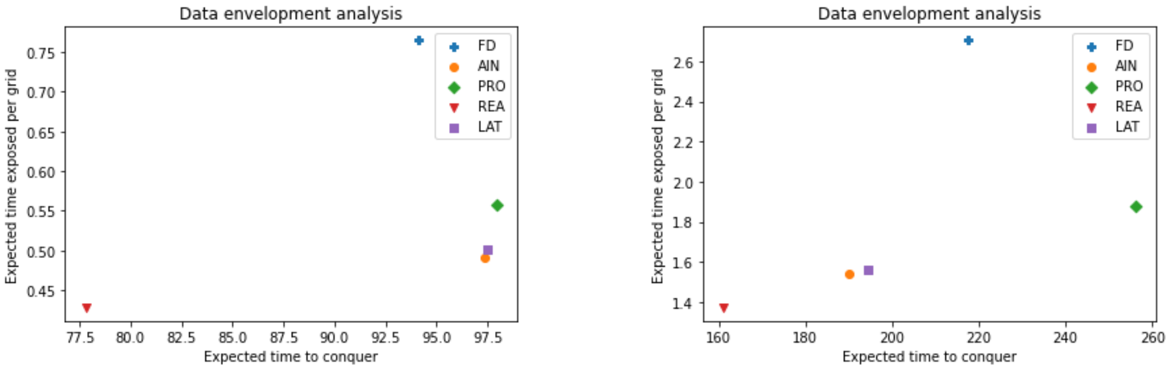
Figure 7.1: Data envelopment analysis of demand levels with the 30 grids per platoon level, low disruption level, and 1 vehicle per FLSB level

The expected time to conquer is the lowest for the FD-structure in all demand levels. Structures with FLSBs could perform worse due to the (vehicle) capacity of the FLSBs. As a result, resupplying TBTs might take longer which could affect the expected conquering times. In the FD-structure, TBTs are resupplied by the VC and the VC has unlimited (vehicle) capacity and could therefore immediately supply TBTs. However, this might also lead to a higher expected exposed time per grid because every time a TBT's IP drops below s_{TBT} a vehicle is sent. While higher order sizes are shipped from the VC to the FLSB due to a higher MOQ for the FLSB than for the TBT. Additionally, in the structures with FLSBs, TBT's orders could be adjusted, meaning that just before a shipment, the IP of a TBT is checked to determine the order size which could result in fewer rides and a lower expected exposed time per grid. However, the number of rides for structures with FLSBs is larger compared to the FD-structure because an additional node results in more rides. Furthermore, it appeared that the ready rate of the REA-structure is slightly lower than for the other structures with FLSBs. This could be due to a small expected conquering time. The small expected conquering time ensures that the platoons are relatively most of the time conquering than defending compared to the other structures. Since it is expected that platoons are most likely short on ammunition when they are conquering and less often when they are defending, the ready rate could be slightly lower. Besides, it was found that the lead-time for priority resupplies is larger than for regular resupplies which might be because each platoon starts conquering a grid at the same time, therefore, it is expected that priority requests arrive closer to each other than regular requests. Due to the (vehicle) capacity of the supplying nodes, platoons might have to wait longer to be resupplied. Since it is expected that the regular requests arrive more dispersed, TBTs have more time to react to these requests.

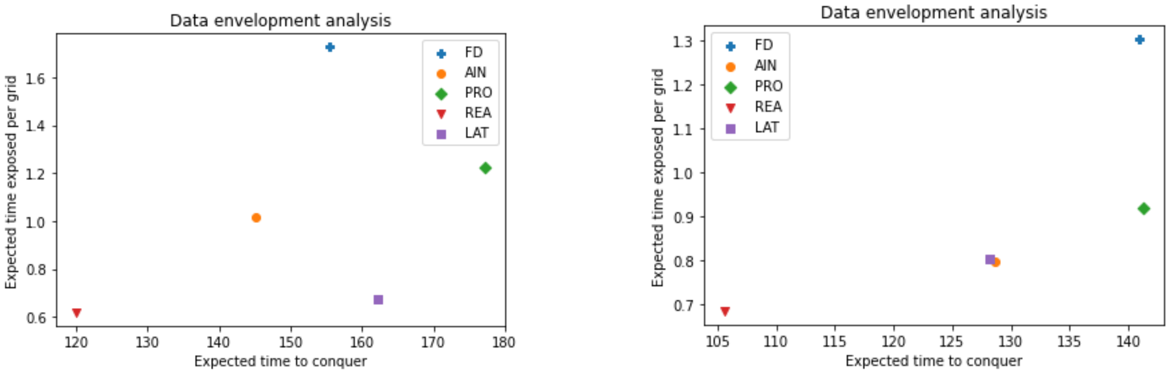
To determine the best-performing structure, the DEA plots are used. The figures show that in all demand levels the FD-structure has the lowest expected conquering time. However, the REA-structure is closest to the origin. As elaborated, the AIN- and LAT-structure perform quite similarly. Moreover, the PRO-structure performed by far the worst, compared to the other structures (with FLSBs).

7.1.1.2 2 vehicles level

In this section, the results of the five network structures with four different demand levels for 30 grids per platoon with the low disruption level and 2 vehicles per FLSB are discussed. Since the FD-structure has no FLSBs, the results of the FD-structure do not change compared to Section 7.1.1.1.



(a) Low (b) High



(c) Wavy (d) Peak

Figure 7.2: Data envelopment analysis of demand levels with the 30 grids per platoon level, low disruption level, and 2 vehicles per FLSB level

It was found that for all structures with FLSBs the expected time to conquer decreased compared to the previous results with only 1 vehicle. Especially the PRO-structure performed much better. A striking thing is that the expected time exposed per grid and the number of rides for the structures with FLSBs decreased as well. It was expected that this would increase because shipments are sent more often and would thus contain a lower order size due to fewer adjustments. However, due to a shorter expected time to conquer, less resupplies were probably needed which resulted in fewer rides and less expected time exposed per grid. Another striking thing is that in the peak demand level, the LAT-structure performed slightly better on the expected time to conquer KPI than the AIN-structure. It could be that an additional vehicle makes it more favorable to make a lateral-transshipment. However, the difference is extremely small, it only holds for the peak demand level, and the LAT-structure performs worse on the expected time exposed per grid KPI compared to the AIN-structure. The DEA plots in Figure 7.2 show that the REA-structure performs best on both axes in all demand levels, while in the experiment with 1 vehicle the FD-structure performed better in the expected time to conquer.

7.1.2 High disruption level

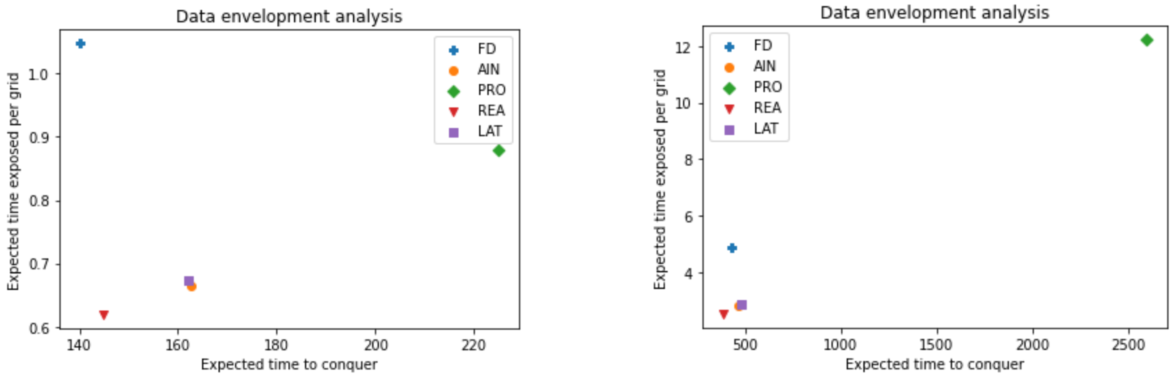
7.1.2.1 1 vehicle level

This section discusses the results of the five network structures with four different demand levels for the 30 grids per platoon with the high disruption level and one vehicle per FLSB.

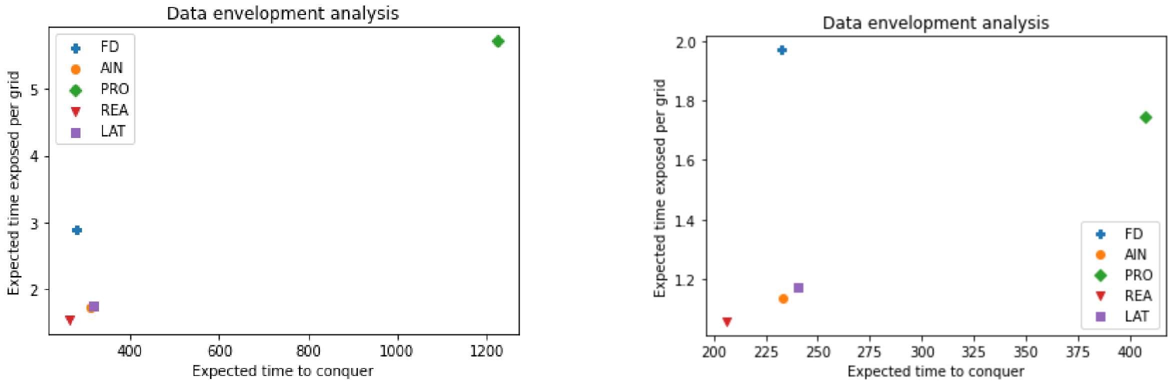
It was found that the expected time to conquer and expected exposed time per grid increased for all structures compared to the low disruption level. However, the increase was highest for the FD- and PRO-structure and the lowest for the REA-structure. Figure 7.3 shows that the FD-structure still had the shortest expected time to conquer in the low demand level, however, in the other demand levels the REA-structure had both the smallest expected time to conquer and expected exposed time per grid. Additionally, the AIN- and LAT-structure scored better compared to the FD-structure.

7.1.2.2 2 vehicles level

Compared to the results of the low disruption level and two vehicles per FLSB it appeared that the structures with FLSBs performed better with more disruptions than the FD-structure. The REA-structure performs on both KPIs by far the best in all demand levels as shown in Figure 7.4. Moreover, compared to the results with the high disruption level and one vehicle per FLSB, it could be seen that the FD-structure performed much worse than the other structures.

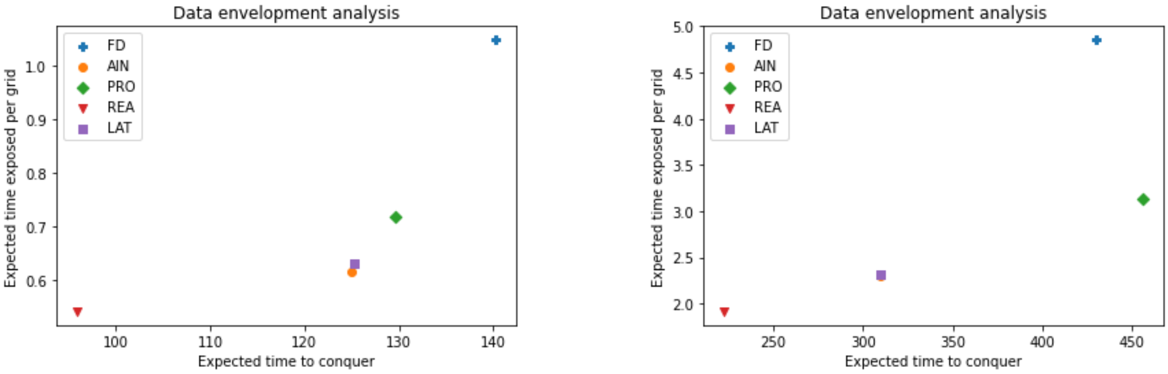


(a) Low (b) High



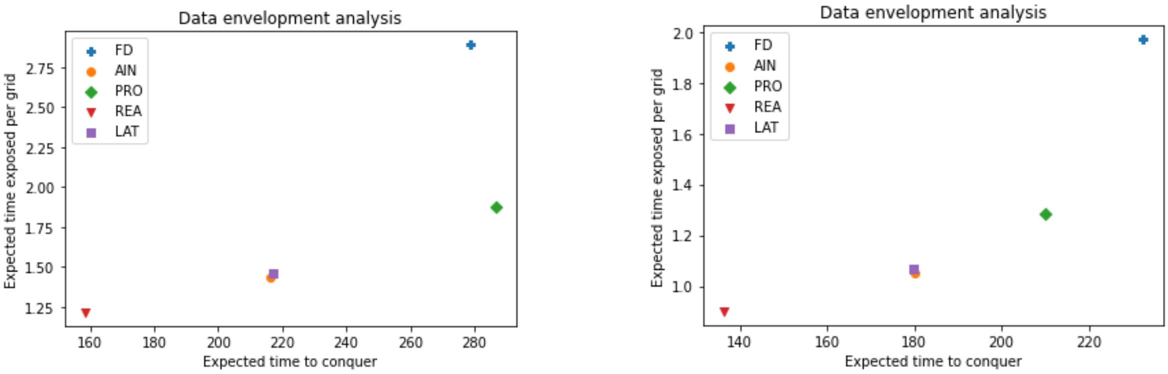
(c) Wavy (d) Peak

Figure 7.3: Data envelopment analysis of demand levels with the 30 grids per platoon level, high disruption level, and 1 vehicle per FLSB level



(a) Low

(b) High



(c) Wavy

(d) Peak

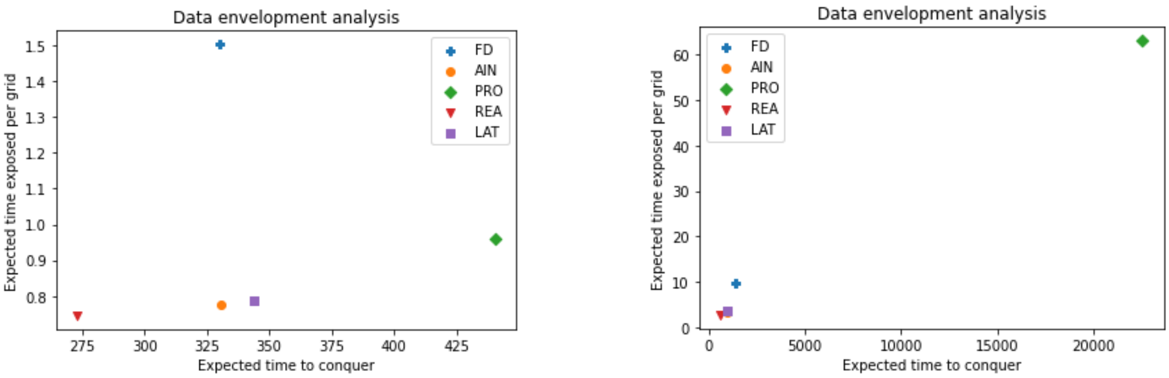
Figure 7.4: Data envelopment analysis of demand levels with the 30 grids per platoon level, high disruption level, and 2 vehicles per FLSB level

