The trade-offs between redundancy and flexibility orientated risk mitigation strategies for improving supply chain performance under disruptive risk

Thesis by

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I hope you enjoy reading it.

ABSTRACT

This thesis examines the trade-off relation between flexibility- and redundancy-orientated strategies and their impact on improving supply chain performance under disruptive forces. It does so by evaluating the supply chain practices at the Ministry of Defence in the Netherlands. Seeking to improve performance in terms of cost efficiency, and continuity of supply flow while disruptions affect multiple regions of the supply chain. Additionally, the impact of these disruptions is considered with no risk-mitigating policies in place. Serving the purpose of creating new insights into the effects of disruption thus assisting supply chain managers to make substantiated decisions based on the supply chain vulnerabilities. The main research question for this thesis is drafted to evaluate these practices:

"What are the trade-offs between flexibility- and redundancy-orientated strategies for supply chain risk management, considering the supply- and environmental risks?"

In order to answer the research question a discrete event simulation model has been set up in the SIMIO software package with the aim of creating new insights into the trade-offs. The simulation model has three key tasks: (1) provide insight into how redundancy and flexibility-orientated strategies influence supply chain performance given supplier characteristics. (2) research how risk appetite, costs and resilience determine the trade-offs when opting for the aforementioned strategies. Lastly, (3) embed pragmatic use in a model where multiple sources of uncertainty are incorporated, the individual suppliers are exposed to unique risks fitting their characteristics and enabling exploratory analysis in a visually comprehensive manner.

To evaluate model results five key performance indicators (KPIs) have been chosen. (1) order fill rate, (2) costs, (3) number of back-orders, (4) average lead time and (5) Average number in stock. Evaluating the results it is concluded that both flexible and redundancy strategies prove useful, the trade-off between both strategies is predominantly determined by the risk appetite of the organisation looking to implement the strategy. A more traditional organisation such as the Ministry of Defence is considered risk averse, this attitude towards risk steers more towards a redundancy approach. In this case, backup suppliers proved to perform more consistently under heavy disruptive risk and although the approach has higher implementation and operating costs, it is better equipped to secure strategically important products. That being said, in an environment where all available suppliers are considered to have poor characteristics (reliability, lead-times, capacity), the flexible approach can outperform redundancy as it is more lenient towards unreliable

suppliers.

The managerial implication of these findings are that more proactive policies at the supply chain manager level can better guarantee the continuity of supply chain processes. Knowing the strategic importance of products and the characteristics and environment of suppliers allows supply chain managers to have more control upstream of the supply chain. The current practices where supplier results are evaluated ex-post are not fitted for risk-averse government policy and should be reconsidered. The implications of the trade-offs between flexibility and redundancy policies are listed below in figure 0.1.

Policy	Factor	Outcomes	Managerial insights
Backup supplier	Material Scarcity	Material scarcity can be mostly negated by a backup supplier as the capacity is reserved at the backup supplier. This policy provides benefits from high internal inventory but with added flexibility due to the buyback contract.	Knowing when to opt for a backup supplier is as important as the effects the policy has. Assortment managers should be able to classify the strategic importance of the product. And relate it to the external environment. Where increased strategic importance and high uncertainty are determinants of choosing this strategy. Finally, assortment managers should be aware that the efficiency of the cost trade-off is finite. And that extra investment in backup suppliers does not linearly create extra certainty.
	Environmental disruption	By geographically spacing suppliers this risk is almost completely negated. The risk of both environments being struck remains a threat but much more unlikely.	
	Process disruption	The backup allocation is reserved in advance, so the supplier should not need to produce goods, this negates this risk.	
	Internal inventory	By outsourcing internal inventory to a backup supplier you receive the same benefits of high internal inventory while remaining flexible. The drawback is that if a disruption does not occur, the higher costs are fixed.	
Volume Flexibility	Material Scarcity	Material scarcity is a greater threat to the volume flexibility strategy as there is no fixed allocation reserved in advance. Therefore, a increase in scarcity does impact this policy, it can be partly negated by selecting suppliers with high capacity and reliability. These characteristics both have a buffer effect on scarcity.	Volume flexibility is a good alternative if upfront investment is not preferred. Additionally it is fitting for less strategic goods as it can also suppress costs. Assortment managers could benefit from actively monitoring external developments such as increasing material scarcity. Than this risk can be mitigated by increasing internal inventory levels.
	Environmental disruption	By geographically spacing suppliers this risk is almost completely negated. The risk of both environments being struck remains a threat but much more unlikely.	
	Process disruption	Assuming there is always a trade-off between reliability and cost, the deciding factor here is capacity. For low reliability can be offset by high capacity as the policy is lenient to some 'bad' characteristics	
	Internal inventory	For this policy, it can be said that higher internal inventory decreases the impact of material scarcity.	

Figure 0.1: Managerial implications

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Chapter 1

INTRODUCTION

Today's world is one of great interconnectedness, in the last decades of globalization, firms took the opportunity to expand to different markets with lower production costs. This has led to firms becoming more competitive. However, the increased interdependence made managing supply chain activities more complex. On a worldwide scale, the operating environment for a supply chain becomes more volatile whilst the overall visibility of the supply chain decreases. This results in the risk of disruption increasing (Kamalahmadi and Parast, 2016). Based on Xu et al. (2021), it can be concluded that the number of disruptions in supply chains is increasing year over year. Take for example the recent COVID-19 pandemic, which halted production in many industries worldwide. On another scale, the grounding of the Evergreen in the Suez-channel impacted many sectors, such as the automobile and computer industry, which could not receive their supplies (Chen, Xu, and Zhou 2020; Dolgui, Ivanov and Sokolov, 2017). Due to increased concerns regarding disruption in supply chains, managers and researchers have increased their efforts on controlling these risks, a field which is aptly named supply chain risk management (SCRM) (Ghadge, Dani, and Kalawsky, 2012; Sodhi, Son, and Tang, 2012; Tang and Musa, 2011; Zhu, Krikke, and Caniëls, 2017). Waters (2011) states this increased attention is caused by the overall recognition of the susceptibility of supply chains to a great variety of disruptions which can have both direct and long-term effects on the efficiency of a supply chain. It is the goal of a supply chain to match the supply with the demand, but the supply chain managers are tasked with the decisions that create continuity despite the risks of disruption (Christopher and Towill, 2001). Firms that boast little or no resilience in their supply chain, expose their business to the negative consequences of their vulnerability. To remain competitive, a shift towards resilience-orientated strategies is noticeable in the SCRM field. Leading to more businesses incorporating resiliency in supply chains to protect them from external threats.

In establishing actions to increase supply chain resiliency, Sheffi and Rice (2005) established a dichotomy in the literature that characterizes decision-making. Strategies focus on either promoting flexibility or on increasing redundancy. Both are found in the literature as means to mitigate risk and place contingencies where risk cannot be avoided (Kamalahmadi and Parast, 2016). In this thesis a closer look will be taken towards this dichotomy, reviewing if these strategies are really mutually exclusive and how they impact the performance of a supply chain. Admitting, there are several studies in SCRM literature that empirically recommend either flexibility or redundancy (Sheffi, 2005; Dabhilkar, Birkie, and Kaulio, 2016; Pal, Torstensson, and Mattila, 2014), yet considering the literature review of Shishodia et al. (2021) there remains a lack of conceptual consensus on methods determining the utility of each option. This falls in a greater pattern of overall insufficient theoretical bases within SCRM literature, where a lack of consensus regarding conceptual definitions is noticeable (Carter, 2011; Halldorsson, Hsuan, and Kotzab, 2015). Key questions remain, to address the relative use of flexibility versus redundancy-focused strategies, and under which circumstances what policies are most effective.

A case study approach is employed to explore the comparative differences between redundancy and flexibility-focused strategies under the risk of disruption. Christopher and Peck (2004) classify five different risk categories in the supply chain: process risk, control risk, demand risk, supply risk, and environmental risk. In this study, the focus is on supply and environmental risk. More specifically, the threats to the product flow before they reach the organization's inventory. The environmental risk relates to external changes that impact the continuity of product flow towards the end users and supply risk relates to disturbances within operating processes in the upstream part of the supply chain (Christopher and Peck, 2004). These risks are captured by examining three areas of uncertainty in the supply chain: (1) raw material price uncertainty, (2) process disruption and (3) environmental disruption. Within the dichotomy, firms can prepare for these upstream risks in two ways. First, by adding redundancies across the supply chain. Ivanov (2021), in his book, names backup suppliers, safety stock and overcapacity as regular instances of redundancy in supply chains. Second, the focus on flexibility takes shape by the ability to take different positions to better respond to changing conditions. Ivanov (2021), names flexible transportation systems or volume flexibility as examples to instill flexibility in the supply chain.

The use case for this study is a supply inventory of the Dutch Ministry of Defence. This creates an interesting angle for academic contribution. The vast majority of the supply chain risk management literature aims to increase a firm's competitiveness. However, in the military domain, competitiveness is measured differently, a topic that will be discussed further in chapter 4. The research method used is a discrete event simulation model, this is chosen over the more conventional mathematical optimization studies in the field because it allows for a wider exploration of parameters. The model is a multiple-stage simulation that focuses on the supply side of the supply chain. The model aims to create new insights into the trade-offs between supply chain redundancy and flexibility its multiple ways: 1) provide insight into how redundancy and flexibility-orientated strategies influence supply chain performance given supplier characteristics. 2) research how risk appetite, costs and resilience determine the trade-offs when opting for the aforementioned strategies. and 3) embed pragmatic use in a model where multiple sources of uncertainty are incorporated, the individual suppliers are exposed to unique risks fitting their characteristics and enabling exploratory analysis in a visually comprehensive manner.

Taking inspiration from the studies of Kamalahmadi et al. and Ruiz-Torres et al. (2016; 2013), flexibility and redundancy are examined on their ability to mitigate disruption risks under uncertainty. Where Kamalahmadi and Parast's (2016) model focused on optimization and utilized limited variables, this thesis opts for a more exploratory approach to allow for more insights into the trade-offs under varying circumstances. For redundancy measures, a policy that employs backup suppliers is chosen as the strategy. For flexibility, measures, volume flexibility contracts with suppliers are evaluated. Furthermore, the necessary quantity of internal inventory is monitored under both strategies. These strategies are evaluated based on key performance indicators (KPIs) considered in the simulation model.

The thesis is structured as followed, First, the concepts and current literature is discussed in chapter 2, then the research question is formulated and the best method choice is discussed in chapter 3. Having defined the goals of the thesis a deeper understanding of the Ministry of Defence case is provided in chapter 4, afterwards the system targeted for simulation purposes is identified in chapter 5 resulting in a proposed meta-model for simulation. From this model a conceptual diagram is setup to serve as reference for operationalization in chapter 6. The proposed risk-mitigating policies are presented in chapter 7, and then the model implementation is discussed in chapter 8. This is followed by the presentation of the results in chapter 9, which will be validated in chapter 10. Concluding this thesis will be the discussion in chapter 11 and finally, the conclusion in chapter 12.

Chapter 2

LITERATURE REVIEW

2.1 Disruption from uncertainty

In this chapter, the relevant background information is discussed and the important academic work in the field of Supply chain risk management (SCRM) is reviewed. SCRM has as a goal to evaluate the potential sources of risk in the supply chain and to develop coping strategies for dealing with them. The definition of Jüttner (2003) is generally accepted in the literature and will be used in this thesis, stating: "the identification of potential sources of risk and implementation of appropriate strategies through a coordinated approach among supply chain risk members, to reduce supply chain vulnerability". However, before discussing how to manage risk and thus prevent supply chain disruption, first a theoretical basis must be provided for how risk manifests itself. Therefore, in this section, the subsequent stages leading to supply chain disruption are discussed.

Uncertainty

As decision-makers, supply chain managers need to be aware of where uncertainty develops in the supply chain. Decision-making under uncertainty is the deciding aspect in the success of supply chain management (Sodhi & Tang, 2012; Ivanov, 2021). To better understand the choices decision-makers face, a further understanding of uncertainty and risk, and how they can lead to disruption, is required.
Uncertainty is a general property of any complex system and can be defined as followed: "Uncertainty is a system property characterizing the incompleteness of our knowledge about the system, its environment, and the conditions of its development" (Ivanov, 2021). To illustrate how uncertainty can be seen as the source of risk and disruption, Ivanov (2018), building upon the conceptualization of Klibi et al. (2010), came up with figure 2.1. Showing how on different levels uncertainty leads to risk which can form a disturbance and eventually disruption. The key takeaway here should be that the level of uncertainty stems from the system in which you operate. For a supply chain, this means manager this means awareness of through which subsystems the supply chain runs (countries, markets, industries, etc.).

Risk

Figure 2.1 also provides insight into how Supply Chain Risk Management (SCRM) relates to Supply Chain Resilience (SCR). SCRM is "the identification of potential sources of risk and imple-

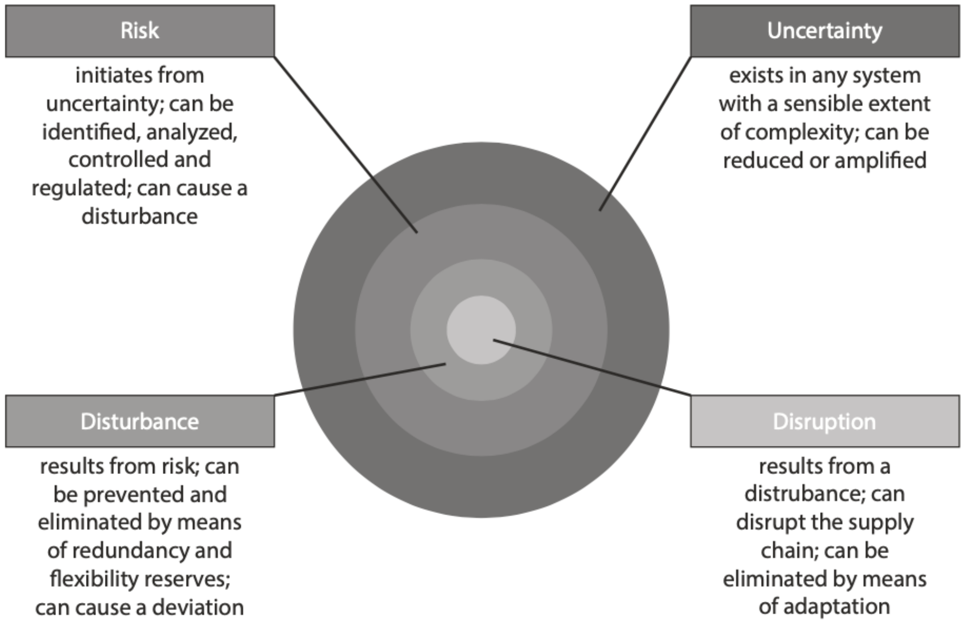

Figure 2.1: Interrelations of uncertainty risk and disruption (Ivanov, 2021)

mentation of appropriate strategies through a coordinated approach among supply chain managers to reduce supply chain vulnerability" (Jüttner et al., 2003). This means that in the first layer of figure 2.1, in the realm of uncertainty, potential risks are being identified, assessed, and appropriate strategies developed. It is important to note that the identification of these risks and strategies is dependent on the system understanding because the understanding of SC managers determines the focus of their attention. Fiksel et al. (2015) state that most SCRM fall short due to traditional risk management relying mainly on statistical information, while many risks are unprecedented. These risks are unknowable on the basis of statistical information which only presents itself after the focus event.

Where SCRM falls short in ensuring unhindered continuity in business operations, the third and fourth levels of Ivanov set in. Leading to disturbance and eventually disruption of supply chain operations. To address this issue the notion of supply chain resilience has become a fast-growing concept in literature in the past decade. Arguing that resilience is a necessary capability that supplements traditional risk management (Fiskel et al., 2015; Ivanov, 2021; Kamalahmadi & Parast, 2016; Shishodia et al., 2021). The increasing attention to resilience literature can be explained by the increasing interconnectedness of modern supply chains. As business operations often transcend borders and involve a multitude of firms in the supply chain, the increased number of involved entities increased the vulnerabilities as well. Therefore, it is understandable that an increase in disruptions was noticeable as well in the past decade. As the increased number of links in the growing operating field leaves the SC more vulnerable. For example, the covid-19 pandemic caused supply chain disruptions all over the world and exposed a risk very few were prepared for. Another example is the blockage of the Suez channel by the Evergreen running aground. The backlog in shipping this caused, led to many supply chain disruptions and is a good example of something traditional risk management did not account for.

Supply chain resilience should fill the gap SCRM leaves in the uncertainty level, where SCRM targets risks that supply chain managers are anticipating. SCR focuses on a general capability of dealing with risks, even if it comes from an unexpected place.