7.2 60 grids per platoon level

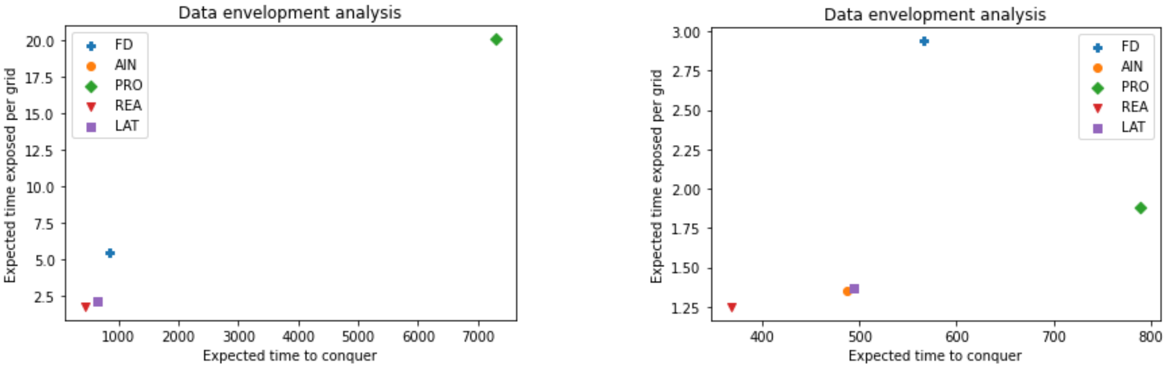
7.2.1 Low disruption level

7.2.1.1 1 vehicle level

This section discusses the results with a run length of 60 grids per platoon with the low disruption level and one vehicle per FLSB. The main difference with the 30 grids per platoon level is that the expected conquering time of the FD-structure increased more than for the experiments with FLSBs. With the 30 grids per platoon level, the FD-structure had always the lowest expected time to conquer and with the 60 grids per platoon level, the REA-structure has the lowest expected time to conquer. Additionally, the AIN-structure performed in all demand levels better on both KPIs compared to the FD-structure. Furthermore, the PRO-structure had in all demand levels by far the largest expected time to conquer. The reason could be that in the PRO-structure the IP of the FLSB decreases as soon as the TBT order is shipped, while in the other structures the FLSB IPs decrease as the TBT order is requested. FLSBs are thus resupplied later and in combination with a larger lead-time between the VC and FLSB, it is ineffective. Figure 7.5 shows that indeed the REA-structure performs best on both measures in all demand levels.



(a) Low (b) High

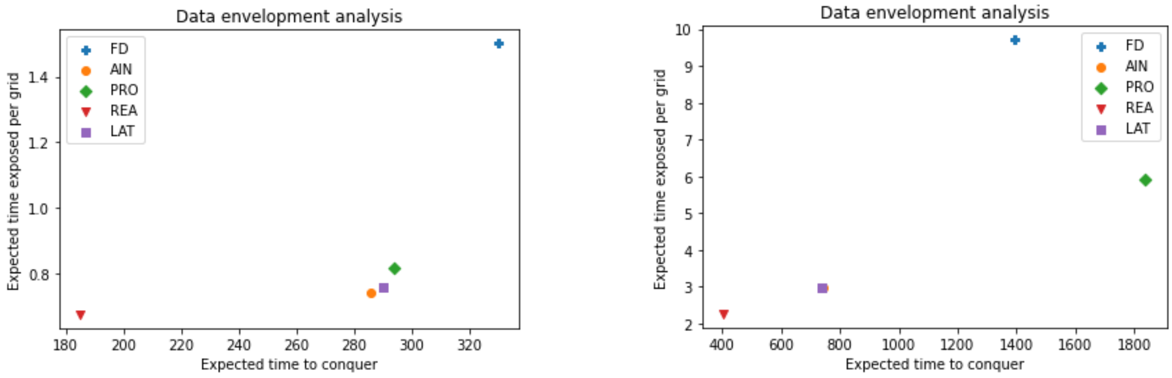


(c) Wavy (d) Peak

Figure 7.5: Data envelopment analysis of demand levels with the 60 grids per platoon level, low disruption level, and 1 vehicle per FLSB level

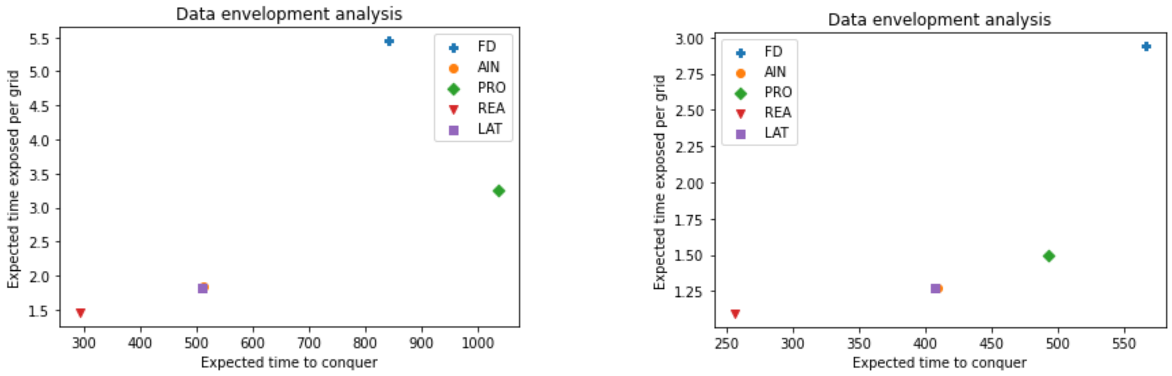
7.2.1.2 2 vehicles level

In this section, the results with a run length of 60 grids with few disruptions and two vehicles per FLSB are elaborated. No striking things were found. The structure with FLSBs performed better with 2 vehicles than with 1 vehicle. Due to a larger run length, the FD-structure performed worse compared to 30 grids. The same as for the 30 grids, the PRO-structure performed much better with two vehicles per FLSB than with one.



(a) Low

(b) High



(c) Wavy

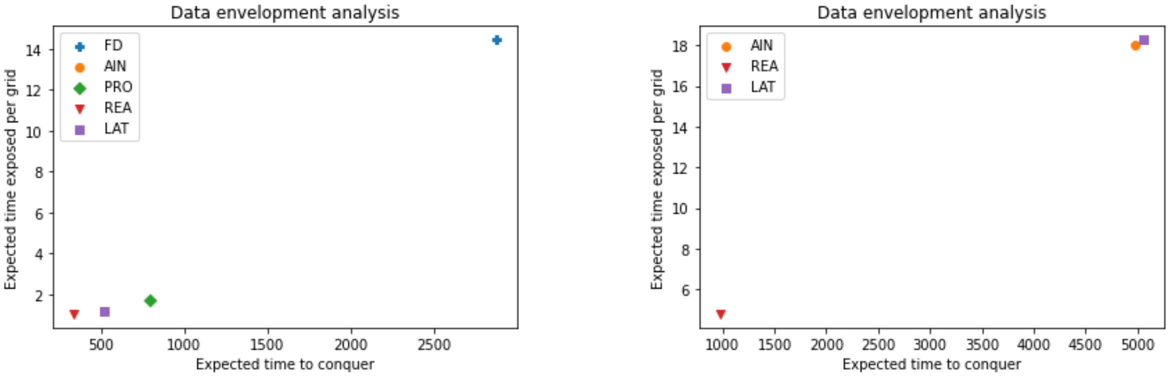
(d) Peak

Figure 7.6: Data envelopment analysis of demand levels with the 60 grids per platoon level, low disruption level, and 2 vehicles per FLSB level

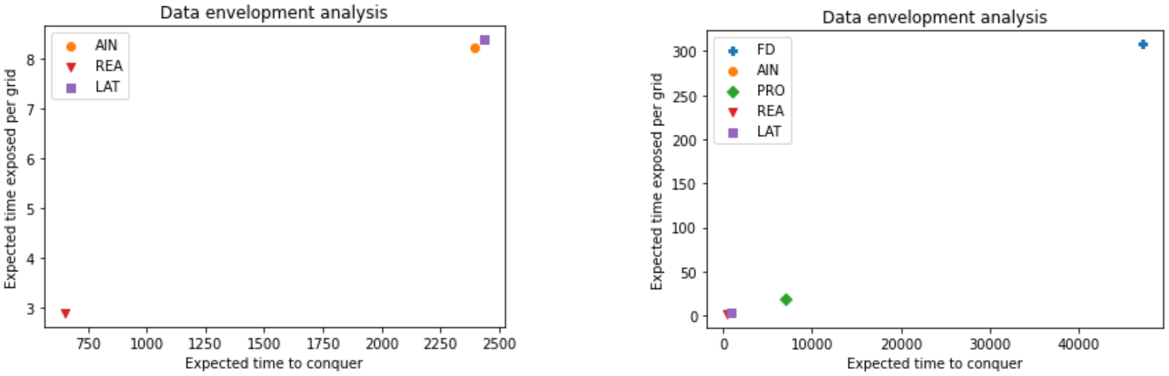
7.2.2 High disruption level

7.2.2.1 1 vehicle level

In this section, the results with a run length of 60 grids per platoon with the high disruption level and only one vehicle per FLSB are elaborated. It appeared that the FD-, and PRO-structure both were infeasible with this set of parameters for the high and wavy demand level. Too many disruptions caused that these network structures could not supply soldiers on time such that they could not conquer all grids. The FD-structure was feasible for the low and peak demand level, however, it performed by far the worst of all structures. Again, the REA-structure performed best for all demand levels. When comparing these results with the results of the low disruption level, it could be seen that the number of disruptions affects the results and the order of best performing structure.



(a) Low (b) High

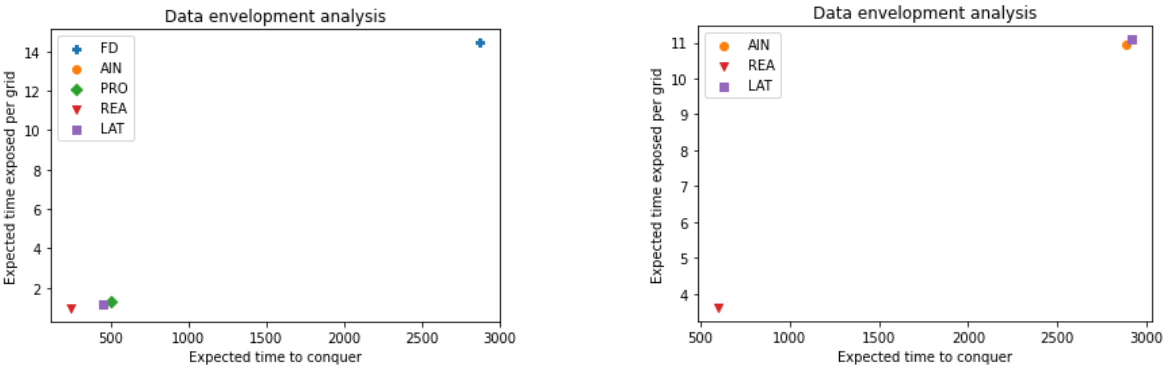


(c) Wavy (d) Peak

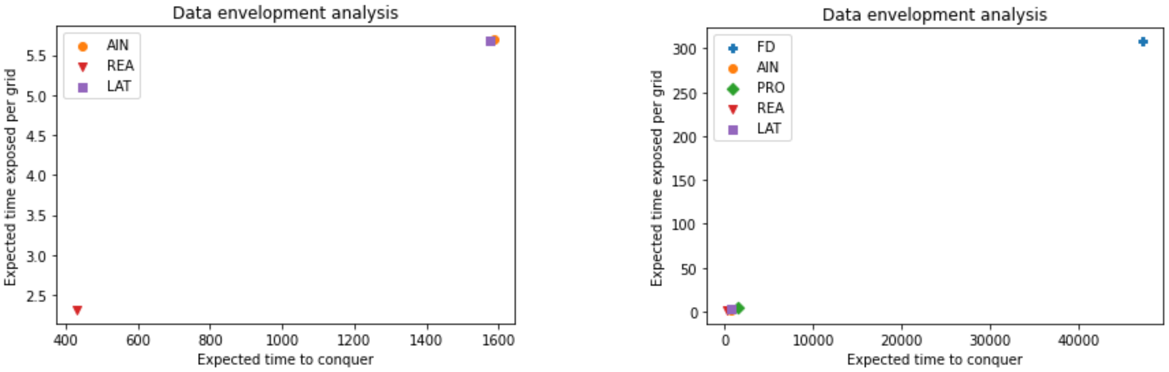
Figure 7.7: Data envelopment analysis of demand levels with the 60 grids per platoon level, high disruption level, and 1 vehicle per FLSB level

7.2.2.2 2 vehicles level

This section shows the results with a run length of 60 grids per platoon with the high disruption level and two vehicles per FLSB. Again, the FD-, and PRO-structure both were infeasible with this set of parameters for the high and wavy demand level. Similar results as in the previous section with only one vehicle were retrieved. However, the structures with FLSBs performed logically better with two vehicles. No changes in best performing structure were found.



(a) Low (b) High



(c) Wavy (d) Peak

Figure 7.8: Data envelopment analysis of demand levels with the 60 grids per platoon level, high disruption level, and 2 vehicles per FLSB level

7.3 Summary

First, the demand levels are evaluated to answer RQ5. In total four different demand levels were tested. The demand levels mainly affected the performances of the FD- and PRO-structure. This might be because in these structures the distances are larger compared to the AIN-, REA-, and LAT-structure. In the FD-structure the distance between VC and TBT is large and in the PRO-structure the distance between the FLSB and TBT is larger due to its allocation rule. Longer distances could result in longer lead-times times which affect the performances. The AIN-structure, REA-structure, and LAT-structure scored relatively similar at all levels. Meaning that for these three structures the demand does not affect the order of best performing structure. These structures could be less affected by different demand levels because the distances between nodes are smaller in these structures than for the FD- and PRO-structure.

Second, the number of vehicles per FLSB is discussed. Two levels were tested, one in which each FLSB had 1 vehicle and one in which each FLSB had 2 vehicles. For all structures with FLSBs, the performance logically increased with more vehicles. The PRO-structure performed much better but it could still not compete with the other structures with FLSBs.

With two vehicles per FLSB, the PRO-structure could earlier supply TBTs which resulted in better performances, however, the distance was still unconsidered which had a large impact on the performance. Furthermore, an additional vehicle does not make lateral trans-shipments favorable. It was expected that with more vehicles lateral trans-shipments would perform better than without, however, it is likely that when a FLSB supplies to another FLSB, the supplying FLSB can get shortages which affect the performances. All in all, more vehicles per FLSB provided better performance for all structures with FLSBs, however, differences remained.

Thirdly, the amount of disruptions is evaluated to answer RQ4. Two levels with different amounts of disruptions both on nodes and edges were tested. It was found that the number of disruptions negatively affected all structures but affected the FD- and PRO-structure the most. This also explains that these structures were infeasible in the high and wavy demand level for 60 grids. Again, it is expected that these two structures are more affected by disruptions due to the large distances, just as with the demand levels. The larger distances affect the lead-times and anticipating on disruptions would take longer. The AIN-, REA-, and LAT-structure were most resilient under disruptions. However, the number of disruptions did not lead to a different best-performing structure.

Fourthly, the run length levels are elaborated. The performances of the FD-structure and PRO-structure are affected most by a larger number of grids. Once more, it is expected that the influence of the larger distances in the FD- and PRO-structure increases as the number of grids per platoon increases. The figures in Appendix D show that the performances of the FD- and PRO-structure are most affected by the run length. However, those figures only show one run. To further investigate the run length on the performances, Appendix G shows the figures with the means of 100 runs with the low disruption level and one vehicle per FLSB. These figures show that in the first grids until the cross points of the FD- and REA-structure line, the FD-structure has the lowest expected conquering time. This is in line since in the 30 grids per platoon level the FD-structure performed best when looking at the conquering time. Furthermore, it could be seen that the conquering time increases more for the FD-structure and PRO-structure than for the AIN-, REA-, and LAT-structure as the run length increases. The findings in the figures correspond to the results retrieved with the full factorial design. Moreover, a larger run length leads, as expected, to large lead-times. However, this is undesired because when soldiers request supplies they want those as soon as possible because their lives could depend on those supplies. Therefore, an additional intermediate node between the FLSB and VC might counter this problem.

Lastly, the different structures are evaluated. In total five structures were tested with 32 different experiments each. The LAT-structure scored in almost all experiments slightly worse than the AIN-structure. Meaning that lateral trans-shipments do not increase the performance in this model. This could be because the supplying FLSB of a lateral trans-shipment can get shortages which affect the performance of the structure. Furthermore, it was found that the expected time to conquer for structures with FLSBs is larger than for the FD-structures if the FLSBs have only one vehicle and each platoon has to conquer 30 grids. The limited (vehicle) capacity of FLSBs increases the lead-time and therefore likely the expected time to conquer. In the FD-structure the TBTs are resupplied by the VC which has unlimited (vehicle) capacity. However, with the 60 grids per platoon level, the FD-structure performed worse because the distance between VC and TBT becomes too large. Furthermore, the REA-structure performed best on both KPI measurements for all experiments except for the 30 grids with 1 vehicle. Moreover, the REA-structure is less affected by the demand, the number of vehicles, and the run length. The REA-structure probably performs well because it has an additional stock point, it considers distances when allocating customers and it allows FLSBs to help each other if a FLSB has the resources to do so. However, the REA-structure has a slightly lower ready rate in some experiments which could be because platoons are relatively more time conquering than defending compared to the other structures. Since it is expected that platoons are most likely short on ammunition when they are conquering and less often when they are defending, the ready rate could be slightly lower. The PRO-structure scored significantly worse compared to the other structures (with FLSBs) because it does not consider the distance when allocating TBTs to FLSBs. All in all, the REA-structure performed best, however, if FLSBs have one vehicle and there are few grids, the FD-structure could have a lower expected time to conquer.

7.4 Sensitivity analysis

The results explained above are based on estimated parameter values. To test the models' sensitivity to these parameters a sensitivity analysis is performed. To do that, parameters are adjusted up and down and the resulting change in KPIs is evaluated. The parameters that are tested in the sensitivity analysis are the TBT's reorder level (s_{TBT}), the amount of FLSBs, the FLSB's order-up-to level (S_{FLSB}), the FLSB's reorder level (s_{FLSB}), and the distance between FLSBs and TBTs. A full overview and explanation of the results of the tests can be found in Appendix H. The model is sensitive to a high TBT reorder level because a high reorder level for TBTs negatively affects the KPIs of some structures. The following tests give answers to RQ6. The model is namely sensitive to the amount of FLSBs since the performance of the models with FLSBs increased with more FLSBs such that they perform better than the FD-structure. Furthermore, the model is not sensitive to the capacity or order up-to-level of the FLSB. Additionally, the model is not sensitive to the FLSB reorder level. Lastly, the model's sensitivity to the distance between the FLSBs and TBTs is tested. It turned out that the model is sensitive to this parameter since the performance decreased a lot with a larger distance.

Chapter 8

Conclusion

The objective of this research was to investigate what a resilient distribution network in urban operations should look like. For this purpose, the problem situation was identified with the use of experts of the RNLA, thereafter different network structures were tested in different experiments with the use of a face-validated simulation model. This final chapter concludes the insights obtained in the research and reflects on the research conducted. Section 8.1 summarizes the conclusions of this research and answers the main research question specified in Section 1.2.2. Thereafter, in Section 8.2 the scientific contributions are elaborated. Section 8.3 discusses the limitations of this research and formulates directions for further research. Lastly, the research ends with some recommendations for the RNLA in Section 8.4.

8.1 Conclusions

More wars will likely take place in urban areas. The traditional method that has been used to fight the enemy in urban areas has been that of massive destruction with bombings. An undesired consequence of these bombings is economic disruptions and usually many civilian casualties. This should be prevented and to do so, armies could siege a city. When sieging a city, all buildings should be cleared from adversaries. However, this method uses many soldiers in the city who should have supplies at all times. Therefore, a resilient distribution network should be designed to supply soldiers. However, the distribution network has to deal with an adversary which can disrupt the network, extreme fluctuations in demand, stochastic lead-times, and changing customer locations. Therefore, the distribution network should be viable to function well in a disruptive and dynamic environment. Thus the following main research question was formulated:

> *What should the design of a resilient distribution network in urban operations look like?*

Six sub-research questions were formulated to answer the main research question. The first sub-research question discussed which distribution network structures are suitable for urban operations. Several experts were asked to reflect on network structures found in the literature. It was found that TBTs, platoons, and groups operate according to an extremely trained routine. These routines were therefore not to be changed. However, between the VC and the TBTs changes in structure were possible. It was discussed that an additional intermediate node (FLSB) between the VC and TBTs might be necessary due to the increasing lead-times.

Moreover, it was argued that multiple resourcing from FLSBs to TBTs might have some potential. Additionally, it was discussed that lateral transshipments between FLSBs might also have some potential. Therefore, it was concluded that five different network structures might be suitable for urban operations.

The second sub-research question focused on the Key Performance Indicators to compare different network structures. Two key performance indicators were formulated. First, is the expected conquering time which denoted the total time it takes to conquer a complete city. This indicator is highly relevant since a lengthy operation may cost many resources and possibly more casualties. However, it is assumed that a lengthy operation increases the number of casualties and resources, this is not investigated. Second, the expected exposed time per grid denoted the sum of the lead times over all echelons divided by the total number of grids. This indicator thus shows the average time vehicles are shipping to supply platoons such that they could conquer a grid. These two key performance indicators were used to evaluate network structures with the use of a data envelopment analysis. Moreover, different indicators and network features were considered when analyzing the structures such as the ready rate, number of nodes, number of edges, average lead-times, and number of rides.

The third sub-research question concerned the scenarios the distribution network should be tested on. Since there was little to no data available regarding urban operations, experiments had to be designed based on the literature study and the information retrieved from the interviews. Concluding, the scenarios tested were two-run lengths, two amounts of disruption, two numbers of FLSB vehicles, and four demand levels.

The fourth sub-research question focused on the influence of disruptions on the distribution network structures. Both disruptions on nodes and edges were considered. The number of disruptions negatively affected the performance. More disruptions lead to lower performances and fewer disruptions lead to higher performances. Especially the current physical distribution and the pro-active multiple resourcing structures performed much worse with more disruptions.

The fifth sub-research question focused on the influence of demand levels on the distribution network structures. The structure with a FLSB, the structure with reactive multiple sourcing, and the structure in which lateral trans-shipments were allowed, performed in all four demand levels quite similarly. However, the current physical distribution structure and the pro-active multiple resourcing structure performed better than the other depending on the demand level. Concluding, the structure with a FLSB, the structure with reactive multiple sourcing, and the structure in which lateral trans-shipments were allowed were less affected by different demand levels. Armies have often some information regarding the demand in urban areas, however, the demand could rapidly change in urban areas. Therefore, structures must be able to withstand different demand consumption. The structure with a FLSB, the structure with reactive multiple sourcing, and the structure in which lateral trans-shipments were allowed thus are more suitable in urban operations than the current physical distribution and pro-active multiple resourcing structure.

The sixth sub-research question discussed the parameters of FLSBs. More FLSBs resulted logically in better performances for structures with FLSBs. Besides, a higher or lower FLSB capacity has a minor influence on the performance of the structures. A higher or lower FLSB reorder level has some influence on the performance. Furthermore, the distance between the

FLSBs and TBTs has a major influence on the results. The parameters could be optimized to find possibly better values. All in all, FLSBs should be located close to the TBTs and more FLSBs result in better performances. However, too many FLSBs are undesirable because more people and resources should operate in dangerous urban areas to keep the FLSBs operational and safe.

In conclusion, the reactive multiple sourcing structure performed best. This structure allows FLSBs to help other FLSBs if it has no tasks themselves and if it has sufficient inventory. In most experiments, the expected conquering time and expected exposed time per grid were the lowest. Since it is hard to forecast the demand in urban operations, a structure must be reliable with different demand levels, which is the case for this structure. Additionally, it performed well with more disruptions. Moreover, the structure performed well in multiple city sizes. On top of that, the lead-times are in most experiments the lowest for this structure. This is important as well since if soldiers in the front request supplies, they want those as soon as possible since their lives could depend on them. This structure has in most experiments both the lowest priority and regular lead-time. Concluding, the reactive multiple resourcing structure performed best in a disruptive and dynamic environment.

8.2 Scientific contributions

This research is an extension of the existing literature on network design structures by adding both disruptions and dynamics. Disruptions are increasingly included to design networks. Disruptions such as the container ship Evergiven which blocked the Suez Canal and the COVID-19 pandemic which caused many disruptions certainly contribute to this. Moreover, changes in customer locations are also becoming an important topic due to for example flash deliveries. With flash deliveries, there are many different customer locations and allocating customers to stores is a part of the network design. However, although disruptions and dynamics are both important when designing a network, most studies only consider either of them. This study stands out since it considers both disruptions and dynamic factors when designing the network structure. Moreover, (Fattahi et al., 2017) stated that as the customers' sensitivity to the delivery lead-time of products increases, the facilities that supply these customers should be located closer to them. This was also found in this research since when the run length increased the supplies had to be located close to the customers. However, an efficient customer allocation policy is important as well since it was found that an inefficient allocation policy has a major influence, likely even more than having supply facilities closer to customers.

8.3 Limitations and future research

The research is limited by a set of assumptions. This research considered ammunition as a black box. While in reality many different types of ammunition are used and each type has specific characteristics regarding volume among others. Further research could, therefore, dive more into these different types of ammunition that are used and to further come up with for example capacity restrictions for vehicles that might affect the results of the network structure. This limitation creates an opportunity to further investigate different ammunition types and ammunition consumption. In addition, when more information is available on these types of ammunition and ammunition consumption, it would be useful to study whether standard ammunition packages could be beneficial for soldiers and the logistics. Additionally, not just ammunition need to be supplied to the soldiers, they also need food, water, batteries, and medical supplies among others. The study could therefore be broadened such that these supplies are also considered when determining the network structure. Moreover, return flows of for example ammunition boxes could also be considered in future research.

The parameter values used in the simulation study can be seen as a limitation of the research. Since little to no data is available regarding urban operations, most parameters were estimated and validated by the supervisors. If more information and data becomes available, the simulation study could be improved. Moreover, future research could optimize parameters such as the distance between FLSBs and TBTs. Additionally, it appeared that lateral trans-shipments were unfavorable in this model. It could be that having a fixed lateral trans-shipment amount, might be unfavorable. Therefore, future research could investigate if lateral trans-shipments become favorable if the lateral trans-shipment amount is lower and/or more flexible.

Furthermore, it was assumed that each platoon had to wait on every other platoon to conquer the next grid. However, it would be interesting to investigate if the performance would increase if platoons only have to wait on the platoon in their battalion or company. The risk of a dispersed field increases, however, if the expected conquering time and/or expected exposed time decreases it might be beneficial. Agreements could still be made to determine maximum differences between attacking units.

Besides, from the results, it appeared that the lead-times were quite high in a large city. It is, therefore, interesting to further investigate what the influence is if an additional echelon, thus between the VC and FLSB, with one or multiple nodes is added to the structures. In addition, there could be a phase difference, thus if a certain distance is conquered, an additional echelon is added to increase the performance for example. Moreover, an additional network structure could be tested which anticipates on disruptions. The reactive-multiple resourcing edges in this study were only used if a node had the resources to help another node. In an additional structure, the reactive-multiple resourcing edges could also be used when a disruption occurred on a node so that another node could help the disrupted node.

Furthermore, since urban operations take a while, people and machines should be altered during an operation. People get exhausted or even wounded and thus should be changed. Machines could get destroyed and must therefore also be changed or maintained. When new soldiers or machines enter the battle, they have likely maximum supplies. This is, however, unconsidered in this research but might be interesting to further investigate if this affects the performance of the structures. Moreover, drones or automated vehicles are likely to be used in the future to supply soldiers. Drones for example could be much faster and the expected exposed time of automated vehicles might be less important. These new developments should therefore be considered when designing the network structure. These developments are not taken into account for this research and are therefore a direction for future research.

8.4 Recommendations

Based on the findings of this study, it is recommended that the RNLA applies a reactive multiple resourcing network structure when operating in urban areas. Disruptions, extreme demand fluctuations, stochastic lead-times, and changing customer locations are all characteristics of urban warfare. The currently used physical distribution concept seemed not that suitable under these conditions. However, the reactive multiple resourcing structure appeared to be most promising under these conditions. The interviews revealed that this strategy was suitable for urban operations. Although, the practice may show differently due to a more complex line of communication for example. Therefore, it is recommended that the RNLA starts training with this network structure to gain experience and drills so that it can be used in real operations if necessary.

However, as explained in the previous section there are many limitations to this research. It is, therefore, also recommended to further investigate the future research directions given in the previous section. To retrieve more information and data about urban operations, it is recommended that in urban operation exercises the logistic should actively participate as well. Currently, only the maneuver trains in urban operations. The logistics trains for urban operations as well, however, not together with the maneuver. Training together might lead to more effective cooperation with the maneuver and logistics and more information regarding network structures which might not be as suitable in urban operations as expected. In addition, if logistics are seriously considered in exercises, there will be more information regarding the types of ammunition needed and the quantities which could also improve the model. Moreover, the logistics participation could be implemented in war game simulations such that training becomes more easily.

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Appendix A

Transportation mode FD concept

A.1 WLS with flatrack

Figure A.1 shows a WLS with a flatrack. The picture is retrieved from https://www.defensie.nl/ onderwerpen/materieel/voertuigen/scania-wissellaadsysteem.