Real State of Knowledge		**Our Perceived Knowledge**	
		Known	Unknown
	Known	*Things we know we know*	*Things we do not realize we know*
	Unknown	*Things we know we don't know*	*Things we do not know we don't know*

Figure 2.2: Rumsfeld's matrix of epistemic uncertainty

Another distinction made in supply chain literature with regards to uncertainty, and perhaps an extension on the previous paragraph, is based on the Rumsfeld matrix (2002; fig 2.2). Which can differentiate different types of disruption ensuing from uncertainty. This matrix is used to illustrate the limited knowledge supply chain managers are operating under. Evaluating the four categories a few conclusions can be made. The first category is known-known uncertainty, i.e., knowing what can happen and roughly how, and when it will happen and the probability of it happening. As an example, a manufacturing machine breakdown is a known risk that can be predicted with the known longevity of parts. These types of risks are often operational risks and statistical data helps to anticipate and prepare for them. Risks stemming from this category are handled by the supply chain managers. Second, known-unknown uncertainty is the risk that is identified, without being able to predict when or estimate the probability of the risk materializing. Therefore making it difficult to plan for. An example is earthquakes at supplier locations, if an area is prone to earthquakes the risk of one disrupting the supply process is known. However, due to the inability to predict an earthquake, it is more troublesome to prepare for this type of risk. Third, there is the unknown-known risk which is the category of risk where most gains can be achieved by proper policy implementation. Here, supply chain managers are capable of estimating the size of the risk but they do not prepare for it because of operational oversight. Meaning, they should have prepared for risk but this was not done due to negligence. Lastly, in the unknown-unknown category, not much can be done in preparation except for general resilience practices. Because what will happen is not known, nor is it known what the repercussions will be. An example of such a risk is the COVID-19 pandemic (Chowdhury et al., 2021). Evaluating risks with such classification systems helps decision makers in identifying all potential risks as it serves as a guide for discussion and assists in identifying exactly how vulnerable a supply chain is. The result of such discussions can lead to more substantiated decisions with regards to how much attention to resilience is necessary for particular processes or product flows.

2.2 Previous research into risk mitigation strategies

Kast and Rosenzweig wrote back in 1972 about how all systems are goal-seeking, with regards to supply chains, this can be profit, reliability, resilience, etc.. Uncertainty plays a crucial role in the ability of a system to reach those goals as it presents a threat to the mechanisms in place and can force a system into disruption. Therefore, by implementing risk mitigating policies, a supply chain can guard itself against the threat imposed by uncertainty. Disruptions can happen at various points across the supply chain, examples of those places are the supply-side (Ellis et al., 2010; Craighead et al. 2007), intra-organisational side (Jüttner, Peck, and Christopher 2003)and demand-side (Roni et al. 2016; Day et al. 2012). Once systems are disrupted, it can lead to the long time degradation of performance, registered as a change in behaviour over time. "The performance prior to, during, and after the disruption is referred to as transient response" (Mackay et al., 2020; Melnyk et al., 2014). This transient response is helpful when determining characteristics in the supply chain such as resilience (Kamalahmadi and Parast, 2016). Resilience is an adaptive system property that allows a supply chain to sense and respond to disruption threats (Walker et al., 2004; Erol et al., 2010). In the literature achieving resiliency in the supply chain is attributed to many different properties and the exact definition is still debated (Mackay et al., 2019; Kamalahmadi and Parast, 2016; Dubey et al., 2019; Chowdhury Quaddus, 2016). That being said, these properties can broadly be categorized as redundancy and flexibility, these antecedents seem central in most literature (Mackay et al., 2020). The antecedents themselves have been researched for a long time, Haimes (1998) talked back in the late nineties about the 'safe yield' through redundancies in supply chains. that being said, most work done is conceptual and does not provide tangible insights into these practices. There have been some qualitative work suggesting the impact but there is a real lack of quantitative studies mapping the effectiveness of these measures in practice (Hosseini et al., 2019).

In the literature, there has been some quantitative research into antecedents of resilience. Chakraborty et al. (2016) used game theory to see the effectiveness of a backup supplier (redundancy) to mitigate supply chain disruption under uncertainty, Saghafian and van Oyen (2016) looked into the effects of contracting a second flexible supplier on supply chain risk mitigation. They measured the added value of this second supplier to determine the upper bounds a manufacturer should be willing to pay to implement this strategy. Jabrazadeh et al. (2018) made a model where they tried to minimize costs under multiple scenarios using secondary suppliers. Torabi et al., (2015) did comparable research differentiating itself with deciding the secondary supplier post-disruption. Practically this makes sense but many assumptions are needed for model implementations and both studies, in broad strokes, had similar outcomes. Other work by Liu and Lam (2013) explored rerouting shipments to prevent delays in a simplified two-tier supply chain model. They investigated disruption at the first tier and concluded the best performance could be achieved by balancing contingency routing and capacity expansion, which are considered redundancy measures.

In the already limited amount of quantitative studies analyzing supply chain resilience, only a couple of studies compare different antecedents of resiliency. which is curious because in the conceptual work it becomes obvious that flexibility and redundancy are in many regards mutually exclusive strategies. Redundancy is a cost-intensive way of building buffer regions in the supply chain making it less flexible in the long term. Flexibility builds on the fast ability to adapt eliminating the need for buffers. In the literature review phase, I found Two studies comparing these different paradigms in a quantitative analysis, where the second one was inspired by the first. Ruiz-Torres and Mahmoodi (2006), made a model to determine the optimal demand allocation considering multiple suppliers with flexibility characteristics. They tested the model to see how many suppliers they would need to mitigate the impact of disruptive events. In 2013 they expanded their own model by evaluating different demand quantities and different reliability characteristics of the suppliers in a mathematical optimization model. In 2016 Kamalahmadi and Parast expanded this model by considering multiple uncertainty locations and modelled regional and supplier disruptions. The main findings were that reserving flexible capacity was a cost-efficient way firms can cope with disruption.

In this thesis, the decision was made to take inspiration from the models of Ruiz-Torres and Mahmoodi 2013, and Kamalahmadi and Parast (2016) but to approach the question from a different angle. Instead of using mathematical optimization, the conclusion was made that Discrete event simulation was more suitable for looking through a more exploratory lens. Where characteristics could easily be added and subtracted from the model and the benefits of simulation pair well with the ability to make results tangible through visualization. The Gap this model should address is threefold: 1) provide insight into how redundancy and flexibility-orientated strategies influence supply chain performance given supplier characteristics. 2) research how risk appetite, costs and resilience determine the trade-offs when opting for the aforementioned strategies. and 3) embed pragmatic use in a model where multiple sources of uncertainty are incorporated, the individual suppliers are exposed to unique risks fitting their characteristics and enabling exploratory analysis in a visually comprehensive manner. Believing these goals would complement previous work nicely and provide pragmatic use for the Ministry of Defence

Chapter 3

RESEARCH FORMULATION

In the previous chapter, several areas in the current scientific literature were identified as insufficient. These knowledge gaps provide the direction for this research. In order to contribute not only in the pragmatic sense but to the scientific community as well, the aim is to address these gaps as well as provide a useful full thesis for the ministry.
In this chapter, the main research question and the subsequent sub-research questions of this thesis, which are formulated on the basis of the knowledge gaps, are presented in section 3.1. Furthermore, the chosen method to provide substantiated answers to these questions is discussed in section 3.2. Here, the different available alternatives are compared and the subsequent choice is justified.

3.1 Research question

In the literature review, the knowledge gap was discussed. Building upon previous studies, here the two antecedents of resilience are evaluated further in a more exploratory model (chapter 2). In order to gain insight into the effects of redundancy and flexibility-orientated strategies, this thesis employs a use case approach. Meaning, a real-world system is used as reference to findings from literature and as a starting point to explore and anticipate the effects within the supply chain. For this research, the Dutch Ministry of Defence is the main subject. More specifically, this thesis will target the assortment management practices at the Ministry. The research question is formulated as:

"What are the trade-offs between flexibility- and redundancy-orientated strategies for supply chain risk management, considering the supply- and environmental risks?"

Within the supply chain literature, multiple antecedents of resilience are defined. However, they can often be aggregated into two categories: flexibility and redundancy. between these two a dichotomy is identified in the literature, where it is argued that these two strategies are mutually exclusive (Sheffi and Rice, 2005). Strategies that optimize flexibility often require a reduction in redundancy and vice versa. The relative importance of the antecedents has received insufficient attention in past literature. In this research, the aim is to compare different resiliency strategies that either are redundancy or flexibility orientated and expose the underlying trade-offs. In collaboration with the Ministry (chapter 5) the choice was made to focus upstream risks, which have been identified as supply- and environmental risks based on the categorisation of Christopher and Peck (2004).

This thesis evaluates the main research question from the perspective of the Ministry of Defence. The military is different from other organisations because it is vital to maintain operational capacity and ensure uninterrupted supply lines as these serve the safety and security of a society. This stresses the importance of resilience in the supply chains but from a scientific perspective it requires a choice. A choice between modelling the specific target system where findings are specific to that system, or modelling a more generic system with findings that can benefit multiple systems and interpret the findings for the specific system. For this thesis the latter is chosen. This was done because of the limited access to the data that would make a specific model more relevant compared to a generic model, this is elaborated upon in chapter 5.

Sub-questions

1. ***What are the important drivers for a supply chain risk management strategy in the military domain, and what are the implications of these drivers for decision-making?***

Key resilience drivers that are relevant for large firms are not necessarily applicable to the Ministry of Defence. For example, a well-known driver for resilience is increased competitiveness. Because a competitor is likely to face the same disruption risks, in military organisations, however, we cannot speak of direct competition because different dynamics drive operations. Where normal corporations need to turn a profit, military organisations' primary task is to ensure the safety and security of the nation and its inhabitants. Therefore, it is important to evaluate how the characteristics embedded in the military domain have an influence on decision-making. Considering key performance indicators found in the relevant literature these different values need to be considered. In answering these questions the aim is to establish how, in the context of this case, the trade-offs are (/or should be) evaluated. Therefore, it is important to know the drivers underlying decisions being made at the Ministry, what values impact the decisions being made? Does this correspond with supply chain risk management literature? Furthermore, it is important to know how the risk appetite of the Ministry translates into supply chain policy. This will be discussed in Chapter 4, and the key takeaways of the chapter are enumerated in table 4.1.

2. ***How do supply risk and environmental risk consolidate, and how can this behaviour be captured and conceptualized for modelling in support of testing risk management strategies?***

This question aims to identify the complexities of modelling the characteristics within (military) supply chains for the purpose of studying resiliency by utilizing a DES modelling approach. To answer this the focus will be on reviewing system practices and capturing the crucial relations in this system and afterwards operationalizing the key dynamics present in the system. The simulation model will be used to assess the impact of different strategies and their ability to handle disruptive events based on the values identified with sub-question one, enabling to evaluate the strategies for the Ministry. DES allows capturing both the stochastic nature of uncertainty intrinsic to disruption events as well as the deterministic nature of supply chain process steps.

Military organisations face different risks than corporate organisations, therefore disruption scenarios that threaten typical supply chains might not be sufficient in this context. In the design phase of the model, this needs to be carefully considered with regards to which risks are being evaluated. This also impacts how the results should be interpreted for the Ministry. This research aims to strike a balance between tailored advice for the ministry and general findings contributing to the academic understanding of supply chain risk management. Sub-question 2 is answered over the span of chapters 5 & 6 .

3. ***What are suitable flexibility- and redundancy strategies and how can they be implemented in the simulation model?***

The main approaches to resilience suggested by literature are based on either redundancy or flexibility. How do these concepts influence resiliency and how does this relate to the values of the Ministry of Defence? Furthermore, potential strategies have elements of multiple antecedents and therefore there can be overlap. Through which lens should we view strategies and what strategies are suitable considering the military domain does not have the same form of competition as regular business practices? Adding, which strategies are suitable for reviewing trade-offs and how can they be implemented for the purpose of this thesis?
this branch of questions needs to be considered when setting up the model, it is important to establish a good experimental design to test the different strategies. Choices such as bundling strategies within a category versus individual testing have an effect on the ability to account for overlap and on the size of the experimental setup and will be discussed in the model implementation section. Sub question 3 is answered in chapter 7 and the key takeaways are enumerated in table 7.1

3.2 Research methods

In order to come to a satisfying answer to the main research question this study uses various research methods. These methods work mutually reinforcing, building a wide substantiation for conclusions. In this section, the reasoning behind the chosen methods will be highlighted and a short description of their contribution will be provided.

Simulation or optimization

When considering the goals of this study multiple approaches are in the realm of suitable solutions. Upon deciding on a method that would fill a gap in current research, interest shifted towards the road less travelled. The literature review revealed a preference towards qualitative research and within the subsection of quantitative research, most works employed optimization(Ruiz-Torres and Mahamoodi, 2013; Kamalahmadi and Parrast, 2016; Hosseini et al., 2019). Which is an understandable avenue considering how these are usually case studies, where an optimal solution is preferred by the case owner. However, in this study, a simulation approach is chosen, not only for its rarity in literature but for the benefits that the method boosts.
Comparing the two quantitative methods on their merits:

1. **"What-if" analysis**, Simulation is a better-suited method when wanting to observe system performance while tweaking initial conditions. In this case, a study where external system conditions are prone to change simulation seems the better choice. Optimization is better suited to find the optimal system design.

2. **Constraints**, optimization requires a very definitive set of constraints under which the 'ideal' outcome is found. Simulation allows for a range of realistic values and the effect of these different constraint values can be observed. This is deemed more useful for expanding organizations.

3. **Randomness**, Simulation allows for variation in certain model parameters, for example, a distribution function over a lead-time parameter can cause a delivery to be delayed or expedited. This is more realistic and can have an impact on the accuracy of the results. optimization works better if system relations do not have large variability.

4. **Decision support**, Optimization is better suited for decision support as it gives a single best solution. In contrast, simulation is more exploratory. In this thesis, it is argued that the external variables are prone to change it is better to find solutions that can provide improvement in a wide range of scenarios. A finding that comes strangely close to the definition of resiliency.

Different simulation methods

Discrete Event Simulation has been the predominant methodology in Operational Research (OR) for over 40 years, but since its introduction, other simulation paradigms have caught on, in order to substantiate a choice between the available methods the mainstream simulation paradigms will be reviewed (Siebers et al., 2010). The three methods considered for this research were Discrete Event Simulation (DES), System Dynamics (SD) and Agent-Based Modelling (ABM). The differences between the methods are discussed below as well as the subsequent choice.

DES vs SD

Both methods, Discrete Event Simulation and System Dynamics are relevant in the simulation of supply chains. Comparing the two has become common in the last decades. However, the two modelling methods have a totally independent backgrounds with little to no communication between both fields and were not designed to tackle the same issues (Tako Robinson, 2012). Substantiating the choice of the modelling approach is a practice that grew alongside the rising research into supply chain logistics. Where first it was claimed that DES and SD were very different approaches to tackling different types of problems, the methods found common ground, among others, in the field of supply chain logistics (Robinson Morecroft, 2005). Here the methods approached the same problem through different approaches, eventually, the outcomes were similar from a user's perspective (Tako Robinson, 2018). That being said, there are unique characteristics prevalent in each method. It is generally agreed upon that DES is suitable for operational/tactical level problems, whereas SD is better equipped to handle problems at the strategic level. Reviewing the underlying principles, SD has a continuous nature where the number of stocks and queues change over time in a flow-like manner. DES requires each entity to be modelled separately where changes in the state happen at discrete points in time. The nature of the state variables in a supply chain model lends itself better to a discrete approach as opposed to a continuous approach. This combined with the focus on the operational and tactical present in the research questions leads to DES being preferred over SD.

ABM vs DES

The third method for simulation is ABM which is based on the constructs of individually interacting and autonomous agents. Depending on the research area the term 'agent' has a different definition. In the context of this research that would be "A system is modelled as a collection of autonomous, interdependent, adaptive and backwards-looking decision-making entities called agents. Each agent makes decisions on the basis of a set of simple rules. Interactions of individual agents result in emergent behaviour of the system." (Macy Willer, 2002). The benefit of an ABM- over a

DES model is the ability to capture emergence and/or self-organisation. Furthermore, ABM is often preferred in situations where individual behaviour is of importance. That being said, in the Operational Research (OR) community DES remains the dominant paradigm. Adding, Brailsford (2014) argues that both simulation paradigms have a lot in common and can be used interchangeably in many situations, even stating that the behaviour ABM can capture as a supposed benefit, is also achievable with DES. The difference is that interactions between entities in a DES model are process based, i.e., competition between resources is reached by means of queues. Siebers et al. (2010) stated that when choosing between DES and ABM the problem requirement should be deciding. Rather than a hammer searching for a nail, it is important to see which method would be most beneficial to answer the research question. For this research, two strategies based on different resilience antecedents are compared with regard to their impact on the supply chain. There is no specific focus on human behaviour nor do I expect emergent behaviour as an important system property. This leads to the decision to choose the more common DES as a method for answering the research questions proposed in this paper.