Figure A.1: WLS with flatrack

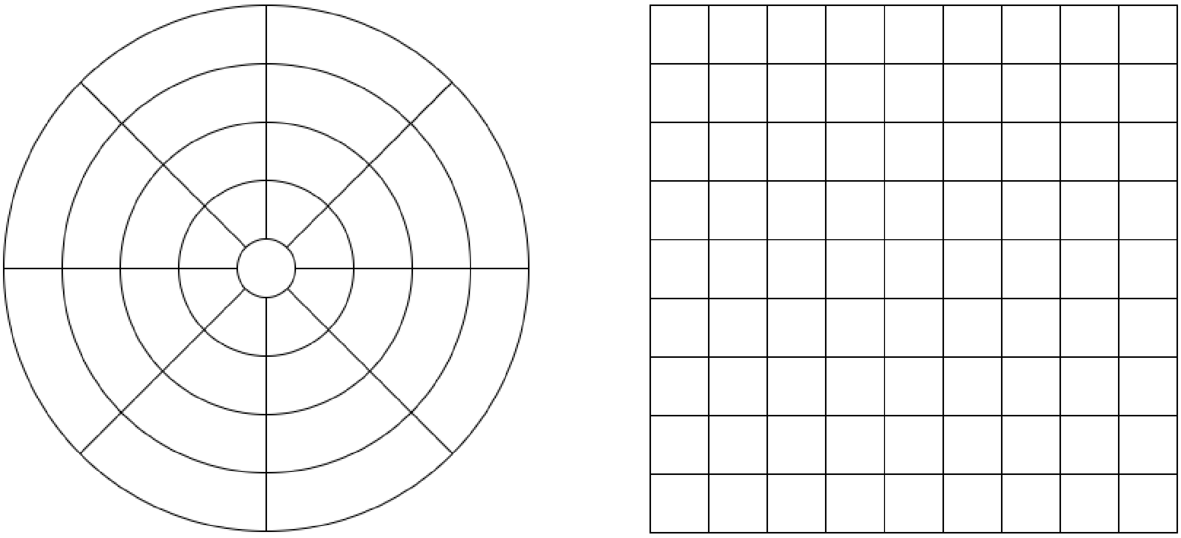
A.2 WLS with container

Figure A.2 shows a WLS with a container. The picture is retrieved from https://www.defensie.nl/ onderwerpen/materieel/voertuigen/scania-wissellaadsysteem.

Figure A.2: WLS with container

Appendix B

Grid examples



(a) Circle (b) Square

Figure B.1: Grid examples

Table B.1 shows the starting situation of the structures with FLSBs in which each platoon should conquer 30 grids in its lane.

Table B.1: Starting grid in which each platoon has to conquer 30 grids

									P																														
								TBT	P																														
									P																														
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					FLSB			TBT	P																														
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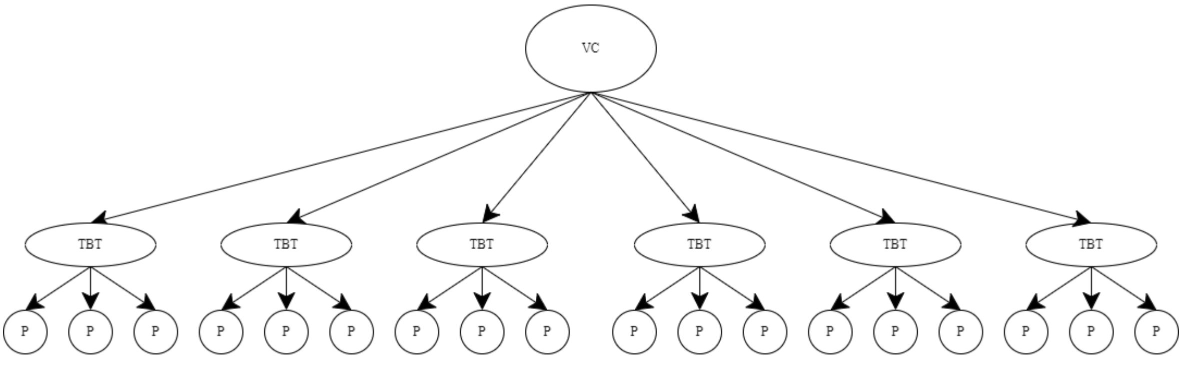
								TBT	P																														
VC									P																														
									P																														
								TBT	P																														
									P																														
									P																														
					FLSB			TBT	P																														
									P																														
									P																														
								TBT	P																														
									P																														

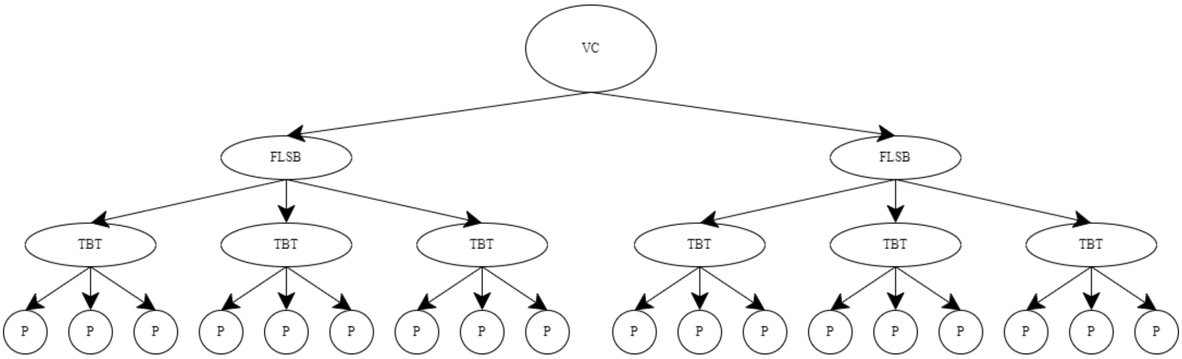
Appendix C

Structures

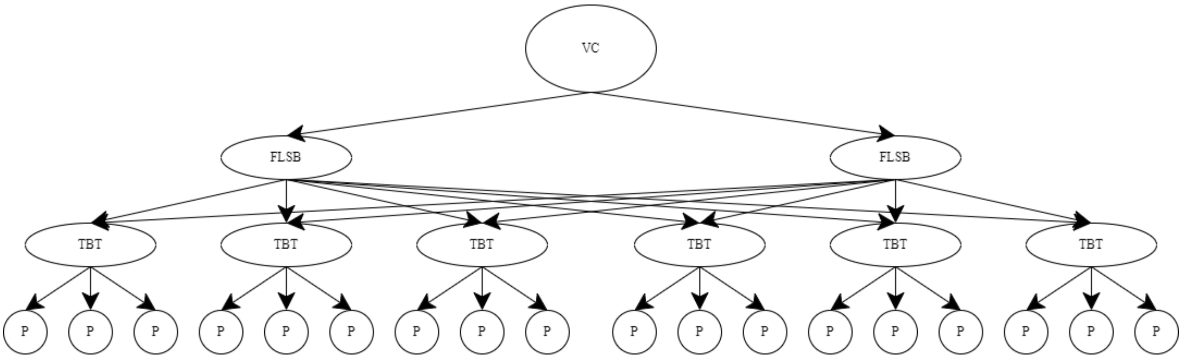
The five network structures that are tested in the simulation model are shown in this section. There is a layering of concepts in these structures. The base is the current FD structure. In the AIN, two additional intermediate nodes (FLSBs) are added. The AIN-structure is the base for the remaining structures. The dashed lines in the REA-structure are only used if the supplying FLSB has an available vehicle, no outstanding orders, and sufficient supplies to complete an order of the other FLSB.



(a) FD-structure

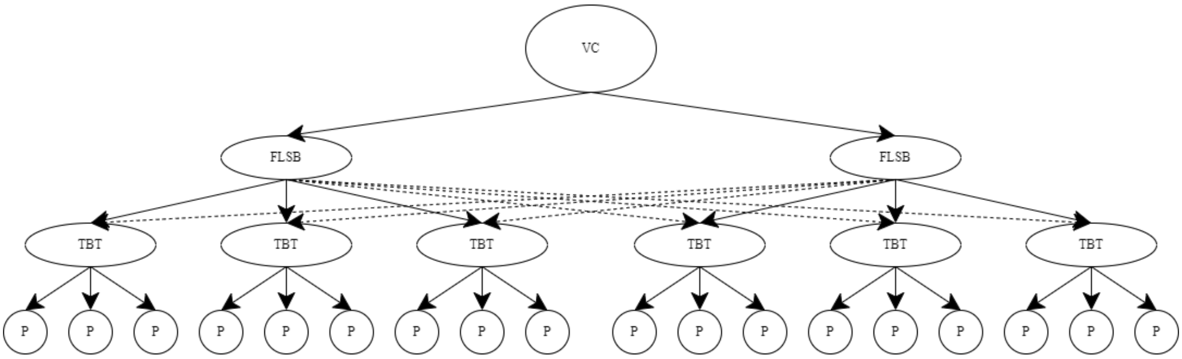


(b) AIN-structure

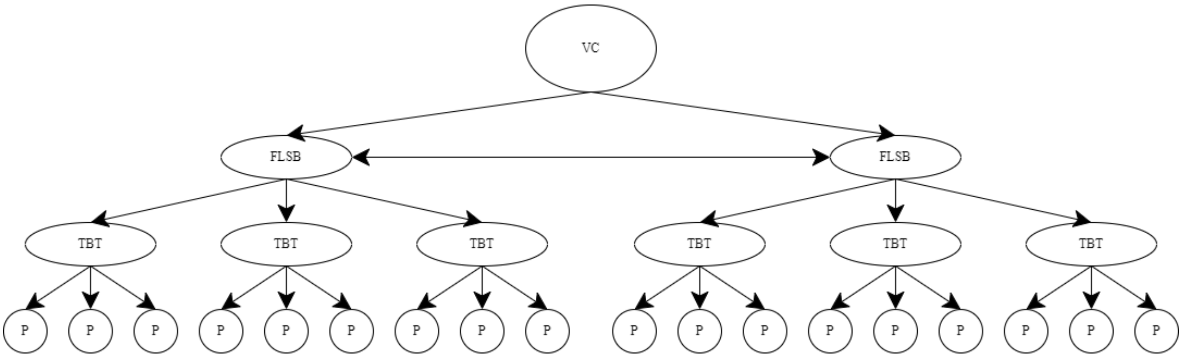


(b)

(c) PRO-structure



(d) REA-structure



(e) LAT-structure

Figure C.1: Structures that are simulated

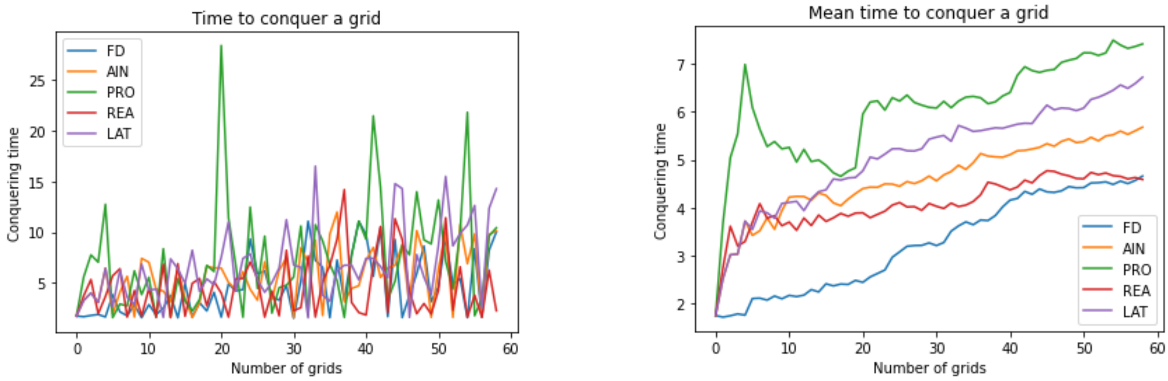
Appendix D

Simulation properties

D.1 Length of a run

The length of a run is based on one run for each model with the same random seed. The initial number of columns is set to 60. The figures below show the actual conquering time per grid and the mean conquering time per grid. The x-axis "Number of grids" denotes the number of grids each platoon has conquered. It could be seen that for the high demand scenario after about 30 grids the conquering time fluctuates heavily for the PRO-structure. For the peak demand scenario both the PRO- and FD-structure fluctuates more. Therefore, in the analysis, two different numbers of grids, 30 and 60, will be tested.

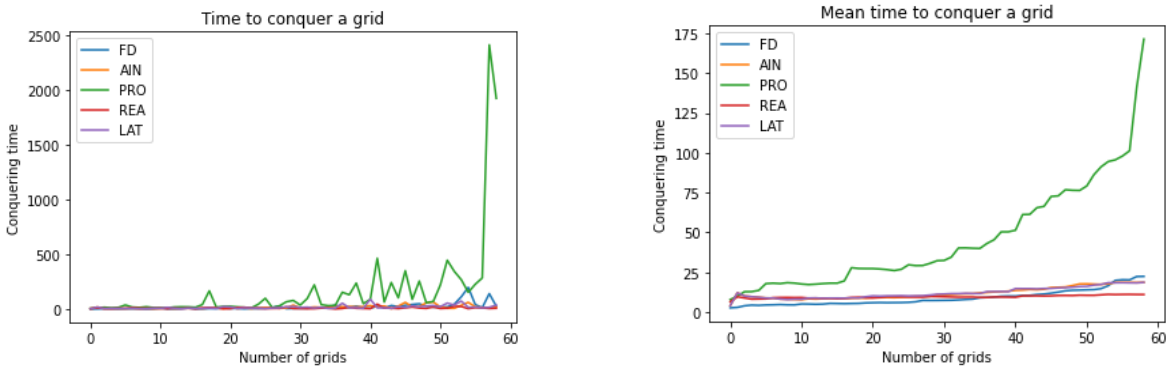
Note that FD denotes the physical distribution structure, AIN denotes the additional intermediate node structure, PRO denotes the pro-active multiple-resourcing structure, REA denotes the reactive multiple-resourcing structure, and LAT denotes the lateral transshipment structure.



(a) Actual

(b) Mean

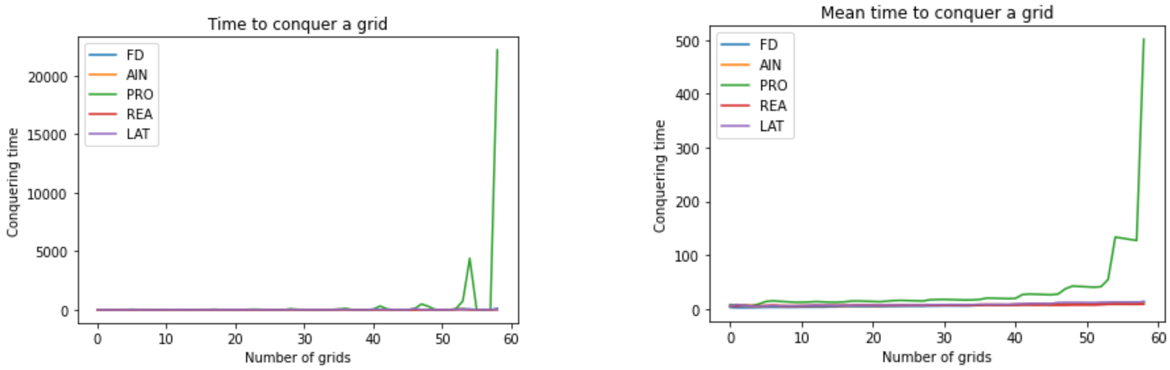
Figure D.1: Time to conquer a grid for the low demand scenario



(a) Actual

(b) Mean

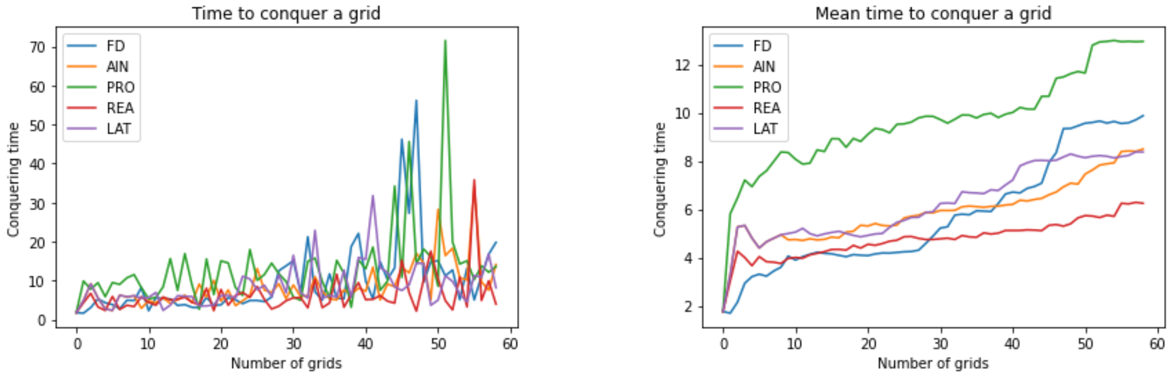
Figure D.2: Time to conquer a grid for the high demand scenario



(a) Actual

(b) Mean

Figure D.3: Time to conquer a grid for the wavy demand scenario



(a) Actual

(b) Mean

Figure D.4: Time to conquer a grid for the peak demand scenario

Appendix E

Simulation Table results

E.1 30 grids per platoon level

E.1.1 Low disruption level

E.1.1.1 1 vehicle level

Low demand level

Table E.1: Results of 30 grids per platoon level, low disruption level, 1 vehicle per FLSB, and low demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	94.107	124.887	170.639	121.651	128.639
Expected exposed time sum	413.215	278.957	360.457	256.618	286.508
Expected exposed time per t	4.411	2.241	2.115	2.117	2.236
Expected exposed time per grid	0.765	0.517	0.668	0.457	0.531
Number of runs	101	101	101	101	101
Ready rate	0.995	0.998	0.998	0.997	0.998
Priority resupplies per grid	0.422	0.422	0.426	0.425	0.423
Regular resupplies per grid	0.088	0.134	0.198	0.127	0.140
Priority lead time	1.598	1.372	1.666	1.287	1.378
Regular lead time	0.703	0.439	0.591	0.442	0.441
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	23,678	27.070	30,273	28,494	27,589

High demand level

Table E.2: Results of 30 grids per platoon level, low disruption level, 1 vehicle per FLSB, and high demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	217.628	276.916	714.372	260.983	282.304
Expected exposed time sum	1,461.484	952.442	1,838.173	903.579	963.080
Expected exposed time per t	6.731	3.445	2.577	3.473	3.416
Expected exposed time per grid	2.706	1.764	3.404	1.637	1.783
Number of runs	101	101	171	101	101
Ready rate	0.923	0.944	0.945	0.943	0.945
Priority resupplies per grid	1.198	1.207	1.293	1.199	1.203
Regular resupplies per grid	0.593	0.812	2.328	0.757	0.832
Priority lead time	4.676	6.778	36.597	6.017	7.255
Regular lead time	1.525	1.239	1.963	1.253	1.286
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,596	92.508	271,721	94,604	93,192

Wavy demand level

Table E.3: Results of 30 grids per platoon level, low disruption level, 1 vehicle per FLSB, and wavy demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	155.418	201.945	432.458	189.632	203.097
Expected exposed time sum	932.815	613.970	1,069.250	567.189	613.986
Expected exposed time per t	6.022	3.046	2.477	2.999	3.030
Expected exposed time per grid	1.727	1.137	1.980	1.050	1.137
Number of runs	101	101	121	101	101
Ready rate	0.945	0.963	0.956	0.962	0.963
Priority resupplies per grid	0.806	0.809	0.859	0.809	0.808
Regular resupplies per grid	0.334	0.463	1.198	0.424	0.462
Priority lead time	3.029	4.476	17.299	3.808	4.260
Regular lead time	1.636	1.251	1.975	1.165	1.288
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	52,746	59.071	111,836	60,885	59,229

Peak demand level

Table E.4: Results of 30 grids per platoon level, low disruption level, 1 vehicle per FLSB, and peak demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	140.957	171.438	268.082	159.892	171.607
Expected exposed time sum	702.965	462.943	626.995	422.359	464.909
Expected exposed time per t	5.005	2.706	2.340	2.646	2.714
Expected exposed time per grid	1.302	0.857	1.161	0.782	0.861
Number of runs	101	101	101	101	101
Ready rate	0.967	0.979	0.978	0.978	0.980
Priority resupplies per grid	0.660	0.664	0.674	0.657	0.654
Regular resupplies per grid	0.207	0.282	0.480	0.256	0.286
Priority lead time	2.875	2.988	6.272	2.815	3.106
Regular lead time	1.055	0.685	1.004	0.701	0.682
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	40,026	44.525	53,719	45,724	44,760

E.1.1.2 2 vehicles level

Low demand level

Table E.5: Results of 30 grids per platoon level, low disruption level, 2 vehicles per FLSB, and low demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	94.107	97.383	97.960	77.810	97.515
Expected exposed time sum	413.215	265.367	301.576	230.941	271.049
Expected exposed time per t	4.411	2.737	3.092	2.987	2.789
Expected exposed time per grid	0.765	0.491	0.558	0.428	0.502
Number of runs	101	101	101	101	101
Ready rate	0.995	0.997	0.996	0.997	0.997
Priority resupplies per grid	0.422	0.426	0.423	0.423	0.424
Regular resupplies per grid	0.088	0.093	0.094	0.066	0.094
Priority lead time	1.598	1.159	1.187	1.069	1.178
Regular lead time	0.703	0.468	0.557	0.474	0.493
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	23,678	25.787	25,665	26,138	25,884

High demand level

Table E.6: Results of 30 grids per platoon level, low disruption level, 2 vehicles per FLSB, and high demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	217.628	190.011	256.101	161.165	194.321
Expected exposed time sum	1,461.484	830.307	1,014.112	741.213	842.777
Expected exposed time per t	6.731	4.381	3.964	4.611	4.347
Expected exposed time per grid	2.706	1.538	1.878	1.373	1.561
Number of runs	101	101	101	101	101
Ready rate	0.923	0.941	0.939	0.940	0.943
Priority resupplies per grid	1.198	1.168	1.193	1.159	1.169
Regular resupplies per grid	0.593	0.524	0.740	0.428	0.539
Priority lead time	4.676	3.517	6.758	2.648	3.591
Regular lead time	1.525	1.119	1.458	0.851	1.082
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,596	79.425	88,108	80,936	80,642

Wavy demand level

Table E.7: Results of 30 grids per platoon level, low disruption level, 2 vehicles per FLSB, and wavy demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	155.418	145.186	177.188	120.036	162.220
Expected exposed time sum	932.815	549.765	661.390	334.490	363.116
Expected exposed time per t	6.022	3.797	3.737	2.317	2.245
Expected exposed time per grid	1.727	1.018	1.225	0.619	0.672
Number of runs	101	101	101	101	101
Ready rate	0.945	0.959	0.956	0.995	0.996
Priority resupplies per grid	0.806	0.795	0.811	0.426	0.425
Regular resupplies per grid	0.334	0.306	0.406	0.161	0.186
Priority lead time	3.029	2.726	4.251	1.967	2.167
Regular lead time	1.636	1.100	1.472	0.687	0.708
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	52,746	52.582	56,655	34,240	33,167

Peak demand level

Table E.8: Results of 30 grids per platoon level, low disruption level, 2 vehicles per FLSB, and peak demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	140.957	128.701	141.272	105.624	128.142
Expected exposed time sum	702.965	430.529	495.902	370.058	433.782
Expected exposed time per t	5.005	3.357	3.517	3.518	3.396
Expected exposed time per grid	1.302	0.797	0.918	0.685	0.803
Number of runs	101	101	101	101	101
Ready rate	0.967	0.977	0.976	0.976	0.977
Priority resupplies per grid	0.660	0.654	0.656	0.643	0.650
Regular resupplies per grid	0.207	0.193	0.218	0.147	0.195
Priority lead time	2.875	2.020	2.489	1.579	2.009
Regular lead time	1.055	0.649	0.709	0.608	0.675
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	40,026	41.127	42,076	41,505	41,403

E.1.2 High disruption level

E.1.2.1 1 vehicle level

Low demand level

Table E.9: Results of 30 grids per platoon level, high disruption level, 1 vehicle per FLSB, and low demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	140.184	162.763	224.890	144.902	162.220
Expected exposed time sum	565.918	358.606	474.981	334.490	363.116
Expected exposed time per t	4.054	2.208	2.114	2.317	2.245
Expected exposed time per grid	1.048	0.664	0.880	0.619	0.672
Number of runs	101	101	101	101	101
Ready rate	0.992	0.996	0.995	0.995	0.996
Priority resupplies per grid	0.423	0.426	0.432	0.426	0.425
Regular resupplies per grid	0.153	0.184	0.272	0.161	0.186
Priority lead time	2.931	2.100	3.259	1.967	2.167
Regular lead time	1.160	0.722	1.000	0.687	0.708
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	30,689	32.888	37,794	34,240	33,167

High demand level

Table E.10: Results of 30 grids per platoon level, high disruption level, 1 vehicle per FLSB, and high demand level

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	429.481	467.576	2,589.806*	386.421	476.769
Expected exposed time sum	2,621.221	1,532.604	6,598.898	1,364.324	1,558.945
Expected exposed time per t	6.122	3.283	2.544	3.538	3.274
Expected exposed time per grid	4.854	2.838	12.220	2.527	2.887
Number of runs	121	101	1000*	101	101
Ready rate	0.916	0.932	0.895	0.931	0.933
Priority resupplies per grid	1.271	1.280	1.429	1.264	1.282
Regular resupplies per grid	1.289	1.427	8.944	1.152	1.455
Priority lead time	15.849	20.780	178.553	15.948	21.430
Regular lead time	2.756	1.895	3.384	1.659	1.948
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	164,887	137.687	5,035,582	132,662	139,599

*Stopped after 1000 runs, confidence interval for expected time to conquer: (2,588.194, 2,591.419).

Wavy demand level

Table E.11: Results of 30 grids per platoon level, high disruption level, 1 vehicle per FLSB, and wavy demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	278.920	312.206	1,225.760	262.860	316.361
Expected exposed time sum	1,560.192	930.729	3,088.911	829.190	940.059
Expected exposed time per t	5.608	2.986	2.510	3.160	2.974
Expected exposed time per grid	2.889	1.724	5.720	1.536	1.741
Number of runs	101	101	921	101	101
Ready rate	0.937	0.951	0.912	0.951	0.952
Priority resupplies per grid	0.847	0.844	0.919	0.842	0.850
Regular resupplies per grid	0.682	0.789	3.919	0.627	0.786
Priority lead time	9.071	11.266	63.759	8.770	11.389
Regular lead time	2.918	1.871	3.300	1.907	2.032
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,676	83.730	2,198,592	81,760	84,520

Peak demand level

Table E.12: Results of 30 grids per platoon level, high disruption level, 1 vehicle per FLSB, and peak demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	232.321	233.249	407.357	206.449	240.427
Expected exposed time sum	1,063.819	613.811	943.094	571.291	634.134
Expected exposed time per t	4.590	2.638	2.317	2.772	2.642
Expected exposed time per grid	1.970	1.137	1.746	1.058	1.174
Number of runs	101	101	101	101	101
Ready rate	0.961	0.972	0.967	0.971	0.972
Priority resupplies per grid	0.686	0.672	0.706	0.675	0.673
Regular resupplies per grid	0.378	0.396	0.751	0.342	0.413
Priority lead time	7.096	6.130	15.312	5.213	6.505
Regular lead time	1.702	1.141	1.652	1.011	1.213
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	56,953	55.700	75,716	57,760	57,015

E.1.2.2 2 vehicles level

Low demand level

Table E.13: Results of 30 grids per platoon level, high disruption level, 2 vehicles per FLSB, and low demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	140.184	124.961	129.697	95.956	125.279
Expected exposed time sum	565.918	332.639	387.285	291.888	340.681
Expected exposed time per t	4.054	2.674	2.996	3.054	2.733
Expected exposed time per grid	1.048	0.616	0.717	0.541	0.631
Number of runs	101	101	101	101	101
Ready rate	0.992	0.995	0.995	0.995	0.996
Priority resupplies per grid	0.423	0.424	0.425	0.422	0.423
Regular resupplies per grid	0.153	0.133	0.138	0.092	0.134
Priority lead time	2.931	1.658	1.856	1.399	1.794
Regular lead time	1.160	0.680	0.777	0.608	0.696
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	30,689	30.551	31,041	30,735	30,886

High demand level

Table E.14: Results of 30 grids per platoon level, high disruption level, 2 vehicles per FLSB, and high demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	429.481	309.463	455.699	222.694	309.540
Expected exposed time sum	2,621.221	1,240.578	1,692.373	1,034.113	1,253.403
Expected exposed time per t	6.122	4.018	3.719	4.661	4.058
Expected exposed time per grid	4.854	2.297	3.134	1.915	2.321
Number of runs	121	101	101	101	101
Ready rate	0.916	0.930	0.916	0.930	0.929
Priority resupplies per grid	1.271	1.225	1.280	1.195	1.230
Regular resupplies per grid	1.289	0.889	1.357	0.617	0.896
Priority lead time	15.849	10.302	23.408	5.328	10.084
Regular lead time	2.756	1.674	2.354	1.308	1.814
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	164,887	109.946	135,274	103,481	111,182