Chapter 4

THE MINISTRY OF DEFENCE CASE

4.1 Introduction

In this chapter, the use case for this research will be presented. Providing some further insight into why this research is of pragmatic use for the ministry and how certain characteristics inherent to the military domain influence the lens through which supply chain concepts must be viewed. First, context will be provided with regard to the recent changes that spurred the increased attention to resilience. Then, a closer look is taken at the formal organizational structures and policies relating to supply chain management. afterwards, supply chain risk management is evaluated from a military perspective. Lastly in the conclusion, the key takeaways are presented and coupled with the corresponding research question.

4.2 A change in the Ministry of defence landscape

Prior to the Ukraine invasion, while the tensions were rising, the European Council (EC) came forward with a press release reiterating the importance of "strengthening the resilience and response capabilities" and their "unwavering support for the independence, sovereignty and territorial integrity of Ukraine and other Eastern Neighbourhood partners" (European Consolium, 24/01/22). Statements that stirred the military landscape in Europe. Therefore, this is a good moment to discuss the paradigm shift that is ongoing within the Dutch (-/European) Defence organizations. That is to say, the shift from austerity to expansion, the Defence budget of the Netherlands has had a downward trend for the past decades (CBS, 2019), but is now increasing as public safety perceptions turn. This increased Defence spending is a trend that can be seen across the EU, not in the least due to the increased Russian threat perception (Beswick, 2019) and the United States publicly discussing leaving NATO under the Trump administration exposing the European Union's dependence (Barnes & Cooper, 2019).

This paradigm shift has exposed inefficiencies in the supply chain process. Due to these decades of austerity, expense regulations increased to minimize wasteful spending. This set-in motion a series of policies that resulted in an overabundance of red tape, causing sluggish processes and loss of flexibility within the Dutch Defence branches. Now that the Defence budget is increasing and priorities within the organization are shifting, end users of military equipment expect to see tangible results from the newly expanded budget. However, the complicated expense procedures function like a black box where request processing takes a long period of time without transparent insight into the critical path. This is, understandably, causing frustration with the end users who

see little fruition of the increased budget. Furthermore, complicated processes can sometimes cost more than the expense itself. The exact opposite result of the intent of these procedures. Therefore, it is necessary to evaluate the organisational structures of the Ministry of Defence.
As Eisenhower said, "You will not find it difficult to prove that military success is primarily dependent on logistics". Through the same lens, responsiveness in a Defence organisation can be defined as, the ability to properly (al)locate its resources in a changing environment. This means that not only the manpower but all the supplies they require need to reach their designated location when strategic response calls for it. These supply flows are key for enabling the operating capacity of a Defence organisation. Attesting to this, are the supply struggles the Russian army displayed during their illegitimate invasion of Ukraine. The Russian military shows inadequate supply flow control causing a halt to their advance while increasing the vulnerability of resources (The New York Times, 2022). This increased the attention to supply chain processes within the Dutch Defence organisation, combined with their stated goals for reliability and flexibility in their recent vision 2035 document (CDS, 2022). This resulted in the motivation for this thesis where Supply Chain Risk Management (SCRM) plays a central role. When implemented, proper SCRM enables and ensures the control of material flow, from suppliers, through manufacturing and distribution to the customer.

In order to contribute to the stated goals of the Ministry, this thesis will take a closer look at the supply side of their supply chain processes, this choice for the supply side is substantiated in chapter 5. Here we continue by discussing the policy-forming process and all relevant actors. Analyzing where risk mitigating policies can be implemented. Additionally, the influence of the military aspect on SCRM literature is discussed, forming evaluating if the trade-offs of different antecedents of resilience are generalizable (Dubey et al., 2019).

4.3 Supply chain management within the military branches

In order to have a functioning military that can execute all tasks required, a huge number of goods are needed within the organization. From the cargo planes and the armed vehicles, they transport, to the ID cards of employees. All these goods are subdivided into assortments to keep visibility across the organization. Within this case, the focus is on the supply chain processes. There are several actors who play a deciding role in decision-making. These actors will be identified, described and their interdependencies explained. This identification helps determine boundaries in the system, e.g., by letting out political actors the boundaries tighten on a strategic plane. This thesis is written from the perspective of the Ministry, therefore, the focus will be on the internal actors.

Within the ministry, it is the responsibility of assortment managers to ensure the timely delivery of goods and services. Assortment management is the overarching term that determines the policies relating to supply flow in the organization. Assortment management is internally defined as the process that controls the organization-wide needs and requirements, including the execution of the fulfilment of the demand for any and all assortment products, combined with the disclosing of product -processes, -information and -implementation provisions (Tossings, 2018). For practical purposes, a closer look will be taken into a single assortment of the Ministry of Defence. This delineation allows for a better understanding of how policies come to be and what considerations take place. Throughout the thesis, the reasoning is from this single assortment perspective, specifically, assortment 017, Industrial substances is chosen. Here I had the possibility, as part of this thesis, to visit and hear firsthand about on-site practices. Although not identical, most of the findings are generalizable to all assortments. In Chapter 11 this will be discussed further.

First, the definition of assortment management, as employed by the ministry, will be elaborated upon, so the gap in SCRM literature can be bridged. Assortment management focuses on the internal environment of the organization and places itself between the end user and the buyer. The goals here are to accurately capture the needs of the end-users in terms of quantity, service level, lead time, etc. and how to meet these needs in an efficient manner (Tossings, 2018). Compare this to the definition provided by Ivanov for supply chain management (2021) and the similarities are uncanny: "the main objectives of supply chain management are to increase total supply chain output performance, which is basically referred to as supply chain effectiveness (i.e., sales and service level) and efficiency (supply chain costs)". So, in broad terms, it can be said that assortment management and supply chain management in the academic literature share the same goals. The difference being supply chain management is a broader term an that the ministry does not act as a competitive business which is the assumption of most supply chain-related literature. However, this does mean that supply chain management approaches are useful because as means to an end the goals are the same.

In figure 4.1 the material and information flow of a Defence assortment are depicted in a flow schematic. With the focus being on supply-side risk, notice that external suppliers only communicate with the purchasing department. If the internal inventory is depleted and an ATB is placed, purchasing will place another order with the external supplier who ships to the internal warehouse or directly to the end user. To ensure timely delivery to the end user's supply chain it is thus important that internal inventories are restocked before they are depleted. This is the responsibility of the assortment manager.

For a better insight into the formal structure within the Ministry of Defence, figure 4.2 shows the

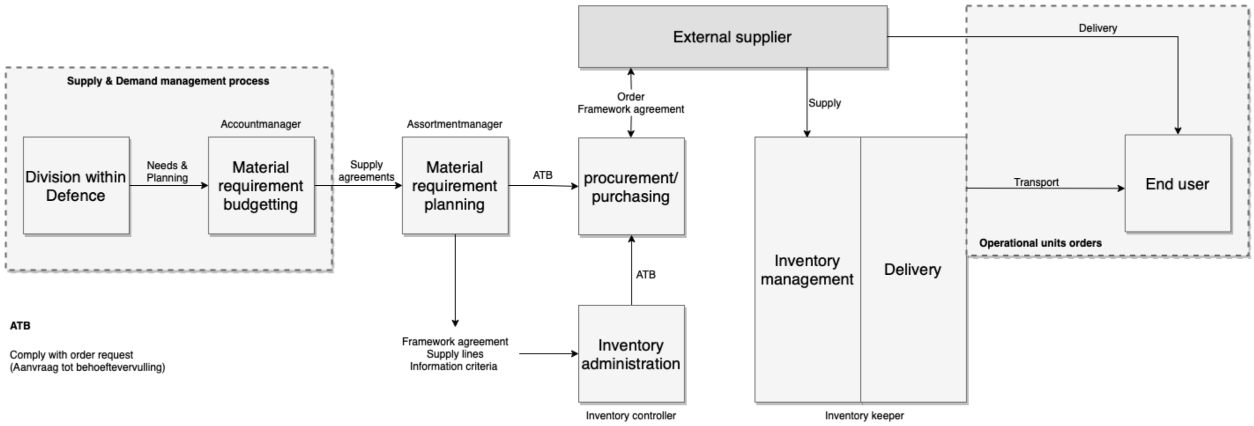

Figure 4.1: Intra-organizational process flow, retrieved from ministry documents (translated)

hierarchical relationship of all actors related to the formal institutions of the supply chain process, here specified as, assortment management. In the next section, the actors are described by their responsibilities. Do note, that although the structure is hierarchical, the lower echelons are the most involved, as depicted by figure 4.1 where higher echelons do not appear. These echelons only interfere when decision levels reach strategic matters. There are seven main actors who play a role in the supply chain processes of an assortment, either directly participating in the flow of goods or indirectly (e.g. advisory, policy forming):

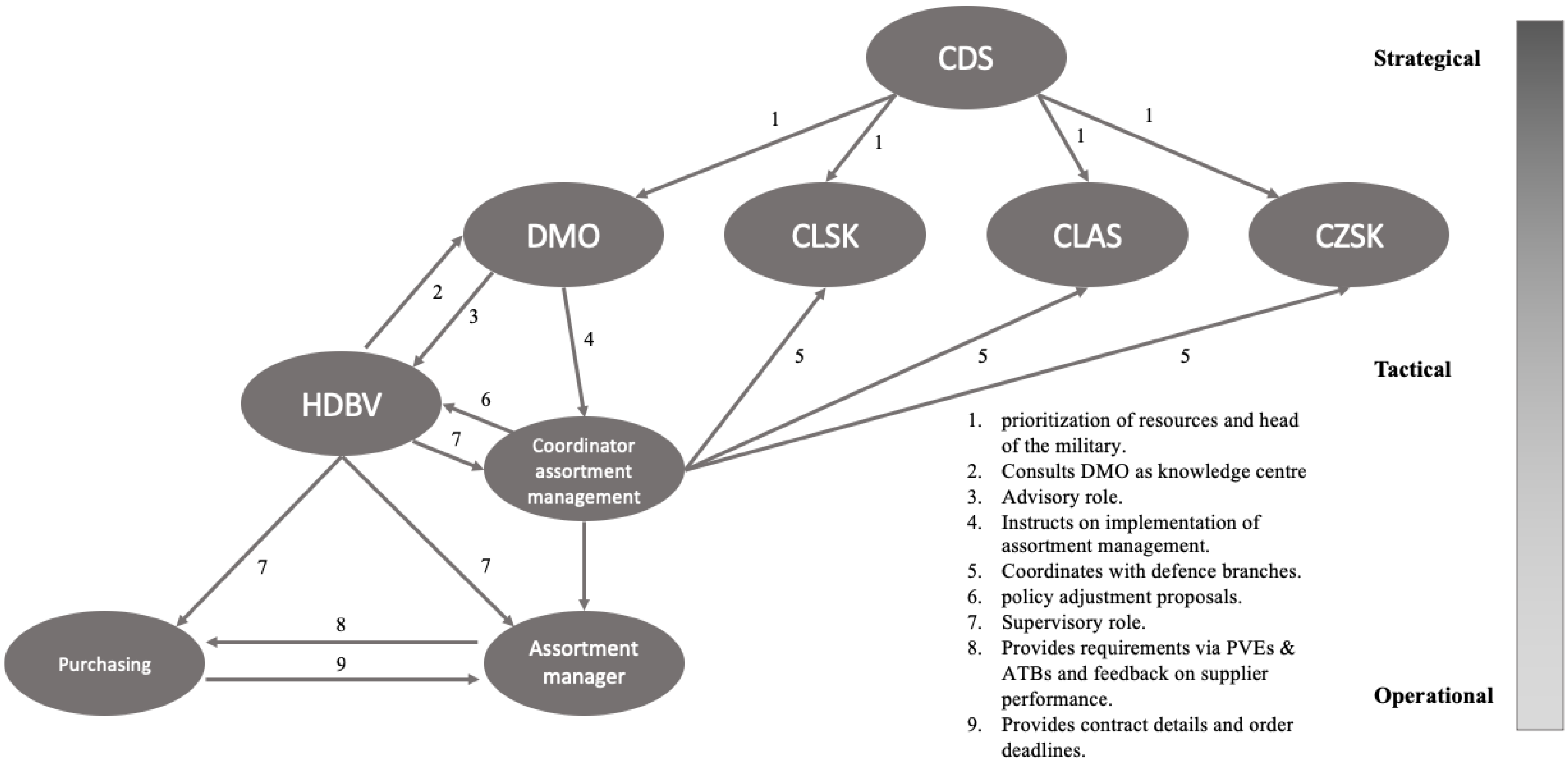

Figure 4.2: Key actor hierarchy

4.4 Actor identification and description

CDS (Commandant der Strijdkrachten, EN: Commander of the armed forces), As head of the Dutch military organization CDS is responsible for the allocation and prioritization of scarce resources. As such, the CDS is the highest level of escalation in the operation of assortment management. Furthermore, CDS establishes the standardization of inventory stocks for deployment, both use and consumable, of all assortments.

DMO BB (Dienst Materieel Organisatie Besturing en Bedrijfsvoering, EN: Department of Materiel Organization Control and Operations), functions as a knowledge centre, manages the collection of sub-assortments within Defence and manages instructions on the establishment and implementation of assortment management.

HDBV (Hoofddirecteur Bedrijfsvoering, EN: Head director of Business Operations), is responsible for the establishment of assortment management and thus the establishment of this designation and related frameworks.

The individual Defence Units, the Defence units are responsible for the performance of assortment management for the (sub)assortments assigned to them. For each sub-assortment, they invest in assortment management within their organization and appoint an assortment management coordinator. The Defence components are further responsible in the role of the end-user for formulating their demand/needs to the assortment managers, both those within their own and other Defence components. Defence components must also comply with the provisions of the assortment instructions. The Direction of the Defence component to the assortment managers is hierarchical.

Coordinator assortment management, Coordinates with regards to the design of the assortment management within the Defence branch, with the coordinator of other branches and with the executive board (for lack of a better term, the top level of the organization, NL: Bestuursstaf). The goal of the coordinator is to ensure that goods are classified correctly and only have a single designated (sub-) assortment. They also align their practices with that of the other coordinators. Proposed policy adjustments come from the coordinator and are submitted to the HBDV (even if they regard the practices of the assortment manager), who can elect to approve the proposed policy adjustment. This means that the coordinator determines the basic principles and conditions in which the assortment manager operates. The clarity and awareness of product-specific information such as specific handling instructions are the responsibility of the coordinator as well.

Purchasing, As mentioned above, assortment management focuses on the internal environment so the contact with external suppliers does not fall under the responsibilities of the assortment manager but to a separate procurement department. The assortment manager conveys his need in the form of PVEs and ATBs and the purchasing department will select a supplier accordingly in the market. Do note that the PVEs determine the framework conditions that need to be met by the suppliers. However, adding to the requirements, the procurement department needs to safeguard other the prerequisites stipulated in, e.g., national or EU agreements.

Assortment manager, realizes the conditions for the effective and efficient supply delivery, maintenance and availability of the products in the sub-assortment. The assortment managers are actors involved with supply chain management in a full-time capacity, and they take the role of core actor in this thesis. The manager is responsible and authorized to:

1. Determine which products are to be carried in a (sub-) assortment
2. identifying and aggregating the needs of the Defence branches and, through consultation, reconciling them with the allocated financial resources, resulting in the order for Defence-wide needs fulfilment
3. determining how the goods and services in the sub-assortment will be delivered (supply chain design) and setting up the chain in the information systems.
4. Monitoring the supply chain and possibly adjusting the parameters and giving indications in case of structural disruptions.
5. securing Defence needs in the context of category management and including Defence needs in category plans.

In order to realize the named responsibilities and set up the supply chain the assortment manager utilizes three tools: 1) assortment instructions, 2) data from information systems and 3) PVEs / ATBs (program of requirements / application for needs fulfilment) (See figure 4.3).

Interaction between purchasing and assortment managers

There is much interplay between the purchasing department and the individual assortment managers. During a contract period, the assortment manager monitors internal and external supplier performance and, in the event of structural underperformance by the external supplier, reports this to the purchasing agent so changes can be made accordingly. Purchasing relays changes in products or pricing back to the assortment manager so he can keep track of changes in efficiency considerations. Furthermore, the assortment manager is kept informed with regard to contract expiration dates in a timely manner so that the assortment manager can prepare a new requirement statement.