Wavy demand level

Table E.15: Results of 30 grids per platoon level, high disruption level, 2 vehicles per FLSB, and wavy demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	278.920	216.380	286.886	158.325	217.035
Expected exposed time sum	1,560.192	776.493	1,015.025	657.047	789.639
Expected exposed time per t	5.608	3.595	3.542	4.160	3.646
Expected exposed time per grid	2.889	1.438	1.880	1.217	1.462
Number of runs	101	101	101	101	101
Ready rate	0.937	0.951	0.937	0.951	0.951
Priority resupplies per grid	0.847	0.820	0.849	0.806	0.882
Regular resupplies per grid	0.682	0.503	0.711	0.343	0.502
Priority lead time	9.071	5.934	11.520	3.568	6.227
Regular lead time	2.918	1.751	2.331	1.310	1.748
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,676	69.411	81,246	66,302	70,044

Peak demand level

Table E.16: Results of 30 grids per platoon level, high disruption level, 2 vehicles per FLSB, and peak demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	232.321	180.028	210.173	136.488	179.929
Expected exposed time sum	1,063.819	568.412	692.268	486.756	575.569
Expected exposed time per t	4.590	3.167	3.298	3.577	3.206
Expected exposed time per grid	1.970	1.053	1.282	0.901	1.066
Number of runs	101	101	101	101	101
Ready rate	0.961	0.971	0.969	0.970	0.970
Priority resupplies per grid	0.686	0.671	0.677	0.661	0.669
Regular resupplies per grid	0.378	0.289	0.349	0.202	0.287
Priority lead time	7.096	4.313	5.643	2.695	4.247
Regular lead time	1.702	0.995	1.157	0.803	1.012
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	56,953	51.056	55,214	50,664	51,357

E.2 60 grids per platoon level

E.2.1 Low disruption level

E.2.1.1 1 vehicle level

Low demand level

Table E.17: Results of 60 grids per platoon level, low disruption level, 1 vehicle per FLSB, and low demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	330.022	330.896	440.448	273.194	343.713
Expected exposed time sum	1,621.749	839.708	1,038.379	806.119	852.451
Expected exposed time per t	4.925	2.483	2.359	2.959	2.484
Expected exposed time per grid	1.502	0.778	0.961	0.746	0.789
Number of runs	101	101	101	101	101
Ready rate	0.990	0.997	0.997	0.996	0.996
Priority resupplies per grid	0.438	0.436	0.441	0.435	0.436
Regular resupplies per grid	0.186	0.196	0.267	0.149	0.200
Priority lead time	3.546	1.937	2.901	1.643	2.129
Regular lead time	1.444	0.630	0.787	0.572	0.647
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	60,728	62.214	69,072	61,338	62,973

High demand level

Table E.18: Results of 60 grids per platoon level, low disruption level, 1 vehicle per FLSB, and high demand level

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	1,395.300	971.496	22,533.891*	612.959	996.918
Expected exposed time sum	10,489.616	3,711.620	68,098.423	2,984.626	3,790.149
Expected exposed time per t	7.531	3.824	2.986	4.877	3.805
Expected exposed time per grid	9.713	3.437	63.054	2.764	3.509
Number of runs	561	171	1000*	101	161
Ready rate	0.898	0.935	0.895	0.938	0.935
Priority resupplies per grid	1.336	1.264	1.384	1.223	1.265
Regular resupplies per grid	2.205	1.521	40.221	0.911	1.565
Priority lead time	65.648	39.761	543.117	15.655	40.324
Regular lead time	3.522	1.890	3.943	1.219	1.804
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	1,909,899	431,660	35,205,735	210,344	411,838

*Stopped after 1000 runs, confidence interval for expected time to conquer: (22,496.853, 22,570.929).

Wavy demand level

Table E.19: Results of 60 grids per platoon level, low disruption level, 1 vehicle per FLSB, and wavy demand level

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	841.849	647.416	7,303.546*	441.316	645.358
Expected exposed time sum	5,883.542	2,237.431	21,682.067	1,881.265	2,228.195
Expected exposed time per t	6.991	3.459	2.922	4.267	3.455
Expected exposed time per grid	5.448	2.072	20.076	1.742	2.063
Number of runs	331	141	1000*	101	121
Ready rate	0.919	0.953	0.887	0.957	0.953
Priority resupplies per grid	0.883	0.846	0.903	0.826	0.843
Regular resupplies per grid	1.146	0.830	12.827	0.522	0.829
Priority lead time	32.214	20.153	171.182	9.598	20.576
Regular lead time	3.580	1.955	3.489	1.228	1.879
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	654,207	218.098	11,867,473	135,033	187,251

*Stopped after 1000 runs, confidence interval for expected time to conquer: (7,303.546, 7,317.782).

Peak demand level

Table E.20: Results of 60 grids per platoon level, low disruption level, 1 vehicle per FLSB, and peak demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	566.366	486.566	789.321	367.688	493.923
Expected exposed time sum	3,173.900	1,455.461	2,036.015	1,349.256	1,475.052
Expected exposed time per t	5.610	2.995	2.579	3.676	2.990
Expected exposed time per grid	2.939	1.348	1.885	1.249	1.366
Number of runs	111	101	171	101	101
Ready rate	0.956	0.975	0.973	0.976	0.976
Priority resupplies per grid	0.700	0.681	0.695	0.669	0.675
Regular resupplies per grid	0.481	0.427	0.752	0.306	0.437
Priority lead time	19.044	9.969	18.922	5.621	9.680
Regular lead time	1.973	1.032	1.402	0.751	1.010
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	126,194	105.518	226,824	99,591	106,604

E.2.1.2 2 vehicles level

Low demand level

Table E.21: Results of 60 grids per platoon level, low disruption level, 2 vehicles per FLSB, and low demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	330.022	285.783	293.714	185.069	289.987
Expected exposed time sum	1,621.749	797.629	881.338	727.937	816.256
Expected exposed time per t	4.925	2.798	3.005	3.954	2.820
Expected exposed time per grid	1.502	0.739	0.816	0.674	0.756
Number of runs	101	101	101	101	101
Ready rate	0.990	0.997	0.996	0.996	0.996
Priority resupplies per grid	0.438	0.438	0.436	0.433	0.437
Regular resupplies per grid	0.186	0.158	0.163	0.087	0.159
Priority lead time	3.546	1.614	1.754	1.132	1.804
Regular lead time	1.444	0.676	0.730	0.626	0.674
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	60,728	59.191	59,341	56,295	59,865

High demand level

Table E.22: Results of 60 grids per platoon level, low disruption level, 2 vehicles per FLSB, and high demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	1,395.300	741.588	1,837.674	404.341	739.464
Expected exposed time sum	10,489.616	3,199.251	6,392.833	2,448.301	3,199.922
Expected exposed time per t	7.531	4.322	3.490	6.070	4.334
Expected exposed time per grid	9.713	2.962	5.919	2.267	2.963
Number of runs	561	131	851	101	121
Ready rate	0.898	0.932	0.907	0.937	0.932
Priority resupplies per grid	1.336	1.228	1.288	1.177	1.230
Regular resupplies per grid	2.205	1.131	3.047	0.568	1.126
Priority lead time	65.648	25.315	67.678	7.445	25.648
Regular lead time	3.522	1.834	2.857	1.019	1.904
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	1,909,899	286,577	3,245,741	180,962	264,559

Wavy demand level

Table E.23: Results of 60 grids per platoon level, low disruption level, 2 vehicles per FLSB, and wavy demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	841.849	513.467	1,035.096	294.429	509.278
Expected exposed time sum	5,883.542	1,985.654	3,518.073	1,579.309	1,978.557
Expected exposed time per t	6.991	3.875	3.411	5.381	3.890
Expected exposed time per grid	5.448	1.839	3.257	1.462	1.832
Number of runs	331	111	611	101	101
Ready rate	0.919	0.950	0.925	0.955	0.953
Priority resupplies per grid	0.883	0.831	0.858	0.808	0.830
Regular resupplies per grid	1.146	0.637	1.538	0.321	0.630
Priority lead time	32.214	13.638	29.630	4.734	13.225
Regular lead time	3.580	1.811	2.721	1.029	1.724
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	654,207	152.961	1,301,834	118,508	138,460

Peak demand level

Table E.24: Results of 60 grids per platoon level, low disruption level, 2 vehicles per FLSB, and peak demand level

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	566.366	409.759	492.528	256.372	406.950
Expected exposed time sum	3,173.900	1,376.746	1,611.663	1,182.158	1,376.098
Expected exposed time per t	5.610	3.365	3.275	4.631	3.386
Expected exposed time per grid	2.939	1.275	1.492	1.095	1.274
Number of runs	111	101	101	101	101
Ready rate	0.956	0.975	0.972	0.974	0.975
Priority resupplies per grid	0.700	0.674	0.679	0.659	0.671
Regular resupplies per grid	0.481	0.351	0.438	0.191	0.348
Priority lead time	19.044	7.245	9.480	3.070	6.966
Regular lead time	1.973	0.980	1.135	0.766	1.009
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	126,194	99.702	106,523	90,360	99,697

E.2.2 High disruption level

E.2.2.1 1 vehicle level

Low demand level

Table E.25: Results of 60 grids per platoon level, high disruption level, 1 vehicle per FLSB, and low demand level

Indicator	FD-structure*	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	2,870.363*	517.809	790.940	339.059	516.778
Expected exposed time sum	15,593.512	1,279.790	1,850.999	1,140.117	1,294.060
Expected exposed time per t	5.349	2.474	2.340	3.372	2.511
Expected exposed time per grid	14.438	1.185	1.714	1.056	1.200
Number of runs	1000*	101	161	101	101
Ready rate	0.877	0.993	0.987	0.994	0.993
Priority resupplies per grid	0.458	0.441	0.451	0.438	0.440
Regular resupplies per grid	1.896	0.321	0.516	0.196	0.321
Priority lead time	49.293	4.532	8.413	2.694	4.549
Regular lead time	7.338	1.233	1.877	0.853	1.204
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	3,938,537	83.653	168,982	76,470	84,227

*Stopped after 1000 runs, confidence interval for expected time to conquer: (2,867.582; 2,873.145).

High demand level

Table E.26: Results of 60 grids per platoon level, high disruption level, 1 vehicle per FLSB, and high demand level

Indicator	FD-structure***	AIN-structure*	PRO-structure***	REA-structure	LAT-structure**
Expected time to conquer	***	4,970.237*	***	980.473	5,050.820**
Expected exposed time sum	***	19,422.180	***	5,174.443	19,734.751
Expected exposed time per t	***	3.897	***	5.281	3.896
Expected exposed time per grid	***	17.983	***	4.791	18.273
Number of runs	***	1000*	***	141	1000**
Ready rate	***	0.856	***	0.922	0.856
Priority resupplies per grid	***	1.392	***	1.297	1.393
Regular resupplies per grid	***	8.373	***	1.495	8.513
Priority lead time	***	215.182	***	46.067	216.759
Regular lead time	***	3.919	***	1.807	3.990
Number of nodes	***	27	***	27	27
Number of edges	***	24.0	***	32.0	28.0
Number of rides	***	10,018,521	***	446,890	10,258,048

*Stopped after 1000 runs, confidence interval for expected time to conquer: (4,967.591; 4,972.882).

**Stopped after 1000 runs, confidence interval for expected time to conquer: (5,048.013; 5,053.627).

***Infeasible scenario, no results could be retrieved.

Wavy demand level

Table E.27: Results of 60 grids per platoon level, high disruption level, 1 vehicle per FLSB, and wavy demand level

Indicator	FD-structure***	AIN-structure*	PRO-structure***	REA-structure	LAT-structure**
Expected time to conquer	***	2,396.814*	***	651.610	2,436.210**
Expected exposed time sum	***	2,396.814	***	651.610	2,436.210
Expected exposed time per t	***	3.691	***	4.783	3.699
Expected exposed time per grid	***	8.235	***	2.884	8.392
Number of runs	***	1000*	***	101	1000**
Ready rate	***	0.883	***	0.942	0.882
Priority resupplies per grid	***	0.911	***	0.866	0.913
Regular resupplies per grid	***	3.732	***	0.823	3.801
Priority lead time	***	89.178	***	24.579	91.260
Regular lead time	***	3.808	***	1.810	3.755
Number of nodes	***	27	***	27	27
Number of edges	***	26.0	***	32.0	28.0
Number of rides	***	4,742,224	***	197,301	4,873,900

*Stopped after 1000 runs, confidence interval for expected time to conquer: (7,001.317; 7,165.110).

**Stopped after 1000 runs, confidence interval for expected time to conquer: (2,434.785; 2,437.634).

***Infeasible scenario, no results could be retrieved.

Peak demand level

Table E.28: Results of 60 grids per platoon level, high disruption level, 1 vehicle per FLSB, and peak demand level

Indicator	FD-structure*	AIN-structure	PRO-structure**	REA-structure	LAT-structure
Expected time to conquer	47,176.689*	926.083	7,083.213**	499.903	929.216
Expected exposed time sum	332,793.526	2,734.449	20,337.435	2,023.793	2,755.811
Expected exposed time per t	6.672	2.949	2.627	4.052	2.964
Expected exposed time per grid	308.142	2.532	18.831	1.874	2.552
Number of runs	100*	241	1000**	101	241
Ready rate	0.724	0.958	0.883	0.968	0.958
Priority resupplies per grid	0.773	0.706	0.741	0.689	0.704
Regular resupplies per grid	40.315	0.875	8.129	0.429	0.875
Priority lead time	724.473	27.661	136.990	12.208	28.041
Regular lead time	11.649	2.019	4.364	1.197	1.986
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	7,510,215	404.928	8,564,117	132,390	402,433

*Stopped after 100 runs, confidence interval for expected time to conquer: (46,010.689; 48,342.975).

**Stopped after 1000 runs, confidence interval for expected time to conquer: (7,001.317; 7,165.110).

E.2.2.2 2 vehicles level

Low demand level

Table E.29: Results of 60 grids per platoon level, high disruption level, 2 vehicles per FLSB, and low demand level

Indicator	FD-structure*	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	2,870.363*	455.644	507.188	246.643	450.998
Expected exposed time sum	15,593.512	1,228.917	1,431.004	1,039.216	1,234.668
Expected exposed time per t	5.349	2.702	2.825	4.231	2.742
Expected exposed time per grid	14.438	1.138	1.325	0.962	1.143
Number of runs	1000*	101	111	101	101
Ready rate	0.877	0.992	0.989	0.993	0.993
Priority resupplies per grid	0.458	0.439	0.444	0.435	0.442
Regular resupplies per grid	1.896	0.277	0.311	0.130	0.273
Priority lead time	49.293	4.115	4.734	2.144	3.523
Regular lead time	7.338	1.284	1.585	0.865	1.283
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	3,938,537	80.059	92,287	70,581	80,178

*Stopped after 1000 runs, confidence interval for expected time to conquer: (2,867.582; 2,873.145).