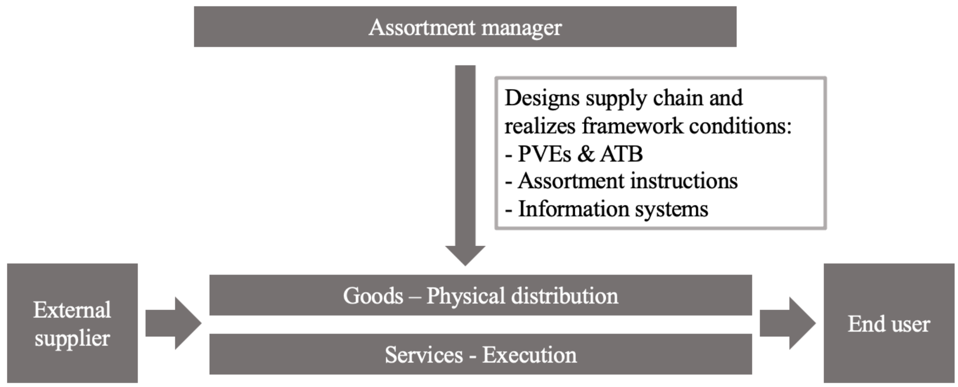

Figure 4.3: Assortment manager tools

4.5 Key performance indicators for the Ministry of Defence

According to formal policy, the assortment manager uses four key performance indicators (KPI) to evaluate the performance of the supply chain. Here these KPIs will be presented and evaluated for their use in this research:

Chain Performance, Percentage of end-user (internal) orders delivered on time and in the correct quantity. On-time is established by "the last partial delivery occurred on or before the last required need date". Definitely useful, and is the main indicator to evaluate any supply chain.

Post-contract leadtime The average amount of days exceeding the agreed-upon delivery dates with the suppliers. This indicator is very valuable for an organisation that holds reliability in high regard. However, this indicator has to be altered for the purposes of the simulation study where the focus is on the supply side under high uncertainty. This will be further discussed in Chapter 6

Granted logistic response time The average amount of time between the moment the internal need is known and the last desirable delivery date. Although the indicator is useful for the Ministry, this targets the intra-organisational and demand side of the supply chain. It relates to accurate demand forecasting and proper information sharing within the organisation. Therefore, it is outside the scope of this thesis.

Inventory availability Percentage of orders that is in-stock the moment the order is placed. This indicator is related to Chain performance and for the purposes of the simulation, it does not have additional benefits.

It is the responsibility of the assortment manager to evaluate suppliers and provide restraints for the purchasing departments to select said, suppliers. In accordance with the internal policy documents, these are the prescribed KPIs (Aanwijzing HDBV-015, 2018). This means, that if the assortment manager deems a supplier's performance underwhelming, he will provide more constraints in the PVE when the contract expires and a new contract or supplier is selected. The purchasing department then searches for the most competitive price in the market that meets the standards (Aanbestedingsleiddraad AW2012). However, this means that costs are only evaluated ex-ante and do not play a factor in the performance evaluation of the assortment manager. Although, there is communication between the assortment managers and purchasing this is not a formal process. In the current process, reliability is not weighed against costs in performance evaluation. It would provide for more substantiated and informed decisions if more information is used for evaluating the performance of suppliers, ideally ex-ante and ex-post.

4.6 Formal structure versus practice

In the sections above the formal structures related to supply chain management are presented. However, it is no secret that the Ministry is operating with an employee shortage. Due to a large number of vacant positions, the separation between different formal roles starts to fade. For example within the industrial substances assortment, there is a big shortage of people in management positions. During informal talks, it was discussed that management positions are difficult to fill and as a result, employees are promoted from the inventory floor to management based on seniority. This has led to a quality problem with management staff. The combined effect of quality and quantity problems in management positions has had the consequence of there not being dedicated assortment managers capable of performing all their responsibilities to the required standards. Resulting in fuzzy mixing of responsibilities which lowers accountability. During talks on-site of assortment 017 it became apparent that due to this understaffing the monitoring and demand forecasting within the supply chain are not executed to the preferred standards.

4.7 Supply chain risk management in the military domain

In supply chain risk management literature, competitiveness is often named as a driver for implementing policies (Shishodia et al., 2021). In traditional markets, the firm that handles the threat of disruption the most efficiently brings down its cost more and, therefore, has an edge over other firms in the market space. In the military domain, competition works differently, two military organisations do not compete in the same market space. That would be like the Dutch government hiring a foreign military because they can do the job at a better price. The price competition of regular markets does not hold for the military domain. The size of the budget is a political decision instead of being determined by supply and demand. The government assigns the tasks that the Ministry of Defence must be able to carry out and allocates a budget. the Ministry has the responsibility to perform those tasks to the best of its ability within the budget constraint. That is not to say that competition does not exist. On the contrary, technological and/or equipment competition is very important. Having the most advanced equipment is definitely a large advantage. However, that enters into the concept of deterrence. deterrence plays a big role in military thinking but for the purposes of this research, it is out of scope.

So, if competition is not the driver for supply chain risk management in the military domain, what is? And does it change the way the relevant SCRM literature should be interpreted? To answer these questions, the values underlying the driver must be reviewed. In a regular marketplace, firms can only exist if they generate income, to do so they must be competitive. the military branches exist because they safeguard values such as security and freedom. From this perspective, SCRM is important because it enables the military to better safeguard its values. The way this alters how the literature should be interpreted is thus a shift in the priority of values. Where literature values cost efficiency and competitiveness above continuity, this changes for military organisations because running on a budget deficit does not remove the need for the institution as it would do for a regular firm.

Continuity can thus be seen as a driver for SCRM. This corresponds with the findings of other advisory reports for the ministry. TNO wrote a report about the adaptivity of the Defence organisation (2016). This was more holistic than a supply chain approach, therefore, the jargon is different but it corresponds to the findings of this thesis. The report stresses the importance of organisational adaptivity to deal with 'strategic shocks'. On a supply chain level, this translates into maintaining continuity under disruptive uncertainty. Furthermore, the article concludes that flexibility and robustness are the two global orientations to reach adaptivity. Consider this thesis, where flexibility and redundancy contribute to resiliency which ensures continuity and it can be concluded that this thesis is a supply chain-orientated extension of the TNO report.

4.8 Conclusion

This chapter presented the case for the Ministry of Defence and discussed defining properties of the supply chain structure in terms of the responsibilities of involved actors and system characteristics in the military domain. Here, the main findings are recapped in relation to the first research question. First, as part of the goal to become more 'reliable' and 'adaptive' the ministry, alongside competitive businesses, has taken an increased interest in supply chain risk management (SCRM). The most important takeaway is that the Ministry of Defence differentiates itself as an organisation from regular competitive market businesses by harbouring different values. One of the main tasks of the Ministry as instructed by the government is to protect order and stability and safeguard the territory of the Netherlands and its inhabitants. This presents underlying values that cause different priorities when evaluating supply chain performance. Traditional supply chain risk management literature values profitability above continuity. In this case, continuity is considered a main driver for the Ministry. This corresponds with previous findings of military advisory reports by TNO, where ensuring the continuation of operations during strategic shocks was stated to be vital to the existence of the military (TNO, 2016). This stresses the need for SCRM to and being vigilant against uncertainty in the supply chain as disruption affects continuity by definition.

Second, Due to a large number of unfulfilled positions, it is common that separate positions, according to the formal structure, are merged and executed by a single person. This leads to decreased attention to individual responsibilities and the removal of checks and balances. Furthermore, an additional effect of these unfilled positions is that the required qualification standards for management positions have dropped. Therefore, the Ministry of defence struggles with both quality and quantity issues in management positions which impacts the overall quality of the decision-making process.

Third, it is the responsibility of the assortment manager to evaluate the performance of suppliers, and if deemed underwhelming provide an iterated version of the PVE when it is time to renew contracts. The key performance indicators prescribed for this end are lacking in their ability to substantiate good decision making and the information exchange between purchasing and assortment managers are insufficient (at least formally). Furthermore, supplier evaluation is done ex-post, with the only ex-ante consideration is meeting requirements that do not have explicit policies directing them.

Concluding, In a supply chain there is an inherent dependence on upstream entities in the chain. The only tools assortment managers have to deal with the supply risks is the supplier selection and inventory management. At this moment the supplier selection process is not executed thoroughly with key positions not filled and incomplete information due to the departmental separation of the supplier communication from the inventory management. To assist in supplier selection a simulation model is proposed in this thesis. The model aims to create insight into the behaviour of important supplier characteristics and how policies can further improve performance under disruptive force. Furthermore, it makes ex-ante decisions far more substantiated compared to current practices that do not support conscious trade-offs.

Table 4.1: Key takeaways and providing insights answering sub-question 3

What are the important drivers for a supply chain risk management strategy in the military domain, and what are the implications of these drivers for decision making?
§ In contrast to competitive market businesses, which is the assumption in most SCRM literature, military organizations consider continuity of operation as driver above all else.
§ The importance of SCRM is highlighted by this desire for continuity although you should evaluate the literature through a different lens.
§ Current Performance indicators are insufficient for evaluating risk trade-offs.
§ Open vacancies have led to the merging of functions which influences the quality of decision-making.
§ The contracting procedure is divided between purchasing and assortment managers which can lead to incomplete information during supplier selection.

Chapter 5

SYSTEM IDENTIFICATION

In the previous chapter, an outline of the supply chain processes and the relevant actors for policy formulation at the Ministry of Defence were presented alongside drivers and values which spurred on demand for supply chain risk management policies. In this chapter, the gap from supply chain risk management theory to practice is bridged by delineating the system of our use case and identifying important system behaviour for modelling purposes. This delineated system will provide a platform to test the different risk mitigation policies targeted in the main research question. One important caveat must be noted first. Although the case used for this study is with the Ministry of Defence and the risks relating to this domain will be discussed, the model itself will be general and focus on dynamics present in every supply chain. There are two main reasons for this choice. First, the findings are more generalizable and can thus extend their use outside of this individual case. Second, the products that significantly differ from other industries are less accessible in terms of data collection and have very limited supplier choices due to NATO restrictions (think weapon systems, munition, etc.).

5.1 Supply chain vulnerabilities

In order to improve the resiliency of the supply chain for the Ministry, the vulnerabilities need to be identified. Within a big organization such as the Ministry of Defence, the supply chains' magnitude increases vastly due to the wide stretched, international nature and sheer quantity of goods involved in the operations. This also means it is susceptible to a wide variety of disruptions as well. As mentioned in the literature review, disruptions are a product of uncertainty. These uncertainties can be traced back to various locations in the chain. This thesis focuses on part of the supply chain but other vulnerabilities are identified as well and could serve as new avenues for future research.

In the literature, multiple focal target areas are identified, in the conceptualization of Mackay et al. (2020) a division is made between supply-side disruptions, demand-side disruptions and intra-organisational disruptions. These categories can be compared to three main disruption threats in military organisations as identified by Elvira et al. (2015), in qualitative research conducted with the American Defence organization. Although the scales are different, the principles and arguments hold up for the Dutch Defence organization. Therefore, it is assumed that these military supply chain threats are industry specific instead of organization specific. This allows for a relationship to be established, the threats can be matched with the categories of Mackay et al. (see figure 5.1).

Figure 5.1 denotes the material flow through the three stages of a supply chain and shows the major threats and their causes in each stage.

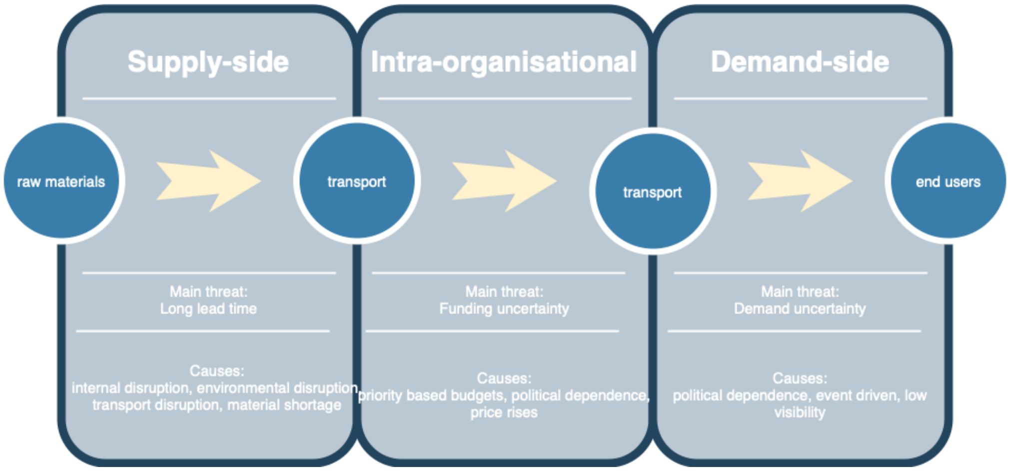

Figure 5.1: Schematic depiction of the supply chain

First, on the supply side, here the main disruption threat is long lead times. Long lead times can result in the depletion of internal inventory which leads to a loss of operational capacity. This threat differentiates from the other two by originating, for the most, outside of the military organisation. Meaning, for mitigating this risk there is a dependency on the capabilities of the suppliers. However, this does not mean it is beyond the ministry's influence. Rather, this stresses the importance of prudent supplier relationship management to minimize the chance of risks manifesting in disruption. Knowing where your suppliers are vulnerable can help anticipate and prepare the military in preventing disruption. The strategies for doing so will be discussed in chapter 7, but it starts by understanding the origin of the risks.

Second, intra-organisational, this encompasses all the material flow processes after receiving the goods from the supplier up to the delivery to the final user (operational units or training). Furthermore, all the information flows not including the supplier are considered intra-organisational as well. This means that solutions to supply chain issues originate here by means of implementing strategies. The main threats in this stage are therefore more bureaucratic than anything else. Elvira et al. (2015) identifies funding uncertainty as the greatest threat to disruption at this stage. This corresponds with informal discussions that took place at the Ministry of Defence as part of this thesis, where funding and budget allocation were regular topics of debate. Being outside of the scope of this research it could be well suited for further research.

Last, the demand side, in regular supply chains, this would be customers but, in the military, end users are the units that use the material in the field for missions or training purposes. The main identified threat is the volatility and uncertainty in the demand. This is a complex issue, mainly because of two reasons. First, due to the responsibilities adopted by the military, they carry an obligation to act in unstable environments if deemed necessary for national security. this means that due to the inherent uncertainty of these situations it is hard to predict where, how, and on what scale deployment will be required. This leads to high uncertainty on the demand side because not only is it unknown in what capacity the military needs to act in the future, the type of materials needed is dependent on the situation as well.
Second, due to limited budgets and priority-based allocation of these budgets, commanders of operational units need to find a balance in their requirements. Where they have enough to carry out their responsibilities but not too much because that could mean a deficit elsewhere in the budget. The uncertainty in demand is therefore largely a consequence of shifts in the geopolitical landscape. This is because deployment takes priority over training and certain procurement needs to be fast-tracked which can lead to a backlog of orders for training purposes. This dual-track approach for training and mission could be an interesting topic for further study but falls outside of the scope of this thesis.

To relate this new knowledge of supply chain vulnerability to the case for the Ministry, figure 5.2 shows the conceptualization of Mackay et al. (2020) applied to the process diagram from chapter 4. In figure 5.2 it can be seen that external suppliers only interact with the purchasing department and that their goods go to the assortment or directly to the end users. From this, it can be concluded that there are three controllable factors to reduce supply-side risks. First, the selection of the suppliers themself is controllable. Second, the order framework agreement is drafted between suppliers and the purchasing department. Third, the internal stock held in inventory can act as buffer.

5.2 Supply side decomposition

This thesis focuses on supply-side risks, this area was chosen based on discussions at the Ministry, where this area of the supply chain was identified as the primary concern. This decision falls in line with the perspective of military thinking, where there is an aversion to dependence. Amongst military employees, there was also a noticeable ’can do’ mentality. The belief is that, when necessary, intra-organisational issues can and will be solved. For the supply-side, Long lead times are identified as the main threat (see figure 5.1). Comparing this with the five sources of risk identified by Christopher and Peck (2004), discussed in the literature review (Chapter 2), supply and environmental risk are the main causes of long lead times. To create more insight into how a supplier is also dependent on his suppliers, this study proposes a to analyze a second tier supplier and decompose supply risk further into production risks and material scarcity.

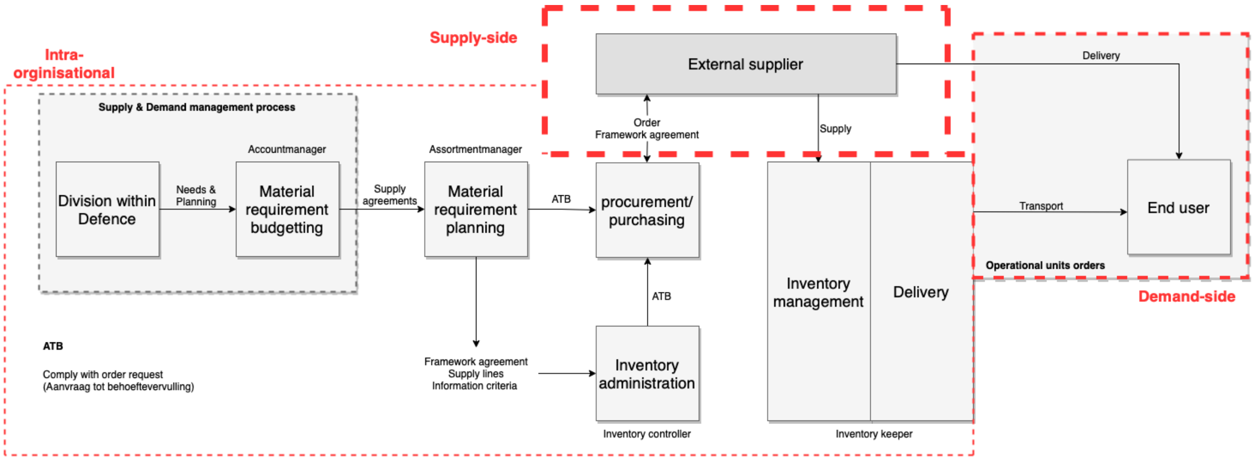

Figure 5.2: composition of the supply chain within the use case

Visualizing the targeted system, a meta-model of the supply flow is proposed in figure 5.3. The two-tier supplier model is set up as followed: an assortment of the Ministry of Defence depletes due to internal demand. Therefore, it needs to source products from a supplier. This external supplier creates the finished products from raw materials. These materials need to be sourced as well from a second-tier supplier. The arrows in the figure illustrate the available controls, required resources and product flow, with the sources of risk marked in red.