High demand level

Table E.30: Results of 60 grids per platoon level, high disruption level, 2 vehicles per FLSB, and high demand level

Indicator	FD-structure***	AIN-structure*	PRO-structure***	REA-structure	LAT-structure**
Expected time to conquer	***	2,885.075*	***	601.399	2,912.591**
Expected exposed time sum	***	11,833.501	***	3,909.223	11,973.411
Expected exposed time per t	***	4.102	***	6.512	4.111
Expected exposed time per grid	***	10.957	***	3.620	11.086
Number of runs	***	1000*	***	101	1000**
Ready rate	***	0.867	***	0.924	0.866
Priority resupplies per grid	***	1.339	***	1.224	1.340
Regular resupplies per grid	***	4.751	***	0.878	4.805
Priority lead time	***	122.352	***	18.038	122.956
Regular lead time	***	3.666	***	1.441	3.694
Number of nodes	***	27	***	27	27
Number of edges	***	24.0	***	32.0	28.0
Number of rides	***	6,319,149	***	251,383	6,355,618

*Stopped after 1000 runs, confidence interval for expected time to conquer: (2,883.903; 2,886.246).

**Stopped after 1000 runs, confidence interval for expected time to conquer: (2,911.399; 2,913.783).

***Infeasible scenario, no results could be retrieved.

Wavy demand level

Table E.31: Results of 60 grids per platoon level, high disruption level, 2 vehicles per FLSB, and wavy demand level

Indicator	FD-structure***	AIN-structure	PRO-structure***	REA-structure	LAT-structure
Expected time to conquer	***	1,586.616	***	431.643	1,576.282
Expected exposed time sum	***	6,150.536	***	2,500.021	6,138.1500
Expected exposed time per t	***	3.868	***	5.804	3.885
Expected exposed time per grid	***	5.695	***	2.315	5.683
Number of runs	***	771	***	101	761
Ready rate	***	0.892	***	0.943	0.891
Priority resupplies per grid	***	0.886	***	0.829	0.886
Regular resupplies per grid	***	2.357	***	0.512	2.342
Priority lead time	***	55.702	***	10.854	54.944
Regular lead time	***	3.564	***	1.604	3.614
Number of nodes	***	27	***	27	27
Number of edges	***	26.0	***	32.0	28.0
Number of rides	***	2,614.635	***	163,186	2,561,172

Peak demand level

Table E.32: Results of 60 grids per platoon level, high disruption level, 2 vehicles per FLSB, and peak demand level

Indicator	FD-structure*	AIN-structure	PRO-structure**	REA-structure	LAT-structure
Expected time to conquer	47,176.689*	770.649	1,451.667**	359.982	775.769
Expected exposed time sum	332,793.526	2,452.115	4,401.483	1,780.043	2,492.250
Expected exposed time per t	6.672	3.185	3.019	4.956	3.217
Expected exposed time per grid	308.142	2.270	4.075	1.648	2.308
Number of runs	100*	191	1000**	101	181
Ready rate	0.724	0.959	0.923	0.966	0.957
Priority resupplies per grid	0.773	0.699	0.711	0.677	0.699
Regular resupplies per grid	40.315	0.706	1.446	0.289	0.713
Priority lead time	724.473	21.515	34.330	6.722	21.258
Regular lead time	11.469	1.981	3.234	1.094	2.059
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	7,510,215	286.322	2,337,268	118,597	275,728

*Stopped after 100 runs, confidence interval for expected time to conquer: (46,010.403; 48,342.975).

**Stopped after 1000 runs, confidence interval for expected time to conquer: (1,447.995; 1,455.339).

***Infeasible scenario, no results could be retrieved.

Appendix F

Full factorial table

Table F.1 shows the comprehensive table of the full factorial experiments. The color indications show the performance, meaning that green is good and red is worse. The colors are indicated per demand level (thus per five rows). It could be seen that in most experiments, the REA-structure has both the lowest value and thus a green color in the expected conquering time and expected exposed time per grid.

Table F.1: Fulll factorial results

Expt. No.	Levels					Exp. conq. time	Exp. exposed time per grid
	Grids	Disruptions	Vehicle	Demand	Structure		
1	30	Low	1	Low	FD	94.107	0.765
2	30	Low	1	Low	AIN	124.870	0.517
3	30	Low	1	Low	PRO	170.639	0.668
4	30	Low	1	Low	REA	121.651	0.457
5	30	Low	1	Low	LAT	128.639	0.531
6	30	Low	1	High	FD	217.628	2.706
7	30	Low	1	High	AIN	276.916	1.764
8	30	Low	1	High	PRO	714.372	3.404
9	30	Low	1	High	REA	260.983	1.637
10	30	Low	1	High	LAT	282.304	1.783
11	30	Low	1	Wavy	FD	155.418	1.727
12	30	Low	1	Wavy	AIN	201.945	1.137
13	30	Low	1	Wavy	PRO	432.458	1.980
14	30	Low	1	Wavy	REA	189.632	1.050
15	30	Low	1	Wavy	LAT	203.097	1.137
16	30	Low	1	Peak	FD	140.957	1.302
17	30	Low	1	Peak	AIN	171.438	0.857
18	30	Low	1	Peak	PRO	268.082	1.161
19	30	Low	1	Peak	REA	159.892	0.782
20	30	Low	1	Peak	LAT	171.607	0.861
21	30	Low	2	Low	FD	94.107	0.765
22	30	Low	2	Low	AIN	97.383	0.491

23	30	Low	2	Low	PRO	97.960	0.558
24	30	Low	2	Low	REA	77.810	0.428
25	30	Low	2	Low	LAT	97.515	0.502
26	30	Low	2	High	FD	217.628	2.706
27	30	Low	2	High	AIN	190.011	1.538
28	30	Low	2	High	PRO	256.101	1.878
29	30	Low	2	High	REA	161.165	1.373
30	30	Low	2	High	LAT	194.321	1.561
31	30	Low	2	Wavy	FD	155.418	1.727
32	30	Low	2	Wavy	AIN	145.186	1.018
33	30	Low	2	Wavy	PRO	177.188	1.225
34	30	Low	2	Wavy	REA	120.036	0.619
35	30	Low	2	Wavy	LAT	162.220	0.672
36	30	Few	2	Peak	FD	140,957	1,302
37	30	Few	2	Peak	AIN	128,701	0,797
38	30	Few	2	Peak	PRO	141,272	0,918
39	30	Few	2	Peak	REA	105,624	0,685
40	30	Few	2	Peak	LAT	128,142	0,803
41	30	High	1	Low	FD	140.184	1.048
42	30	High	1	Low	AIN	162.763	0.664
43	30	High	1	Low	PRO	224.890	0.880
44	30	High	1	Low	REA	144.902	0.619
45	30	High	1	Low	LAT	162.220	0.672
46	30	High	1	High	FD	429.481	4.854
47	30	High	1	High	AIN	467.576	2.838
48	30	High	1	High	PRO	2,589.806	12.220
49	30	High	1	High	REA	386.421	2.527
50	30	High	1	High	LAT	476.769	2.887
51	30	High	1	Wavy	FD	278.920	2.889
52	30	High	1	Wavy	AIN	312.206	1.724
53	30	High	1	Wavy	PRO	1,225.760	5.720
54	30	High	1	Wavy	REA	262.860	1.536
55	30	High	1	Wavy	LAT	316.361	1.741
56	30	High	1	Peak	FD	232.321	1.970
57	30	High	1	Peak	AIN	233.249	1.137
58	30	High	1	Peak	PRO	407.357	1.746
59	30	High	1	Peak	REA	206.449	1.058
60	30	High	1	Peak	LAT	240.427	1.174
61	30	High	2	Low	FD	140.184	1.048
62	30	High	2	Low	AIN	124.961	0.616
63	30	High	2	Low	PRO	129.697	0.717
64	30	High	2	Low	REA	95.956	0.541
65	30	High	2	Low	LAT	125.279	0.631
66	30	High	2	High	FD	429.481	4.854
67	30	High	2	High	AIN	309.463	2.297
68	30	High	2	High	PRO	455.699	3.134

69	30	High	2	High	REA	22.694	1.915
70	30	High	2	High	LAT	309.540	2.321
71	30	High	2	Wavy	FD	278.920	2.889
72	30	High	2	Wavy	AIN	16.380	1.438
73	30	High	2	Wavy	PRO	286.886	1.880
74	30	High	2	Wavy	REA	158.325	1.217
75	30	High	2	Wavy	LAT	217.035	1.462
76	30	High	2	Peak	FD	232.321	1.970
77	30	High	2	Peak	AIN	180.028	1.053
78	30	High	2	Peak	PRO	210.173	1.282
79	30	High	2	Peak	REA	136.488	0.901
80	30	High	2	Peak	LAT	179.929	1.066
81	60	Low	1	Low	FD	330.022	1.502
82	60	Low	1	Low	AIN	330.896	0.778
83	60	Low	1	Low	PRO	440.448	0.961
84	60	Low	1	Low	REA	273.194	0.746
85	60	Low	1	Low	LAT	343.713	0.789
86	60	Low	1	High	FD	1,395.300	9.713
87	60	Low	1	High	AIN	971.496	3.437
88	60	Low	1	High	PRO	22,533.891	63.054
89	60	Low	1	High	REA	612.959	2.764
90	60	Low	1	High	LAT	996.918	3.509
91	60	Low	1	Wavy	FD	841.849	5.448
92	60	Low	1	Wavy	AIN	647.416	2.072
93	60	Low	1	Wavy	PRO	7303.546	20.076
94	60	Low	1	Wavy	REA	441.316	1.742
95	60	Low	1	Wavy	LAT	645.358	2.063
96	60	Low	1	Peak	FD	566.366	2.939
97	60	Low	1	Peak	AIN	486.566	1.348
98	60	Low	1	Peak	PRO	789.321	1.885
99	60	Low	1	Peak	REA	367.688	1.249
100	60	Low	1	Peak	LAT	493.923	1.366
101	60	Low	2	Low	FD	330.022	1.502
102	60	Low	2	Low	AIN	285.783	0.739
103	60	Low	2	Low	PRO	293.714	0.816
104	60	Low	2	Low	REA	185.069	0.674
105	60	Low	2	Low	LAT	289.987	0.756
106	60	Low	2	High	FD	1,395.300	9.713
107	60	Low	2	High	AIN	741.588	2.962
108	60	Low	2	High	PRO	1,837.674	5.919
109	60	Low	2	High	REA	404.341	2.267
110	60	Low	2	High	LAT	739.464	2.963
111	60	Low	2	Wavy	FD	841.849	5.448
112	60	Low	2	Wavy	AIN	513.467	1.839
113	60	Low	2	Wavy	PRO	1,035.096	3.257
114	60	Low	2	Wavy	REA	294.429	1.462

115	60	Low	2	Wavy	LAT	509.278	1.832
116	60	Low	2	Peak	FD	566.366	2.939
117	60	Low	2	Peak	AIN	409.759	1.275
118	60	Low	2	Peak	PRO	492.528	1.492
119	60	Low	2	Peak	REA	256.372	1.095
120	60	Low	2	Peak	LAT	406.950	1.274
121	60	High	1	Low	FD	2,870.363	14.438
122	60	High	1	Low	AIN	517.809	1.185
123	60	High	1	Low	PRO	790.940	1.714
124	60	High	1	Low	REA	339.059	1.056
125	60	High	1	Low	LAT	516.778	1.200
126	60	High	1	High	FD	*	*
127	60	High	1	High	AIN	4,970.237	17.983
128	60	High	1	High	PRO	*	*
129	60	High	1	High	REA	980.473	4.791
130	60	High	1	High	LAT	5,050.820	18.273
131	60	High	1	Wavy	FD	*	*
132	60	High	1	Wavy	AIN	2,396.814	8.235
133	60	High	1	Wavy	PRO	*	*
134	60	High	1	Wavy	REA	651.610	2.884
135	60	High	1	Wavy	LAT	2,436.210	8.392
136	60	High	1	Peak	FD	47,176.689	308.142
137	60	High	1	Peak	AIN	926.083	2.532
138	60	High	1	Peak	PRO	7,083.213	18.831
139	60	High	1	Peak	REA	499.903	1.784
140	60	High	1	Peak	LAT	929.216	2.522
141	60	High	2	Low	FD	2,870.363	14.438
142	60	High	2	Low	AIN	455.644	1.138
143	60	High	2	Low	PRO	507.188	1.325
144	60	High	2	Low	REA	246.643	0.962
145	60	High	2	Low	LAT	450.995	1.143
146	60	High	2	High	FD	*	*
147	60	High	2	High	AIN	2,885.075	10.957
148	60	High	2	High	PRO	*	*
149	60	High	2	High	REA	601.399	3.620
150	60	High	2	High	LAT	2,912.591	11.086
151	60	High	2	Wavy	FD	*	*
152	60	High	2	Wavy	AIN	1,586.616	5.695
153	60	High	2	Wavy	PRO	*	*
154	60	High	2	Wavy	REA	431.643	2.315
155	60	High	2	Wavy	LAT	1,576.282	5.683
156	60	High	2	Peak	FD	47,176.689	308.142
157	60	High	2	Peak	AIN	770.649	2.270
158	60	High	2	Peak	PRO	1,451.667	4.075
159	60	High	2	Peak	REA	359.982	1.648

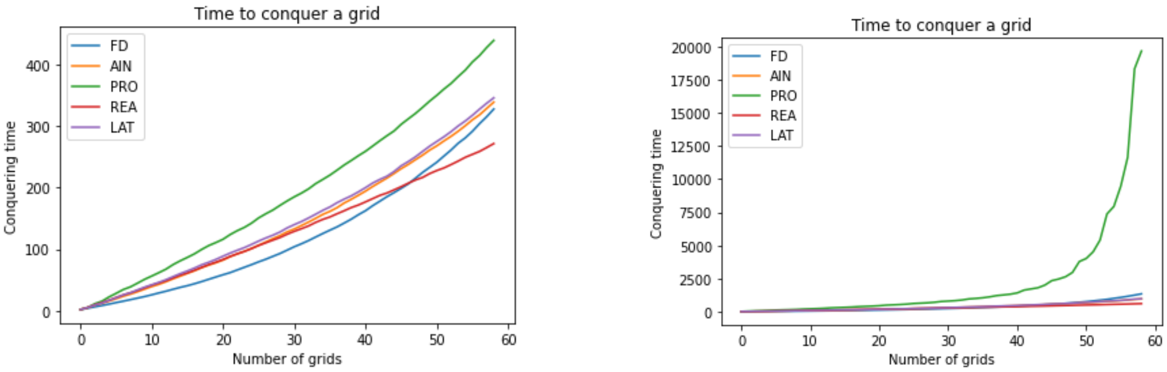
160	60	High	2	Peak	LAT	775.769	2.308

*Infeasible

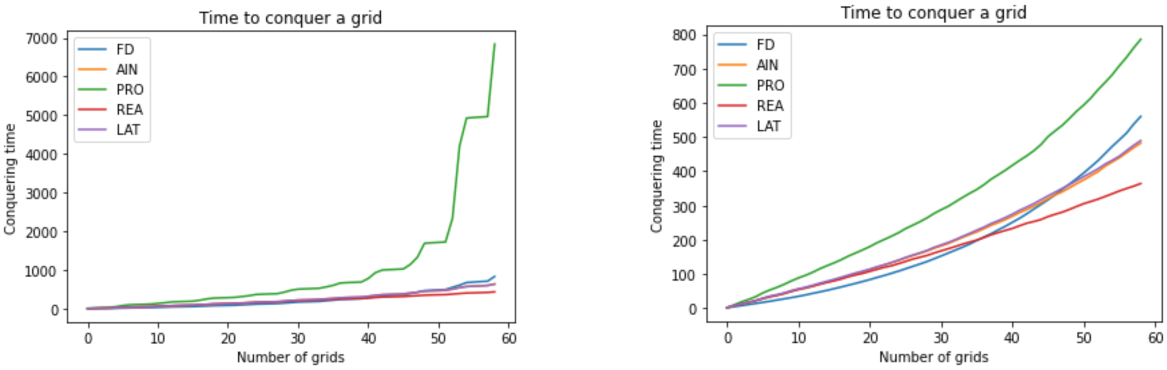
Appendix G

Run length analysis

The figures show that the mean time to conquer a grid for 60 grids per platoon, low disruption level, and one vehicle per FLSB for 100 runs.