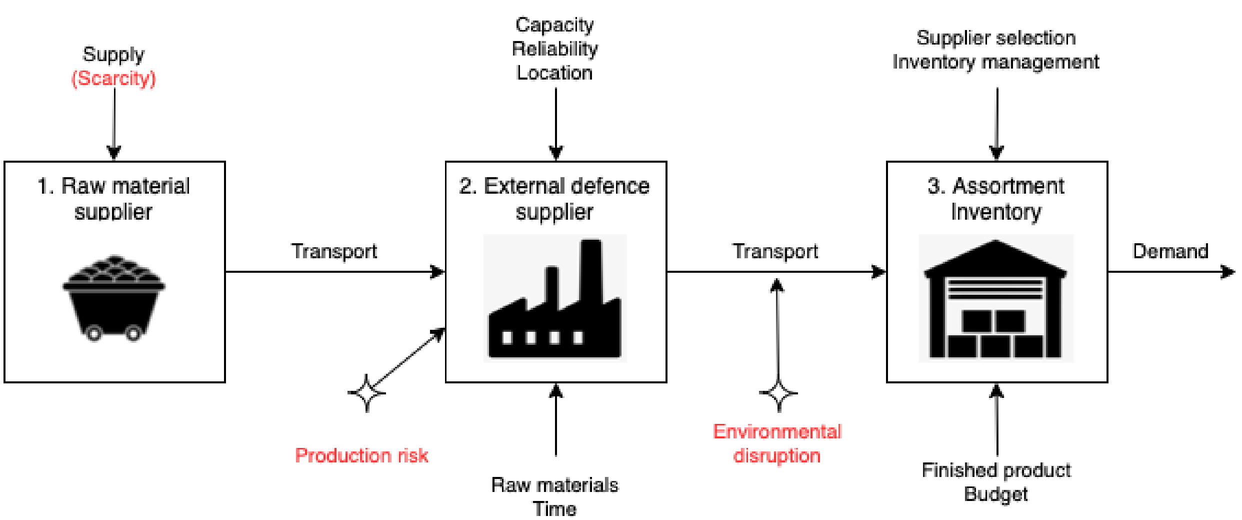

Figure 5.3: Meta model. Arrows from above represent controls. Arrows from below are needed resources. Horizontal arrows are the inflow and outflow

Assortment inventory, First, the assortment inventory of the Ministry. To ensure operational ability the inventory must be able to satisfy the demand from the end users (in this case, military

units). Therefore, the assortment manager must ensure enough inventory is in stock to comply with the incoming requests. In the meta-model (5.3) it can be seen that there are three control measures that can be utilized to this end. The selection of the suppliers themselves, the contract terms included in the order framework agreement and the inventory management.
In the simulation model, these processes have been captured based on several simplifications with underlying assumptions. First, supplier selection is subject to the proposed policies and the base scenario. Second, inventory management is represented by the size of the internal inventory and the threshold value, at which the resupply order is placed. Third, the order framework agreement is not separately considered in the simulation but as part of the policy. In reality, these are contract terms that are determined as part of the supplier selection. In the discussion, normative assumptions will be discussed relating to supplier characteristics to assist assortment managers in the process of drafting this framework.
Furthermore, it is assumed that running a low internal inventory is preferable because this results in less fixed costs and thus more flexibility with the budget. The factor in the simulation model that determines how low inventories should be is the reorder threshold. If it is possible to maintain performance with low order thresholds, the organisation is more flexible. Another simplification is that all orders go through the inventory so direct delivery to the end user is not considered. Lastly, the assortment manager has no fixed budget, but it is known that if he claims a larger portion of the overall budget another department loses out. Therefore there is an incentive to minimize costs.

Assumption 1: The assortment inventory controls a single product.
Assumption 2: Assortment managers have two control options, supplier selection and the order framework agreement are combined in the proposed policy and inventory management can be used separately to optimize the policy.
Assumption 3: The internal demand is assumed to be stochastic, so performance under different peak intensities can be evaluated.
Assumption 4: It is assumed that low internal inventory levels are preferred to improve overall flexibility.
Assumption 5: There is no budget constraint, the cost efficiency trade-off is evaluated ex-post
Assumption 6: Direct delivery to the end user is not possible in the simulation.

External Defence supplier, There are three supplier options in the model, each supplier converts raw material into finished goods. It takes time to convert the raw materials into finished products and this process is vulnerable to disruption. If a supplier receives an order from the Defence assortment and does not have enough finished products to satisfy this order, the order is backlogged until the supplier has produced enough for the full order.

Table 5.1: Supplier archetypes

	Supplier Reliability					
	Production Reliability	*Price Tolerance*	Location	Transport Time	Capacity	Costs
Supplier 1	High	High	Europe	Short	Low	High
Supplier 2	Moderate	Moderate	Europe	Short	Moderate	Moderate
Supplier 3	Low	Low	Intercontinental	Long	High	Low

The idea of the three different suppliers is to represent the different options in the market and is inspired by the model of Kamalahmadi and Parast (2016). Table 5.1 shows the different archetypes of suppliers. The three suppliers have different reliabilities relative to one another, represented by their price tolerance and production reliability. The price tolerance determines when they are able to source raw materials, this is checked daily. Production reliability is captured by the amount of time a supplier is producing products. where a reliable supplier has longer up times and shorter down times. Furthermore, more reliable suppliers are able to produce goods faster. The capacity refers to the size of the supplier, where large suppliers have more inventory of finished goods in stock and due to economies of scale can deliver units at lower prices. This led towards the following assumptions for suppliers:

Assumption 7: There are three suppliers in the market, each with its own characteristics.
Assumption 8: Suppliers have two inventories, one for raw materials and one for finished products.
Assumption 9: If not enough finished products are in inventory to satisfy an order, the order is backlogged until the full quantity can be delivered.
Assumption 10: European suppliers are considered more reliable than intercontinental suppliers.
Assumption 11: There is a trade-off relationship between reliability and costs per unit.

Raw material supplier, In the model all Defence suppliers need to source raw materials to produce their products. they do so from a single supplier. The raw material supplier is assumed to be unaffected by the uncertainty and considered fully reliable. However, to simulate the effect of scarcity it is assumed that the price the raw material supplier sets for its goods is determined by a stochastic function. This price is updated daily and can rise or fall in increments determined by a normal distribution. The model logic works in a way that the price tolerance of the suppliers downstream determines if an order will be placed. The following assumptions have been made for the model:

Assumption 12: Raw material suppliers are considered fully reliable.
Assumption 13: The price of raw materials is updated daily and has an equal chance of going slightly up or down within the upper and lower bounds.

Assumption 14: the transport time of raw materials is equal for all Defence suppliers and is unaffected by environmental disruptions.

Environmental disruption risk, Christopher and Peck (2004) discuss environmental risk as an external event that can impact the focal firm, those upstream or downstream or the marketplace itself. In this study, it is defined as an overarching term covering risks relating to the physical location of the supplier. This covers risks such as political, natural/man-made disasters and transport. I.e., the transport reliability of a supplier located farther away is smaller than that of one close by because the increased spatial exposure. From a military perspective, this source of risk can be extra relevant, considering that military supply chains can be strategic targets. This is not explicitly considered in the simulation but will be a point of attention in the recommendations. For the simulation model, this risk is simplified as an chance-based event that delays the orders from an affected region. The following assumptions are made:

Assumption 15: Environmental risks target a single region and have a stochastic chance of happening.
Assumption 16: Environmental risks disrupt the transportation routes in a single region to assortment inventory.
Assumption 17: The duration of disruption is stochastic and depended on the region where it takes place.

Production risk, Christopher and Peck (2004) discuss supply risk as the upstream disturbance of the supply flow. For this case, this risk is subdivided into production risk and material scarcity risk. Production risk is defined as events that directly threaten the production process of a supplier. For example, a mistake in the planning, a shutdown due to mechanical failure or employees striking. This risk is modelled by suspending the model process that converts raw materials into finished goods. The suppliers' inventory of finished products will then start to run out. The following assumptions are made:

Assumption 18: All suppliers need to produce their finished products from raw materials, this production process can be suspended.
Assumption 19: This process failure can happen stochastically between upper and lower bound intervals depending on the specific supplier.
Assumption 20: The duration of the suspension is stochastic and dependent on the specific supplier.

Material scarcity risk, This risk can also be categorized as a supply risk because it is an upstream disturbance of supply flow. In literature, this risk is often not explicitly incorporated in resilience models. However, it seems like scarcity is a growing problem within many supply chains. Alonso et al. wrote back in 2007 about this increased risk. Furthermore, there is a military aspect, considering the current conversations about the strategic importance of raw materials, where China's dominance in the material market is often cause for concern (Pencke, 2021). Therefore, due to strategic importance and increased relevance, material scarcity is considered as a separate risk in the model. The following assumptions are made:

Assumption 21: Material scarcity is created by a stochastic material price which is updated daily.
Assumption 22: The second-tier raw material supplier is not affected by disruption risks.
Assumption 23: The ability of a first-tier supplier to source raw materials is dependent on their reliability, represented by a price tolerance.
Assumption 24: All suppliers source from the same market and have equal delivery times of the raw materials independent of their region.

5.3 Conceptual diagram

Further developing the meta model (figure, 5.3), a conceptual diagram is presented in figure 5.4 to serve as reference for the simulation model in the SIMIO software package. The idea is to have a three step model with dynamic inventories which can deplete and be restocked. The Defence assortment inventory (on the right) depletes over time due to demand from within the organisation. Once a threshold value, determined in the inventory management policy, is reached, a order is placed with a first tier supplier. Who, upon receiving the order, sends a shipment back to the assortment inventory. This supplier consists out of two inventories: one for raw materials and one for finished goods. When a shipment is send the quantity in stock of the finished goods inventory is reduced. Similar to the Defence assortment, suppliers also use a threshold value in this inventory. If that threshold is reached, production commences. In this production process, raw materials are converted into finished goods. This process starts to restock the finished goods inventory and deplete the raw material inventory. Because a supplier is in turn dependent on his suppliers, a second tier supplier has been added into the model. The difference in this order process is that instead of depending on the inventory stock, a order can only be placed if the price is under the price tolerance of the supplier. This is done to simulate the effects of material scarcity. The idea being to create more insight by decomposing the supply risk into two categories: production risk and material scarcity.

In the bottom left of figure 5.4 the key model variables to be implemented in the simulation model are presented, these variables serve as guide during the modelling process and will be further discussed in chapter 6. Moving to the right, the model processes serve as reference for the key logic operations the model must be able to execute, in appendix B the allocation logic process is discussed and more information with regards to the SIMIO model is provided. Lastly, the model inputs are the supplier policies, the target of this study (see chapter 7), the inventory management policies and the model run-time.

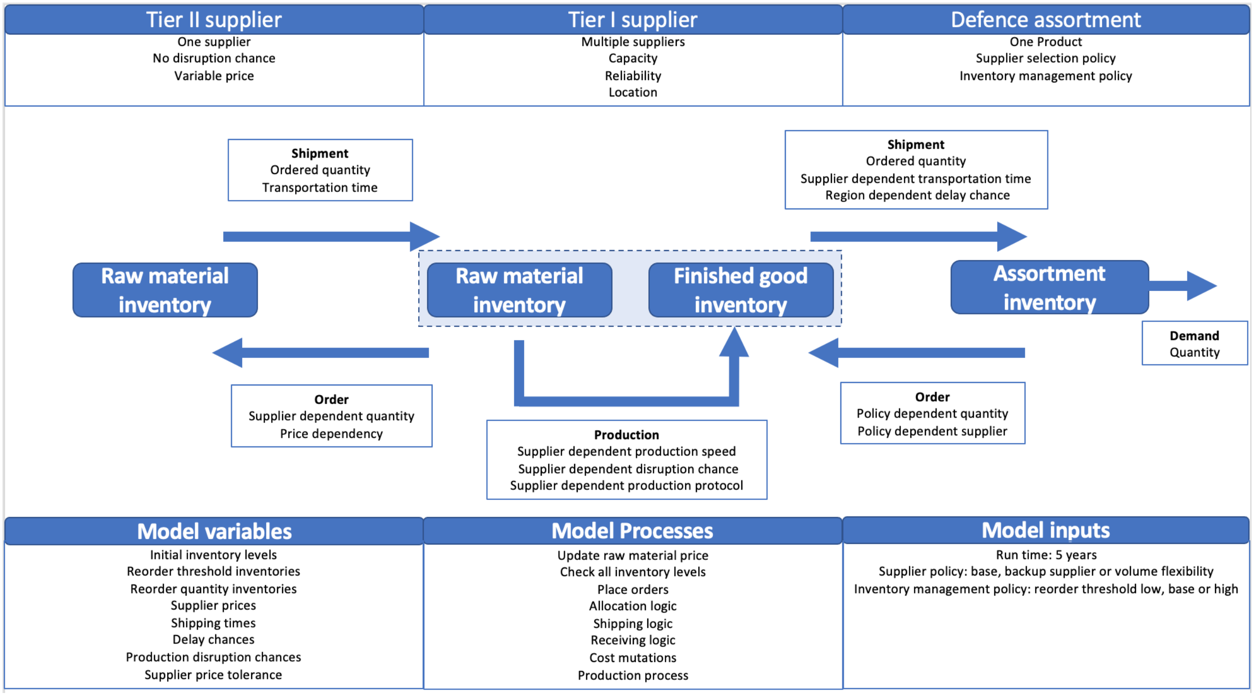

Figure 5.4: Conceptual diagram of target system

Chapter 6

OPERATIONALISATION

In chapter 4 it was discussed why supply chain risk management is relevant for the Ministry, in chapter 5 a delineation is constructed by identifying what part of the supply chain will be modelled and what assumptions and simplifications are made to capture the relevant system behaviour. This Chapter builds on that information by coupling the goals of the Ministry to theoretical constructs found in the literature. Defining the wanted system characteristics and operationalizing them for the purposes of performance measurement. Afterwards, the conceptual diagram shown in figure 5.4 is operationalized based on the structural assumptions made in the previous chapter.

6.1 Resilience in military supply chains

Within the Ministry of Defence vision, there is an expressed desire to incorporate certain characteristics into the organisational structures. Terms such as resilient, flexible, robust, agile and reliable make regular appearances (CDS, 2022). These terms signify good characteristics that are hard to argue against. However, when building these characteristics into organisational structures it is good to be aware of what exactly they mean as the terms are often used mistakenly or interchangeably. In broad terms, the relation between the characteristics can be depicted as shown in figure 6.1 as a temple structure. Reliability is an overarching end goal, resiliency is an approach to become reliable and flexibility, agility and redundancy are antecedents that add contribute to the overall resiliency (Dubey et al., 2019). In the following sections, the terms are explained more explicitly and defined so it can be discussed how they can be measured as performance indicators.

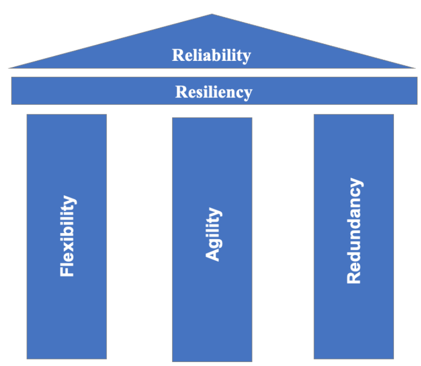

Figure 6.1: Relation between desirable characteristics named by the Ministry

Reliability of supply networks

Last year the Ministry of Defence released a document presenting its vision for 2035. Within this vision, it is stated numerous times that the infrastructure of the organisation should be 'reliable'. Reliability is a term that is broadly used in academic studies and generally refers to the ability of a system to perform. That being said, in supply chain literature the definition is specified more explicitly. *Definition 1: Supply Chain reliability: "Supply chain reliability is the ability of a supply chain to fulfil end customer demand to the desired level continually over the planning horizon, despite the risks of external and/or internal shocks to the system"* (Chen et al. 2017). This definition of reliability is more specific and can be operationalised to establish fitting performance indicators (see section 6.2). Reliability can be seen as the most holistic goal, achieving reliability in a system is dependent on the ability to cope with variance. You can imagine that when all links in the chain have a constant performance it is easier to plan and fulfil customer demand. However, in supply chains, especially international ones, there are a lot of variances inherent to the system. This variance introduces uncertainty which increases the difficulty of reliable performance. Therefore, supply chains are designed with coping abilities in mind. Characteristics such as robustness and resiliency are Incorporated into the supply chain to increase reliability in spite of uncertainty.

Robustness and resiliency

The difference between resilience and robustness is a subtle one but relevant nonetheless. A simple explanation is that robustness focuses on resistance and resilience focuses on recovery as well as resistance. Figure 6.2 illustrates the difference, first take a look at (A) where the ball represents the system in a stable state. When a disruptive force affects the stable condition of the system, the force needs to overcome the resistance represented by the bowl. If the disruptive force does not exceed the resistance capacity the ball will stay in the bowl and return to its equilibrium state. This means the system is not disrupted. Now take a look at (B), here the same applies but when the disruptive force is bigger than the resistance capacity the ball (system) will enter a new state. The amount of time it takes for the ball to end up in the middle of the second state is called the recovery time and represents the ability of the system to find a new stable position after the disruption has occurred.

These principles are commonly agreed upon, but further nuances in the literature are still a point of dispute. For reference in this thesis, the definitions provided by Ivanov in his book "Introduction to supply chain resilience" (2021) are maintained. *Definition 2: supply chain resilience: "The ability to withstand, adapt, and recover from disruptions to meet customer demand and ensure the target performance"* and *Definition 3: supply chain robustness: "The ability to withstand a disruption (or a series of disruptions) to maintain the planned performance".*

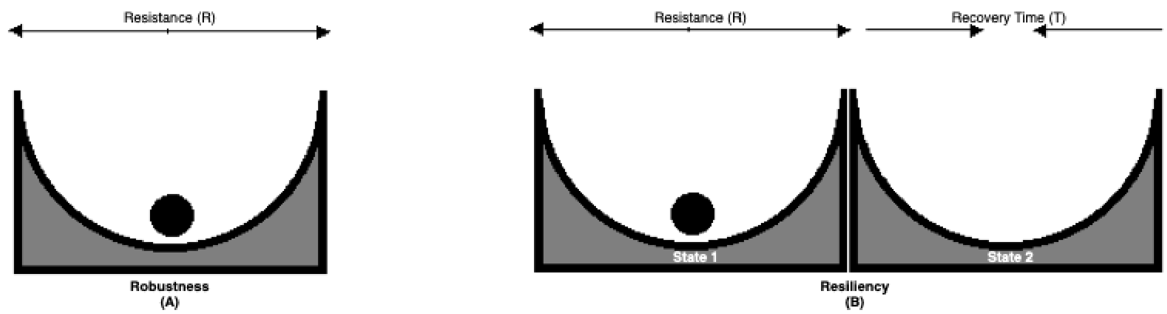

Figure 6.2: Difference robustness and resiliency

Flexibility and agility

Lastly, it is necessary to differentiate between flexibility and agility. Both are trenchant system properties that enable competitive advantage through fast and effective responses to volatile demand (Abdeliah et al., 2018). Furthermore, both are stated as antecedents of resiliency by (Dubey et al., 2019) but too often, the terms are used interchangeably. To help visualize the difference, something more tangible than a supply chain: a gymnast can be described as flexible, being very capable of reacting to different forces exerted on him during a routine. However, you will not confuse a gymnast with a boxer, for the boxer is agile, requiring reaction with speed. This speed factor is a defining trait independent of the field of use. For establishing the definitions in the supply chain context, the literature review of Shekarian et al. (2020) is used as a reference. Here a consensus in the literature is established for supply chain agility, "emphasizing the capability to sense changes, rapidly respond to changes, rapidly reduce the development cycle time or total lead time, rapidly increase the level of customer service, and rapidly improve responsiveness to changing market needs" (Shekarian et al., 2020; Alfalla-Luque et al., 2018; Johnson et al., 2013). Contrastingly, flexibility marks the capacity of a firm to react to fundamental changes in the supply chain or the implementation of new strategies that adjust operations in the long term by changing the supply chain configuration. This means flexibility is defined as: *Definition 4: "The capability of a business to react to changes in the environment, technology, demand, or supply by altering their organisational structures"*(Shekarian et al., 2020; Johnson et al., 2013). And finally, Fayezi et al. (2015) stated, *Defintion 5:"Agility is the capability of an organization to respond quickly to external uncertainties, whereas flexibility is the response to uncertainties by means of change"*.

6.2 Measuring performance in the supply chain

In chapter 4 it was established that the ministry values continuity above cost efficiency during disruptive risks to ensure operational capacity. In the section above the definitions of reliability and resilience were discussed, which are system characteristics that contribute to continuity. Therefore,

operationalizing such values in terms of Key Performance Indicators (KPIs) creates evaluative references for the suggested risk-mitigating policies. First, the ability to satisfy end-user demand is vital to measure resiliency. In the simulation model, the end-users represent military branches requesting material. If all material requests are satisfied in a timely manner it means operational capacity is not affected. To capture this two KPIs are proposed: order fill rate and number back ordered).
Additionally, resilience is also determined by the speed and ability with which the supply chain can adapt and recover. To measure this the average lead time of orders is adopted as a KPI as well. Furthermore, although cost efficiency is not a priority, there are budget constraints. Therefore costs are considered an important KPI. Lastly, the average quantity of products in the assortment inventory is considered. These five KPIs will be used to evaluate performance in the results chapter. In chapter 4 the current performance indicators used by assortment managers were discussed. The indicators here can add to those and provide a more substantial basis for decision-making.

Order fill rate, This is the percentage of orders, placed at the assortment inventory, filled over the period the system is observed. When at 100% this means that every end-user order has been satisfied.

Number back ordered, Is the number of orders that have been back-ordered and therefore not been delivered within the agreed-upon delivery time.

Average lead time, Is the average amount of time it takes from an order placed a the supplier to arrive at the assortment inventory over the five-year run-time.

Total costs, Is the costs made over the observed period of time. Including product costs, management costs, and contracting costs.

Average quantity in stock, The average quantity in the assortment inventory of Defence over the five-year run-time.

6.3 Model parametrization

This section takes the assumptions made in Chapter 5 and discusses how they are being incorporated into the simulation model and what values parameters take on. There have been numerous assumptions to simplify the model. The reason is that too much complexity makes the model less workable for analysis and limits generalizability. The simulation model will be discussed based on the model locations of figure 5.3.

Structural assumptions

in table 6.1 the structural model assumptions are presented based on the system identification in Chapter 5. The assumptions cover the two supplier tiers, the assortment inventory of Defence and the disruptive events.

Table 6.1: Structural assumptions for the simulation model

1. Raw material suppliers are considered fully reliable.
2. Raw material prices are updated daily, and have a stochastic chance of rising or declining.
3. Transport time of raw materials is equal for all suppliers.
4. There are three possible first-tier suppliers in the system.
5. Suppliers have internal inventories for raw materials and finished products.
6. Suppliers have a price tolerance for raw materials determined by their reliability.
7. Only complete orders can be shipped, incomplete orders are backlogged.
8. The model looks at a single product type.
9. European suppliers are considered more reliable than intercontinental suppliers.
10. There is a direct relation between reliability and costs.
11. There is no budget constraint, the trade-off relationship between reliability and costs is made ex-post.
12. Assortment managers can select supplier policies and determine the reorder threshold.
13. The end-user demand is stochastic both in frequency and volume.
14. The end-user cannot receive goods directly from the supplier only from the assortment inventory.
15. Low internal inventory is preferred because it allows more organisational flexibility.
16. Environmental disruption risk is stochastic and determined per region.
17. Environmental disruption duration is stochastic and determined per region.
18. Environmental disruption only affects the ability to transport products.
19. Suppliers make their products from sourced raw materials.
20. Supplier process disruption risk is stochastic and determined per supplier.
21. Supplier process disruption duration is stochastic and determined per supplier.

Raw material supplier parametrization

The raw material supplier is assumed to be fully reliable, this is done by setting the inventory level to infinity. So when an order is placed, it will always be able to ship the order. Do note, that a supplier will not place an order if the set price of that day is to high (representing scarcity). This price is calculated with a market price formula with fixed upper and lower bounds: $\alpha_t = \alpha_{t-1} +$

μ, where α_t is the raw material price at time step t which is calculated by the price of the last day (α_{t-1}) plus μ, which is a normal distribution with mean 0. There are more sophisticated methods of price calculation that consider price trends, but for this model, representing a general product, an equal chance of price increase and decline is considered sufficient. The shipping time is set with a normal distribution with a mean of seven days and a variance of two days. This transport time is in line with APQCs open standard benchmarking (2015). a simplification was made so that all suppliers have the same receiving conditions, the only varying factor is their price tolerance, this will be discussed in the supplier section. The values are shown in table 6.2

Table 6.2: Raw material supplier model variables

	Value	Source
Inventory	Infinity	Simplification
Transport time	N ∽ (7,2)	APQC
Material price	lower, upper bound (0, 22)	Simplification

Supplier parametrization

For simulation purposes, three different suppliers have been modelled to represent different supplier archetypes in the market (See table 6.3). The different suppliers are all unique and values are based on the data of Ruiz-Torres et al. (2013) who observed a product manufacturer. This data set was chosen because within the Ministry data collection proved troublesome. However, it does not impact the ability to analyze trade-offs between supplier selection strategies. Furthermore, the supplier characteristics are not industry- or product-specific and are therefore deemed suitable to be generalized. Each of these suppliers has its own advantages and disadvantages, but all of the suppliers are able to satisfy the maximum order an assortment manager can place. This means that with current policies, assuming they satisfy all PVE constraints, the choice would be the cheapest supplier. In this thesis, the argument is made that making decisions this way misses a lot of factors that play a large role in the eventual performance of a supply chain. Consider the following suppliers:

Supplier 1: The first supplier (S1) is located in region A. For the purposes of this case, region A means it is a European supplier and can be considered reliable. The benefits of this supplier are that they have less downtime in their production and deliver fast. Furthermore, European suppliers have a low chance of environmental disruption as the continent can be considered very stable. The drawback of S1 is their price and capacity, European labour is more expensive and this influences the unit costs. This higher price does buy extra guarantees, because of the financial health of this supplier it has a higher tolerance for fluctuating market prices and scarcity of raw materials. Another potential drawback is that S1 has a relatively small capacity so it is less equipped to handle large orders or orders in rapid succession.

Supplier 2: The second supplier (S2) is located in region A as well. although not quite as reliable as S1, it still benefits from the low environmental disruption chance and decent downtime. The benefit of S2 compared to S1 are lower unit costs and higher capacity.
Supplier 3: The third supplier (S3) is located in region B. Which is an intercontinental supplier. Of the three it can be considered the least reliable. Because of the great distance between the supplier and assortment, the delivery times are longer. Where the European suppliers have a delivery time of around one week, S3 has a delivery time of approximately a month. And because of decreased financial standards outside of Europe, it is less capable of sourcing raw materials when there is scarcity. Furthermore, it has considerably more downtime which results in not being able to produce goods as often as S1 and S2. However, S3 does have a large capacity and a bigger inventory of finished goods. S3 has the lowest price of all suppliers as well.

Furthermore, Suppliers all have a flexible order capacity which is relevant for the volume flexibility policy (Chapter 7). This value represents how much a supplier can scale up their order quantity, which is dependent on the supplier's capacity. The values of 50, 75 and 100 per cent are in line with the adaptation potential estimations of Ivanov (2021). Contrasting, Kamalahmadi and Parast (2021) used values between 30 and 80 per cent and refer towards Ruiz-Torres et al. as a justification. Although, this article does not use those specific values. Therefore, there is some uncertainty with regard to flexible capacity and decision-makers should be aware that lower capacities would impact the performance of the policy.

Transportation times are based upon APQCs open standards benchmarking in procurement (2015). where 7 days is the median for close proximity suppliers and 11 days is considered poor performance. Therefore supplier 1 has a deviation of two and supplier 2 of four. A month is considered the standard for intercontinental suppliers.
The supplier's up- and downtime are results of assumptions. The variables represent supplier process disruption but do realize that a supplier has multiple clients so other factors play a part too: there is a production schedule, planned maintenance, mechanical failure and human error that all influence the time that production lines are producing for the ministry. The combination of U_s and F_s represents this available production time accounting for disruptions. The eventual values are the result of balancing output values relative to each other and in correspondence with supplier reliability percentages found in the literature (Ivanov, 2021; Sanchez-Ramirez et al., 2019). The result is captured by a downtime estimation for all suppliers, at which time they can not produce goods for the Ministry. The average is three weeks and the lower and upper bounds are two weeks and two months in a positively skewed distribution (PERT- distribution). The up-time provides the

reliability range for the suppliers and results in the availability of suppliers 1, 2 and 3 at 75 65 and 60 per cent respectively. This means that the suppliers can spend that amount of time producing goods for the Ministry not that they are producing goods that amount of time.

Table 6.3: Supplier characteristics

Supplier characteristics			
Regions	Region A		Region B
Suppliers	1	2	3
$C_{u,s}$: unit cost ($)	25	20	15
$C_{uf,s}$: unit cost above allocation ($)	35	30	25
C_m: management costs ($)	1000	1000	1000
C_{mb}: management costs backup supplier ($)	25000	25000	25000
Cap_s: order capacity supplier s (# units)	1000	1500	2000
$CapF_s$: Flexible order capacity supplier s (# units)	50%	75%	100%
PT_s: production time supplier s	X ∽ N(1, 0.2)	X ∽ N(1.4, 0.2)	X ∽ N(1.6, 0.2)
RP_s: reorder threshold raw materials (# units)	300	300	300
$Cap - r_s$: raw material capacity supplier s (# units)	500	500	500
m_s: maximum material price supplier ($)	18	17	16
TT_s: transportation time supplier s	X ∽ N(7,2)	X ∽ N(7,4)	X ∽ N(30,7)
U_s: uptime supplier s	X ∽ U(60, 90)	X ∽ U(30, 60)	X ∽ U(20, 60)
F_s Downtime supplier s	X ∽ PERT(14, 21, 60)	X ∽ PERT(14, 21, 60)	X ∽ PERT(14, 21, 60)

Assortment inventory parametrization

For the assortment inventory, the variables are within the control of the assortment manager. Therefore, most variables are decision variables that will be subject to policy decisions. First, for deciding which supplier is selected there are the variables R_s and Z_s. R is for the experiments without any risk mitigation policies and takes the value 1 for the supplier that is chosen. Z determines what suppliers are selected in the volume flexibility or backup supplier experiments. With two suppliers being assigned a 1 for volume flexibility. For the backup supplier policy, the primary supplier is assigned a 1 and the backup is assigned a 2. The reorder threshold value is the decision variable for controlling internal inventory size. As previously discussed, this threshold value determines how flexible the organisation is in terms of product switching and freeing up budget space because overall inventory levels can be lower. Therefore Ir can vary between 200, 300 and 400. 200 is the maximum order quantity from end users. That means that at a value of 200 the organisation assumes it can resupply at the speed of average order intervals, promoting flexibility. The initial inventory value for all scenarios and experiments is fixed at 1000 units. This quantity was chosen relating to Ir and demand Q, so that this is some buffer capacity internal but not too much so we can evaluate the full capacity of the policies to place buffers with the suppliers. Iq is based on Ir so that it refills the inventory back to the level of Ii. The demand is determined by a triangular distribution and is stochastic so the performance of the policies can be reviewed under multiple order intensities. The values were determined based on correspondence with the supplier capacities, this includes the order frequency (Ruiz-Torres et al., 2013). The stochastic element of

Table 6.4: Assortment inventory variables

Assortment Inventory	
R_s: Binary variable for supplier s, determining allocation without risk mitigating policy	[0, 1]
Z_s: Choice variable for supplier s, determining supplier selection with risk mitigating policy	[0, 1, 2]
Ii: Initial inventory quantity for the assortment inventory (fixed)	1000
Ir: The reorder threshold value for the assortment inventory	[200, 300, 400]
Iq: The quantity that is reordered	[800, 700, 600]
Q: Demand	X ∽ T(100, 150, 200)
Qf: Demand frequency	X ∽ E(14)

the orders was inspired by the study of Giri and Bardhan (2014), studying backup supplier costs. All variables are presented in table 6.4.