(a) Low (b) High



(c) Wavy (d) Peak

Figure G.1: Mean time to conquer a grid for 60 grids per platoon, low disruption level, 1 vehicle level for 100 runs

Appendix H

Sensitivity analysis

Sensitivity analysis is performed on the 30 grid model with few disruptions, one vehicle per FLSB, and with the high demand scenario. The input parameters that are changed are the TBT reorder level, amount of FLSBs, FLSB order-up-to level, FLSB reorder level and FLSB distance to TBTs.

H.1 TBT reorder level

The original and changes in the TBT reorder level parameter are shown in Table H.1. The results of the low and high input parameters could be found in Tables H.2 and H.3 respectively. As expected a lower reorder level for the TBTs result in a lower ready rate. However, the differences are small. The differences in expected time to conquer and expected exposed time per grid were also small. The difference with a high s_{TBT} parameter, on the other hand, is much greater. Because each time a platoon requests supplies from a TBT, the TBT requests from the FLSB as well. This is because the MOQ of platoons and TBTs is the same. When looking at the results, the FD-structure performs better and the other structures perform worse compared to the analysis. The ready rate increased in all structures which are as expected. The expected time to conquer and expected exposed time per grid for the structures with FLSBs increased a lot. This could be because TBTs order more frequently and the FLSBs have limited vehicle capacity. In the FD-structure, the TBTs ordered from the VC which has unlimited vehicle capacity. Therefore, it could be concluded that the model is sensitive to a high TBT reorder level. The reorder level of TBTs could be optimized to find the best results for all structures.

Table H.1: TBT reorder input parameters sensitivity analysis

Input parameter	*Analysis*	*Low*	*High*
s_{TBT}	60	40	80

Table H.2: Results of sensitivity analysis with low s_{TBT} parameter

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	223.639	273.279	679.534	257.834	276.242
Expected exposed time sum	1,447.190	937.349	1,761.665	893.546	949.482
Expected exposed time per t	6.490	3.435	2.597	3.475	3.444
Expected exposed time per grid	2.680	1.736	3.262	1.655	1.758
Number of runs	101	101	161	101	101
Ready rate	0.920	0.943	0.940	0.941	0.943
Priority resupplies per grid	1.202	1.201	1.298	1.201	1.201
Regular resupplies per grid	0.611	0.797	2.190	0.743	0.809
Priority lead time	4.775	6.699	36.058	6.024	6.878
Regular lead time	1.586	1.348	1.954	1.148	1.254
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	83,110	90,861	246,695	94,206	91.576

Table H.3: Results of sensitivity analysis with high s_{TBT} parameter

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	172.727	1,348.699	13,931.747*	1,139.775	1,352.068
Expected exposed time sum	2,416.628	3,375.720	30,301.982	2,611.891	3,373.147
Expected exposed time per t	14.035	2.516	2.171	2.313	2.510
Expected exposed time per grid	4.475	6.251	56.115	4.837	6.247
Number of runs	101	631	1000*	521	621
Ready rate	0.930	0.986	0.976	0.984	0.986
Priority resupplies per grid	1.170	1.243	1.345	1.243	1.244
Regular resupplies per grid	0.458	4.845	52.389	4.043	4.852
Priority lead time	3.122	29.612	690.943	25.135	30.584
Regular lead time	1.101	0.803	1.579	0.763	0.758
Number of nodes	25	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	104,331	2,008,232	25,205,160	1,530,287	1,964.410

*Stopped after 1000 runs, confidence interval for expected time to conquer: (13,923.474; 13,940.020).

H.2 Amount of FLSBs

The original and change in the amount of TBTs per FLSB parameter are shown in Table H.4. The results of the low input parameters could be found in Table H.5. Since with only one FLSB, no pro-active, re-active, and lateral transshipment could take place, this scenario is not tested. With 2 TBTs per FLSB, thus with an additional FLSB, it was found that the expected time to conquer and expected exposed time per grid decreased which is as expected. The expected exposed time per grid decreased since the distance between FLSBs and TBT decreased. However, more shipments from the VC to the FLSBs are needed. Furthermore, no change in order from best performing was found. However, the ready rate decreased for the AIN-structure and PRO-structure. Concluding, the model is sensitive to the amount of FLSBs, since the performance of the models with FLSBs increased such that they perform better than the FD-structure.

Table H.4: Number of FLSBs input parameters sensitivity analysis

Input parameter	*Analysis*	*Low*
#TBT_per_FLSB	3	2

Table H.5: Results of sensitivity analysis with low #TBT_per_FLSB parameter

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	217.628	196.881	290.719	188.775	200.917
Expected exposed time sum	1,461.484	821.077	1,071.642	788.756	836.192
Expected exposed time per t	6.731	4.181	3.689	4.192	4.172
Expected exposed time per grid	2.706	1.521	1.985	1.461	1.549
Number of runs	101	101	101	101	101
Ready rate	0.923	0.944	0.938	0.939	0.943
Priority resupplies per grid	1.198	1.165	1.214	1.169	1.170
Regular resupplies per grid	0.593	0.554	0.845	0.518	0.562
Priority lead time	4.676	3.629	8.711	3.452	3.724
Regular lead time	1.525	0.989	1.528	1.005	1.101
Number of nodes	25	26	26	26	26
Number of edges	24.0	27.0	39.0	39.0	33.0
Number of rides	82,596	80,695	93,059	83,616	81.721

H.3 FLSB order up to level

The original and changes in the FLSB order-up-to level parameter are shown in Table H.6. The results of the low and high input parameters could be found in Tables H.7 and H.8 respectively. The AIN-structure and LAT-structure perform equally in with the low parameters because the minimum amount that should be shipped is 120 and an FLSB should have an IP greater than s_{FLSB} after a lateral transshipment which is not possible in the low settings. The tables show that the S_{FLSB} does affect the results but also show that there are no changes in which structure performs better than the others. A striking thing is that with a lower order-up-to level for the FLSBs in the REA-structure, the expected time to conquer is slightly smaller compared to a higher order-up-to level. All in all, the model is not sensitive to the FLSB order-up-to level.

Table H.6: FLSB order up to level input parameters sensitivity analysis

Input parameter	*Analysis*	*Low*	*High*
S_{FLSB}	360	180	540
s_{FLSB}	180	90	270

Table H.7: Results of sensitivity analysis with low S_{FLSB} parameter

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	217.628	362.783	1,860.573*	261.488	362.097
Expected exposed time sum	1,461.484	1,441.196	5,002.029	1,130.035	1,441.196
Expected exposed time per t	6.731	3.980	2.204	4.331	3.980
Expected exposed time per grid	2.706	2.669	9.263	2.093	2.669
Number of runs	101	101	1000*	101	101
Ready rate	0.923	0.946	0.949	0.943	0.946
Priority resupplies per grid	1.198	1.234	0.550	1.197	1.234
Regular resupplies per grid	0.593	1.098	6.788	0.758	1.098
Priority lead time	4.676	11.005	59.136	5.980	11.005
Regular lead time	1.525	1.638	6.279	1.204	1.638
Number of nodes	24	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	26.0
Number of rides	82,596	114,580	3,470,501	101,709	114.580

*Stopped after 1000 runs, confidence interval for expected time to conquer: (1,851.753, 1,869.393).

Table H.8: Results of sensitivity analysis with high S_{FLSB} parameter

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	217.628	258.079	619.789	265.648	261.884
Expected exposed time sum	1,461.484	793.339	1,470.333	770.360	803.606
Expected exposed time per t	6.731	3.079	2.377	2.909	3.075
Expected exposed time per grid	2.706	1.469	2.723	1.427	1.488
Number of runs	101	101	131	101	101
Ready rate	0.923	0.946	0.945	0.944	0.945
Priority resupplies per grid	1.198	1.199	1.280	1.202	1.199
Regular resupplies per grid	0.593	0.749	1.996	0.771	0.761
Priority lead time	4.676	5.637	29.066	6.136	5.965
Regular lead time	1.525	1.173	1.831	1.116	1.225
Number of nodes	24	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,596	85,578	181,287	91,634	86.290

H.4 FLSB reorder level

The original and changes in the FLSB reorder level parameter are shown in Table H.9. The results of the low and high input parameters could be found in Tables H.10 and H.11 respectively. For the lower FLSB reorder level, it was found that the expected time to conquer increased for the AIN-, PRO, and LAT-structure. This is as expected since it is expected that it would take longer to conquer because the FLSB has likely a lower fill rate. The expected time to conquer of the REA-structure was the same as in the analysis. This could be because FLSBs could help each other more often with this structure which appears to be more favorable. The expected exposed time per grid of the AIN-, REA-, and LAT-structure decreased which is likely due to higher order sizes that will be shipped between the VC and FLSBs resulting in fewer rides and less exposed time. Although, the PRO-structure had more rides in this case than with a higher reorder level for the FLSB. For the higher FLSB reorder level no striking things were found. The expected conquering time decreased and the expected exposed time per grid increased. All in all, the model is not sensitive to the reorder level of the FLSBs. The reorder level for FLSBs could be optimized to find potential better results for all structures.

Table H.9: FLSB reorder input parameters sensitivity analysis

Input parameter	*Analysis*	*Low*	*High*
s_{FLSB}	180	120	240

Table H.10: Results of sensitivity analysis with low s_{FLSB} parameter

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	217.628	288.234	799.719	262.240	297.388
Expected exposed time sum	1,461.484	885.392	1,840.539	826.705	906.739
Expected exposed time per t	6.731	3.079	2.304	3.162	3.056
Expected exposed time per grid	2.706	1.640	3.408	1.531	1.679
Number of runs	101	101	241	101	101
Ready rate	0.923	0.945	0.944	0.942	0.944
Priority resupplies per grid	1.198	1.205	1.296	1.204	1.209
Regular resupplies per grid	0.593	0.851	2.633	0.758	0.882
Priority lead time	4.676	7.208	42.167	5.946	8.014
Regular lead time	1.525	1.327	2.020	1.250	1.385
Number of nodes	24	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,596	90,849	402,661	93,341	93.160

Table H.11: Results of sensitivity analysis with high s_{FLSB} parameter

Indicator	FD-structure	AIN-structure	PRO-structure	REA-structure	LAT-structure
Expected time to conquer	217.628	261.764	629.893	258.842	265.550
Expected exposed time sum	1,461.484	1,154.038	1,984.445	1,109.802	1,165.391
Expected exposed time per t	6.731	4.418	3.157	4.297	4.395
Expected exposed time per grid	2.706	2.137	3.675	2.055	2.158
Number of runs	101	101	141	101	101
Ready rate	0.923	0.946	0.944	0.943	0.946
Priority resupplies per grid	1.198	1.194	1.287	1.202	1.199
Regular resupplies per grid	0.593	0.766	2.027	0.745	0.775
Priority lead time	4.676	5.811	31.370	5.862	6.043
Regular lead time	1.525	1.236	1.821	1.231	1.205
Number of nodes	24	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	27.99
Number of rides	82,596	96,460	217,780	100,704	97.391

H.5 FLSB distance to TBTs

The original and changes in the distance between FLSBs and TBTs are shown in Table H.12. The results of the low and high input parameters could be found in Tables H.10 and H.11 respectively. With the low parameters, the FLSBs move less often. The distance between the TBT and FLSB becomes therefore larger. This is also evident in the results. The structures with FLSBs perform much worse when the distance increases especially the PRO-structure. With the high parameters, the distance between the FLSBs and TBTs is always quite large which negatively affects the results. The model is thus sensitive to the distance between the FLSBs and TBTs.

Table H.12: Distance FLSB and TBT input parameters sensitivity analysis

Input parameter	*Analysis*	*Low*	*High*
FLSB_TBT_minDist	2	2	5
FLSB_TBT_maxDist	5	10	10

Table H.13: Results of sensitivity analysis with low FLSB-TBT distance parameter

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	217.628	892.942	26,888.593*	781.065	883.394
Expected exposed time sum	1,461.484	2,107.841	52,817.317	1,599.663	2,153.461
Expected exposed time per t	6.731	2.464	1.959	2.081	2.461
Expected exposed time per grid	2.706	3.903	97.810	2.962	3.988
Number of runs	101	461	1,000*	451	491
Ready rate	0.923	0.954	0.881	0.950	0.954
Priority resupplies per grid	1.198	1.268	1.398	1.276	1.267
Regular resupplies per grid	0.593	2.943	98.572	2.622	3.019
Priority lead time	4.676	35.394	1,998.041	33.753	36.391
Regular lead time	1.525	1.543	3.421	1.528	1.537
Number of nodes	24	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,596	876,457	42,259,642	855,802	946.697

*Stopped after 1000 runs, confidence interval for expected time to conquer: (26,830.004, 26,947.182).

Table H.14: Results of sensitivity analysis with high FLSB-TBT distance parameter

Indicator	FD-structure	AIN-structure	PRO-structure*	REA-structure	LAT-structure
Expected time to conquer	217.628	1,137.192	39,866.899*	1,008.767	1,136.698
Expected exposed time sum	1,461.484	2,669.693	78,440.876	1,934.028	2,671.771
Expected exposed time per t	6.731	2.363	1.960	1.936	2.367
Expected exposed time per grid	2.706	4.944	145.261	3.582	4.948
Number of runs	101	661	1,000*	501	641
Ready rate	0.923	0.955	0.877	0.951	0.955
Priority resupplies per grid	1.198	1.301	1.447	1.311	1.302
Regular resupplies per grid	0.593	3.939	146.449	3.436	3.933
Priority lead time	4.676	57.732	3,514.324	55.139	58.382
Regular lead time	1.525	1.770	3.681	1.736	1.691
Number of nodes	24	27	27	27	27
Number of edges	24.0	26.0	32.0	32.0	28.0
Number of rides	82,596	1,555,045	63,439,916	1,157,485	1,510.217

*Stopped after 1000 runs, confidence interval for expected time to conquer: (39,780.804, 39,952.994).