Disruptive events parametrization

The chances of disruptive events have been inspired by multiple articles in the literature. The starting point was the data sets used by Ruiz-Torres et al. and Kamalahmadi and Parast (2013; 2016), but as this simulation captures more uncertainties and variables, additions have been made. The up-time parameters are explained above with the supplier parametrization. The chances for environmental disasters are set in ranges from 2-5 and 2-10 per cent so they are expected to occur relatively frequently in a run as the average amount of orders in a run is a little over 20. Region B is assumed up to twice as vulnerable for environmental impact because the travel distance is greater and intercontinental regions are assumed less stable. The delay time of environmental impact is based on average shipping delay data from Freightos, a global freight shipping intermediary (Freightos, 2022). The average of the last three years is taken at a value of 50 days, The values post COVID are higher but seem to be receding again at the time of writing. The average value is taken as the maximum in a uniform distribution because the environmental disruption does not have to be shipping related and road disruptions take less time (discussed in chapter 5). The disparity between A and B is based on the assumption that region A is more reliable overall. In table 9.1 the values assigned to the events in the simulation model is shown.

6.4 Conclusion

The operationalisation of the system identified in chapter 5 is based on a plethora of assumptions. From a modelling standpoint some of the values attributed to variables could be more substantiated and developed more specifically. Due to time constraints and limited access to data within the Ministry this is not done to the extend that it could have with more time and resources. However, since the simulation model is build for exploratory purposes this is acceptable. The key task of the simulation model is to capture the dynamics present in the system to aid in establishing relevant trade-offs. Furthermore, the simulation model is non-product specific and therefore its aim is to provide a basis for a wide variety of products in the assortments of the Ministry and for supply

Table 6.5: Disruption variables

Disruptive event	Value
U_1: Uptime for supplier 1	X ∽ U(60,90)
U_2: Uptime for supplier 2	X ∽ U(30,60)
U_3: Uptime for supplier 3	X ∽ U(20, 60)
$P_{e,A}$ Chance of environmental disaster in region A	X ∽ U(2, 5)
$P_{e,B}$ Chance of environmental disaster in region B	X ∽ U(2, 10)
DT_A Delay time of environmental disaster in region A	X ∽ U(30, 50)
DT_B Delay time of environmental disaster in region B	X ∽ U(40, 50)
α_t The price of raw materials at timepoint t	$\alpha_t = \alpha_{t-1} + \mu$ Upper bound(20), Lower bound (0),

chains in general. The results from this model should serve as basis in decision making. In further research, assortment managers could customize models such as this into tailored versions fitting specific strategic supplies. This is not viable to do for all products, certainly not the less strategic ones, so for those the basic principles learned here should be relevant for better decision-making.

Table 6.6: Key takeaways and providing insights answering subquestion 2

How does supply risk and environmental risk consolidate, and how can this behaviour be captured and conceptualized for modelling in support of testing risk management strategies?
§ The supply chain can be divided into three regions of vulnerability: supply-side, intra-organisational-side and demand-side.
§ The Ministry sees supply-side risks as all risk to material flow before arriving in the Defence assortment.
§ Sheffi and Rice (2005) defined 5 categories of risk, Supply- and environmental risk capture the risks of the target system.
§ The supply- and environmental risk have been decomposed to three sources of disruption for the simulation model: 1) Material scarcity, 2) process risk and 3) environmental disruption.
§ The structural model assumptions to represent key system dynamics are presented in table 6.1
§ Tables 6.2, 6.3, 6.4, and 6.5 show the variable values used for the simulation.

Chapter 7

RISK MITIGATION POLICIES

In this chapter, the proposed risk-mitigating policies are explained. In the meta-model (figure 5.3) it was learned that assortment managers have two controls they can alter. First, supplier selection is the primary policy that is being evaluated in this thesis and is the subject of the main research question. The proposed supplier selection policies effectively aim to do two things: 1) enable the supply chain to better withstand disruptive forces and 2) create more manoeuvrability by enabling assortment managers to place buffer zones outside the organisation. Both these aims contribute to the overall resilience of the supply chain. Second, inventory management is considered in the simulation model as a secondary policy that can improve or decrease performance. This is considered a secondary policy because of the supply-side orientation of this research. Although inventory management influences the effect of the primary policies it is considered more of an intra-organisational approach.

In the main research question, a differentiation is made between the flexible orientation and the redundancy orientation. In this chapter, first, the redundancy orientation is discussed and then the redundancy policies. Thereafter the same is done for the flexibility orientation and policy. Both of the proposed strategies should improve the resilience of the ministry's supply chain by reducing the dependence on internal inventory sizes and placing buffer zones outside the organisation.

7.1 Redundancy orientated strategy

"Redundancy involves the strategic and selective use of spare capacity and inventory that can be invoked to cope with a crisis, such as demand surges or supply shortages" (Parast Shekarian, 2019). Redundancy is perhaps the most obvious strategy to become more resilient because it is easy to implement. However, in order to make use of its potential benefits it should be applied with consideration. In practice, it is mostly applied as a reactive strategy. That means that enterprises often react to disruption by overstocking on a particular item, where in this instance a shortage caused disruption. This reactive approach is not in line with proper Supply Chain Risk Management (SCRM), because it is treating the symptoms. In the literature review it was learned that SCRM should anticipate and identify potential sources of risk. This means, SCRM should be orientated on addressing the causes of disruptions, not the manifestations.

Furthermore, although it can be an effective option to create resilience, redundancy is costly and potentially endless in magnitude. Therefore, it should only be built to a certain extent to prevent overspending (Sheffi Rice, 2005). Furthermore, it is important to realize that redundancies offer no benefit to a system when a disruption does not occur. Redundancy strategies are considered a cost trade-off, and the supply chain manager should be aware of the point where extra investment no longer yields enough benefit. In the military domain, this is especially true, because it is easier to undervalue the cost aspect of these strategies when you consider national safety. Therefore, there is a danger of unnecessarily inflating your fixed costs due to additional asset investments (Ivanov and Sokolov, 2013). Take, for example, an increased internal inventory, without extraordinary demand your budget is lying on a shelf. Perhaps it could have made a larger impact somewhere else in the organization. Increased inventory is a robustness improvement but not resilience. The work of Kamalahmadi and Parast (2017) was consulted for a suitable redundancy strategy to improve resilience. Kamalahmadi and Parast (2017) differentiate between three types of redundancy strategies. First, the pre-positioning of inventory is the same as the increased internal inventory discussed. Second, a backup supplier, by pre-contracting a second supplier, which can be approached if the primary supplier defaults, the flow of goods can be redirected. Lastly, protected suppliers, investing (together with other clients) in the safety and security of suppliers to ensure the continuation of operations. These strategies could enhance a business's performance and mitigate the potentially disruptive effects of uncertainty. For the purposes of this simulation study, a backup supplier is chosen as the redundancy strategy.

Backup supplier

A backup supplier is a practice of engaging with a second supplier when the primary supplier is disrupted. A backup supplier is contracted in anticipation of future needs and therefore there are costs to maintain this contract but it ensures that the material flow is continuous when a disruption occurs at a primary supplier (Sodhi and Lee, 2007). In some literature, a backup supplier is classified as a flexible strategy because it allows businesses to redirect the flow of goods in case of disruption. However, following the definition of redundancy established in chapter 6, it should be considered a redundancy strategy, as the contracts are drafted prior to disruption, have fixed costs, and do not yield benefits when disruption does not take place.

There are multiple ways a backup supplier can be contracted, with the predetermined terms varying to fit specific risks or circumstances. In this study, a general approach is followed as described in the study of Giri and Bardhan (2014). A backup supplier can be seen as an insurance policy and requires action in advance of any disruption event. Furthermore, the capacity of a backup supplier is not unlimited and is discussed and evaluated in advance of the contracting phase. In the simulation model, the contract period is assumed to be five years, this means that a backup supplier needs to be contracted for this period in advance as well. The way these contracts work is that a certain amount of goods is bought in advance and stored in the inventory of the backup supplier. If the primary supplier defaults, the backup supplier takes your already-bought backup goods and delivers them. But there is a catch, to make this proposition interesting for the backup supplier, he charges a premium for the backup goods because he has to store them in his own inventory. If the contract expires and the backup supplier was not needed, there is a buy-back contract. The buy-back value of these goods is the market value and not the premium value at which the supplier sold them. This means that if a disruption does not happen the difference between the market value and the premium that has been paid over the backup goods is lost.

In table 6.3 the premium is shown by variable $C_{uf,s}$. For each supplier an extra \$10 per unit is charged (equal to the premium costs in the volume flexibility strategy). Normally, the backup supplies being pre-bought is a percentage of the total demand. For this simulation model, it is assumed that the backup capacity is unlimited but the potential financial liability is limited to 10% of the average total demand over the five-year contract period. This is done because if demand exceeds this point better prices should be negotiable. This means that if a disruption does not happen, the costs made for the backup supplier strategy are \$25000 (the premium of \$10 times 10% of average total demand). In figure 7.1, an example is shown where supplier 1 is the primary supplier and supplier 3 acts as a backup. On the left side we see that S1 is in disruption and an order of 700 units is placed with S1. S1 is not able to satisfy the required demand and therefore the order is shifted to the backup supplier (S3). S3, who normally charges 15 per unit, charges a premium to deliver as backup supplier. On the right side, disruption does not happen, supplier 1 can deliver the goods but costs are still made with supplier 3 because the buy-back contract is at market price. Do note, this example shows a single order, over a 5 year contracting period you do not insure 100% of the required goods.

For the purposes of this simulation study a few assumptions are made relating to the backup supplier strategy:

Assumption 1: Although contracts with backup can take various forms, for the purposes of this study it is assumed that maintaining a backup supplier has fixed costs over the duration of the contract period irrelevant of disruption taking place (Ruiz et al., 2013; Giri and Bardhan, 2014).
Assumption 2: The Defence assortment inventory can only have one primary and one backup supplier.
Assumption 3: The assortment manager knows instantly if a supplier cannot make his order so the backup supplier receives the order with no time delay.

Increased inventory or capacity buffers

The implementation of inventory pre-positioning also referred to as increased inventory or capacity buffers can also be considered a redundancy strategy. Considering figure 5.3, this is part of inventory

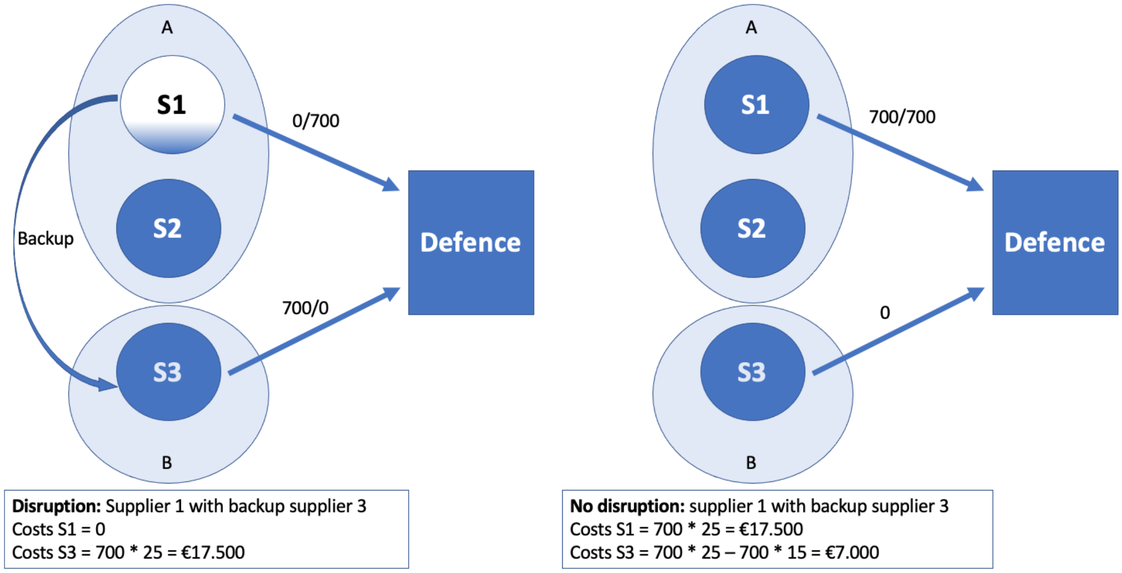

Figure 7.1: Backup supplier policy during disruption (left) and non disruption (right) examples with supplier 1 and 3 contracted.

management. In this thesis, policies for supplier selection are the main focus as they are proactive and affect the causes of supply-side risks and not the consequences. Therefore, increasing internal inventory is not considered as a policy option. The assumption here is that being able to maximize the performance of the current capacity is a more useful approach for the Ministry. Considering the large amount of items all assortments harbor, an overall increase would require a large increase in warehouse capacity and an increase in fixed costs within the budget. The backup supplier strategy can create buffer capacity at lower costs while having less impact on the flexibility. That being said, inventory management is not disregarded all together. Having a fixed capacity still requires a decision with regards to the threshold point where the inventory is restocked. By restocking early, thus ordering more often, the strategy can create greater independence from suppliers as internal stocks can meet the end-user demand for a greater amount of time and should not be disregarded but respected as a complementary control for assortment managers. The biggest drawback of a high reorder threshold is its inefficiency, boasting increased transportation and management costs. Therefore, the primary policy being evaluated as a redundancy strategy is the backup supplier policy and inventory management is evaluated as a complementary control that can increase or decrease performance under the effect of the primary policy. The reasons for doing this are twofold: 1) it increases the overall flexibility of the organisation which contributes to the stated goals of Defence (CDS, 2021). 2) when considering the vast amount of products in inventory at the organisation, a high inventory policy would shrink the operating budget immensely as the fixed costs increase with the inventory, this budget can be allocated with more efficiency. For the simulation model the following is assumed for inventory management:

Assumption 1: There is a preference for a low number of orders.
Assumption 2: Inventory management is controlled by the reorder threshold and reorder quantity.
Assumption 3: The total inventory capacity is consistent, meaning a higher reorder threshold equals the same reduction in order quantity.

7.2 Flexibility orientated strategy

'Flexibility refers to the ability of a firm to respond to long-term or fundamental changes in the supply chain and market environment by adjusting the configuration of the supply chain' (Parast Shekarian 2019). In uncertain markets, flexible supply chains can exercise their options more quickly than the competition. These market changes can arise from a variety of changes ranging from environmental changes, demand changes, supply changes, technological changes, and (geo-)political changes (Dominik et al., 2015). Flexibility is indicated as an important factor in enhancing supply change resilience in much of the recent literature (Carbonara Pellegrino, 2017; Manuj Metzer, 2008; Aldrighetti et al., 2021). Fang, Li, and Xiao (2012) stated through incorporating flexibility within system organisations, a resilient supply chain can be realised in an effective and efficient manner. Adding, flexibility creates resilience by improving adaptability during unstable conditions. However, there is a drawback to flexibility, as it comes at a cost and is often difficult to implement. Furthermore, it does not necessarily provide an advantage in every situation. Therefore, it should be determined by the amount of uncertainty faced in the supply chain. This is because it requires significant capital investments in the form of a "multi-skilled workforce, versatile equipment, multiple suppliers, or flexible contracts with suppliers" (Yang and Yang, 2010). Eventually, Supply Chain managers should balance the potential payoff, considering the high costs and determining if it is worthwhile (Shishodia et al., 2021; Sodhi Tang, 2012).
Where redundancy strategies create buffers in the supply chain structure, flexibility strategies do the opposite, they often aim to reduce buffers to decrease dependency in the form of sunk costs and are looking for how structural change can improve the supply chain. Flexible supply chains are usually more cost-effective and when implemented properly they can increase resilience (Ivanov, 2021). There is a wide selection of flexibility-increasing measures but for the purposes of this thesis, the focus will be on volume flexibility. The reason for this is that complements the backup supplier strategy as a supply-side-orientated strategy.

Volume flexibility

Volume flexibility is the practice of having a wider supply base as standard. By spreading demand between suppliers you can protect yourself against regional disruptions. Furthermore, working with suppliers that are able to scale orders to the demand makes the supply chain as a whole more

flexible. Gosling and Naim (2010) found that vendor flexibility is one of the main contributors to supply chain flexibility. Not only is it possible to scale up during peak demand, but it is also a layer of protection against disruption. You reserve extra capacity with the suppliers, when one supplier defaults on an order, another supplier can scale up their shipment to (partly) compensate for that loss. In the simulation model, this is done by dividing the order in two, and allocating the demand with separate suppliers. When a single supplier fails the order is redirected to the other supplier, who can increase their order quantity. Do note that this 'extra' allocation comes at a premium because this reserved capacity is costly for the supplier.
Furthermore, It is not possible for a supplier to scale up their order indefinitely, it is assumed that a supplier can scale up their order size relative to their capacity. In the simulation, suppliers 1, 2 and 3 have a flexible capacity of 50%, 75% and 100% respectively of their original order size. This is a generalization, in practice, this value is dependent on product specificity. With more arbitrary products it might be possible to scale further and vice versa. This is also the limitation of this policy, Kamalahmadi and Parast (2021) stated that the possibility for volume flexibility is product-dependent. Both the supplier must be capable and the product needs to be suitable for such flexibility. In figure 7.2 a example of volume flexibility is depicted. On the left side of the figure it is seen that in disruption supplier 3 with a flexibility capacity of 100% can double his order size to still ensure the 700 units for the Ministry. With regards to the costs, it is seen that there are no additional costs when disruption does not appear. In disruption, supplier 3 charges a premium for the units delivered above the normal allocation. However, since supplier 3 is a cheaper supplier it does not result in extra costs for the Ministry. Lastly, for the purposes of this simulation study, these assumptions are made with regards to the volume flexibility policy:

Assumption 1: The assortment manager can only have two contracts with suppliers
Assumption 2: Suppliers have a maximum capacity, this determines how much extra allocation they can receive. In this simulation study set at 50, 75 and 100 per cent for suppliers 1, 2 and 3 respectively.
Assumption 3: The suppliers receive their orders at the same time.
Assumption 4: If an order cannot be satisfied by either supplier it is backlogged.

7.3 Qualitative policy comparison

Before testing the policies in the simulation model, some findings can already be established. First, with regards to the dichotomy between flexibility and redundancy described in the literature, it can be established that these are not necessarily mutually exclusive (Sheffi and Rice, 2005). There are two important caveats present here. First, is that the definitions matter, which are not uncontested in supply chain literature. However, academics such as Ivanov, who is well established in the field, are making headway with their research (Ivanov, 2021). Second is the scope, reasoning from a

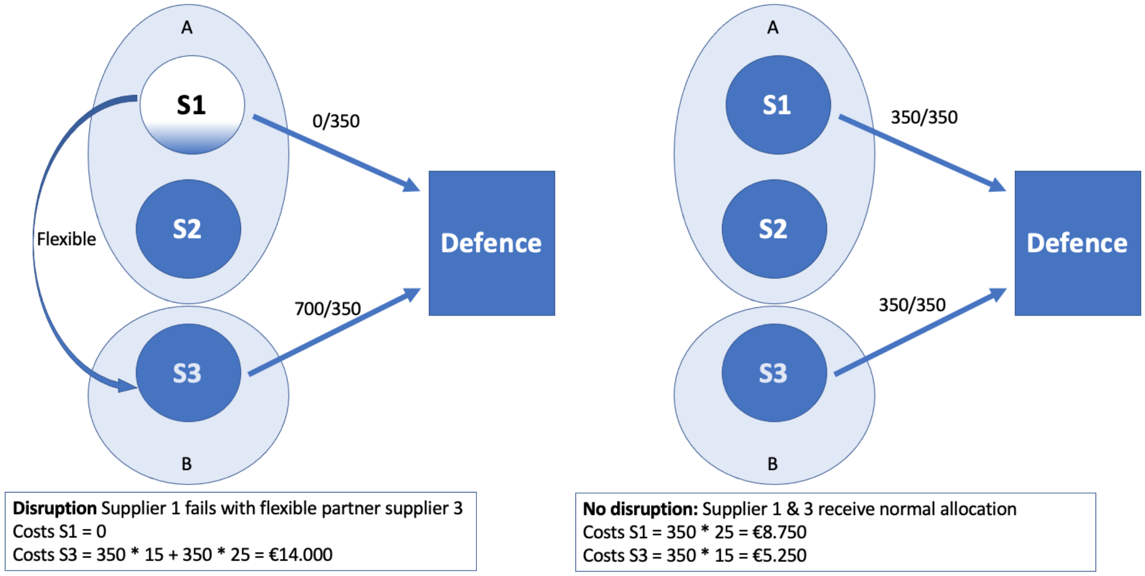

Figure 7.2: Volume flexibility policy during disruption (left) and non disruption (right) examples with supplier 1 and 3 contracted.

holistic view of the entire supply chain is different then reasoning from a entity within th supply chain. However, considering the Ministry's perspective, this study concludes that redundancy measures such as backup suppliers, which position buffer capacities outside the target organisation can increase the flexibility of the organisation.

Furthermore, it would be possible to implement both volume flexibility and a backup suppliers int the supply base of an organisation. Although this would increase resilience, it is not advisable as it would be a overkill of measures not justifying its costs.

Table 7.1: Key takeaways and providing insights answering sub-question 3

What are suitable flexibility- and redundancy strategies and how can they be implemented in the simulation model?
§ supply chain resilience: "The ability to withstand, adapt, and recover from disruptions to meet customer demand and ensure the target performance"
§ Redundancy involves the strategic and selective use of spare capacity and inventory that can be invoked to cope with a crisis, such as demand surges or supply shortages
§ Redundancy is costly and only effective up to a certain extent making it vulnerable to overspending
§ Flexibility refers to the ability of a firm to respond to long-term or fundamental changes in the supply chain and market environment by adjusting the configuration of the supply chain'
§ Where redundancy strategies create buffers in the supply chain structure, flexibility strategies do the opposite, they aim to reduce buffers and rely on the ability to flexibly adapt the product flow
§ From a actor perspective flexibility and redundancy are not mutually exclusive. Backup suppliers can increase flexibility by placing buffers outside the organisation.
§ A backup supplier is contracted in anticipation of future needs and therefore there are costs to maintain this contract but it ensures that the material flow is continuous when a disruption occurs at a primary supplier (see figure 7.1)
§ Volume flexibility, is the practice of reserving extra capacity with your suppliers so that when one supplier defaults on an order, another supplier can scale up their shipment to (partly) compensate for that loss (see figure 7.2)

Chapter 8

MODEL IMPLEMENTATION

In this chapter, the system identified in chapter 5 will be implemented in a discrete event simulation model. In chapter 7 the different flexibility and redundancy strategies were described. in the following section, the implementation of those strategies is discussed alongside the insights the DES model will provide.

8.1 Model Description

The model is constructed for determining critical trade-offs for supplier selection and determining the effectiveness of flexible- and redundancy-based strategies under uncertainty. The model is inspired by the model proposed by Ruiz et al. (2013). Ruiz et al. (2013) focused on optimal demand allocation among a set of suppliers with reliability characteristics, this model looks at trade-offs in supplier selection under high uncertainty emulated by multiple disruption locations in the supply chain. It is assumed items can be sourced from three different suppliers based in two different regions. Each supplier has its own set of input variables that combined define their characteristics, which in turn, determines the overall reliability. The costs considered in this model are Unit costs (C_u), management costs (primary and back-up;C_m C_{mb}) and a premium that is charged per unit above normal allocation during disruption ($C_u f$), this cost is the same for both policies. Because there is no revenue there is no missed revenue when a shipment fails. Therefore, the model does not aim to maximize profit but does track the costs. This allows assortment managers to understand how extra costs can improve reliability in the supply chain due to resilience strategies.
In chapter 6 the used model values were introduced, here it is discussed how they are used in the SIMIO model, for more insight into the SIMIO model see B. The Assortment inventory of Defence (I) holds a single item type in stock. The outflow of this stock is simulated by incoming orders from within the military branches. The inter-arrival time of these orders is simulated with a random exponential distribution with λ = 14 days. The order size is estimated with the PERT distribution. Which is a smooth version of the triangular distribution which enables the modeller to achieve small odds for large values but not past a fixed minimum or maximum which could disturb the simulation. If the demand can not be met out of the inventory the order is backlogged and will be fulfilled as soon as it becomes available. The assortment inventory can be resupplied by three different suppliers: s=1,2,3, all three suppliers are first-tier suppliers and deliver the same items but have different costs, capacity and reliability. These suppliers fabricate the item out of raw materials and need to source this material from a single second-tier supplier. In table 8.1 all-important model

variables and their definitions are presented.

Suppliers: When selecting a supplier there are fixed management costs (C_m) for working with that supplier, which is a one-time fee for the duration of the contract (Berger et al., 2004). When a supplier is chosen as a backup, these costs are higher becks they need to reserve capacity without actually selling items. This is defined by the backup management costs C_{mb} (Kamalahmadi and Parast, 2017). The contract period is set at five years, which is the runtime of the model. Therefore, it is not possible to switch suppliers during a model run. This is intentionally chosen so individual strategies can be compared. The maximum capacity for supplier s is Cap_s, which is defined as the maximum number of items supplier S can deliver in a single order. C_{us} is the cost per unit for supplier s, which include transportation costs. With a flexibility strategy, a supplier can be allocated more of the demand if the other supplier defaults, for this extra allocation a premium price is set at C_{uf}. A supplier needs to produce their products which it does at processing timePT_s. production starts when the amount of finished goods in their inventory drops below a threshold value RP_s. The supplier then starts to produce goods from their raw material inventory $Cap - r_s$. The rate at which a supplier replenishes their finished goods is defined by the production rate, PR_s. To refill their raw material inventory, a supplier can reorder raw materials with a second-tier supplier. this second-tier supplier sells raw materials at a daily fluctuating material price α_t. Suppliers have a maximum buy price to represent scarcity which is defined by m_s. Last, suppliers are located in either region A or region B, this impacts their transportation time TT_s.

Assortment inventory Defence: The assortment of Defence has an outflow determined by demand Q as stated above. To manage this inventory, assortment managers have four Decision variables. In formal processes, the assortment manager would provide a PVE and ATB to the purchasing department and they would set up a contract with one of the suppliers in the market. In the model, intra-organisational processes are outside of the scope so this process is simplified. In the base scenario with one supplier, the binary variable R_s takes the value of 1 or 0 (where 1 means the supplier has the contract). For the resilience strategies, the value Z_s is not binary but in the range 0,1,2 where 0 = no allocation, 1 = priority allocation and 2 = backup allocation. The assumption here is that these strategies use two suppliers, for example, Flexibility (S1= 1, S2= 1, S3=0) and Redundancy (S1=0, S2=1, S3=2). The other choices for the assortment manager are their internal inventory policies. Where it is determined how large the internal initial inventory is (I_i), at what level the inventory is resupplied (I_r) and the quantity of the order (I_q). A large internal inventory is beneficial as it functions as an extra buffer. However, as there are many different product types across all inventories it is very taxing on the budget to have large internal stocks and decreases the agility of the organisation. Therefore, assortment managers are assumed to have an averse attitude towards large internal inventories.

Disruption sources: In this model, there are three sources of uncertainty modelled that can lead to disruption. First, a supplier can experience a supply problem themselves. Material prices are becoming more unstable and scarcity is a problem in many industries (Zanoletti, 2021). To simulate this raw material shortage the second tier supplier sells its supply at a cost that is coupled to a market price formula with fixed upper and lower bounds: $\alpha_t = \alpha_{t-1} + \mu$, where α_t is the raw material price at time step t which is calculated by the price of the last day (α_{t-1}) plus μ, which is a normal distribution with mean 0. If α_t stays above a supplier's threshold value the raw materials are not being bought, the reasoning being that the price is not just high, but the good is also scarce. This means a less reliable supplier will have to wait until prices come down to be able to refill its raw material inventory. Second, a supplier can have operational downtime, which means they are not producing goods at that moment. The downtime represents multiple reasons: this can be due to mechanical problems, prioritizing, poor planning, or scheduled maintenance. In the model, this is simulated by a server failure. Each of the suppliers has an 'up-time' in which they can produce goods, this time is randomly drawn from a uniform distribution. When a server fails the 'downtime' is drawn from a positively skewed distribution so that there is a small chance for a very large down-time. Third, is an environmental disruption event which affects all suppliers in the region (Kamalahmadi and Parast, 2016; Sarkar and Mohapatra, 2009; Sawik 2014). During an environmental disruption, all suppliers in that region can not deliver any goods until the event resolves. The chance of such an event is modelled by the environmental disruption chance P_e and the duration is determined by a positively skewed distribution (PERT).

Table 8.1: Model variables

Decision variables	
Rs	Binary variable decides which supplier (s) receives and which determines if they are selected for demand allocation.
Zs	Choice variable which determines what suppliers are selected for (primary-) demand allocation.
Ii	Initial inventory quantity for the Defence assortment.
Ir	The reorder threshold for the inventory assortment of Defence.
Iq	The quantity that is reordered for the inventory of Defence.
Input variables	
S	Set of suppliers S = {1,2,3}
R	Set of regions R = {A, B}
$C_{u,s}$	The purchasing costs per ordered unit with supplier s under normal allocation.
$C_{uf,s}$	The purchasing costs per ordered unit with supplier s above normal allocation in flexible strategy scenario.
C_m	The management costs of working with a supplier over the contract duration time, is assumed equal for all suppliers.
C_{mb}	The fixed costs made with a backup supplier, even if they do not receive any demand allocation.
Cap_s	The maximum quantity supplier s is able to deliver in one order.
$CapF_s$	The flexible capacity percentage supplier s is able to deliver relating to order quantity.
PT_s	The processing time for supplier s, determines how fast a supplier can produce goods for a new order.
RP_s	The reorder point for supplier s, determines the threshold value at which point the supplier starts to produce goods for the next order.
$Cap-r_s$	The inventory capacity of suppliers for raw materials.
α_t	The price of raw materials at time t, is updated daily.
m_s	The maximum price at which suppliers are willing to place an order for resupplying their raw materials.
TT_s	The transportation time for a shipment from supplier s.
$P_{e,r}$	The probability of environmental disruption in region r.
U_s	the up-time for supplier s between production stops.
F_s	The downtime for supplier s before they resume production.
Key Performance Indicators	
OFR	The Order Fill Rate is the percentage of orders at the assortment inventory of Defence that is satisfied.
ALT	the Average Lead Time is the average time in days that passed between placing the order and receiving the shipment.
NBO	the Number Back Ordered, is the number of orders that were delivered with a delay.
AQIS	Average Quantity In Stock, is the average number of products held in the Defence assortment.
TC	Total cost for the assortment of Defence made over a period of 5 years.

8.2 Experimental design

In order to identify the effects of the different supply chain risk management strategies, and weigh them not only against each other but against null-scenario as well, multiple experiments have been set up inside the simulation model. The null scenario is added and reviewed in an experiment which looked at the performance of the individual suppliers as sole contractees of Defence. Because this thesis has a focus on scenarios under disruptive effects, an additional experiment has been run with the disruption sources not present. This is done partly as validation, checking if model results correspond with reality, whereas the day-to-day operations don't experience the extremes targeted here. The second reason for doing so is to create an idea of how much impact it can have if multiple risks consolidate at the same time and the impact this can have on a supply chain.

The experimental design plan is employed to test the proposed policies in varying conditions. The run length of the model is set to five years with a 24-hour timestep. This time period was chosen. Currently, the 'policy planning budgeting - process (NL: BPB-process) takes two years, this was the initial runtime but to approach a more average contract duration and get a better sense of the performance over time this was increased to five years. During the runtime, disruptive forces occur and it is measured how effective the risk-mitigating policies are to avert performance loss.

The number of replications used for evaluating the policies is set to 100. 100 was chosen as it resulted in a stable confidence interval where almost no observations fell out of the interval. Furthermore, 100 was a fitting balance between enough for sensitivity analysis of the input variables and not so much that the runtime became a burden on the experimenting process.

Output values The SIMIO software tracks a large amount of data and provides it afterwords in tables for the user to perform deep analysis. However, not all these output values are useful. Therefore the focus in the result section is on the KPIs and the other output values were used to better interpret the results. Table information in the result section will use the averages of the scenario's, though more detailed information is recorded by SIMIO. For interest in the more detailed results and the simulation model, appendix C shows more extensive results and appendix B explains how to get access to the full analytic capacity with the SIMIO model.

Scenario selection The first experiment is the base scenario with the disruptive forces not implemented, the scenario's in the experiment are shown in table 8.2. varying the supplier choice and the inventory reorders threshold to see if the lower internal inventory is possible. This scenario is run to create a baseline of system performance under non-disruptive circumstances. The second experiment is the same setup as shown in table 8.2 but with the disruptive forces added to the model. This experiment is done to indicate the necessity of risk mitigation policies.

Table 8.2: Base scenario, experiment 1 & 2

Scenario	Ii	Ir	Iq
R1=1, R2=0, R3=0	1000	200	800
R1=1, R2=0, R3=0	1000	300	700
R1=1, R2=0, R3=0	1000	400	600
R1=0, R2=1, R3=0	1000	200	800
R1=0, R2=1, R3=0	1000	300	700
R1=0, R2=1, R3=0	1000	400	600
R1=0, R2=0, R3=1	1000	200	800
R1=0, R2=0, R3=1	1000	300	700
R1=0, R2=0, R3=1	1000	400	600

In table 8.2 the third experiment is presented. Here the backup supplier policy is tested. Because each of the three suppliers can function as a primary as well as a backup supplier, this experiment creates 18 scenarios.

The fourth and final experiment is presented in table 8.4. Here combinations between the suppliers are made, to test the volume flexibility policy. A total of nine scenarios are run to create the results.

Table 8.3: Backup policy scenario's

Scenario	Ii	Ir	Iq	Primary	Backup
S1 S2 Low	1000	200	800	S1	S2
S1 S2 Mid	1000	300	700	S1	S2
S1 S2 High	1000	400	600	S1	S2
S1 S3 Low	1000	200	800	S1	S3
S1 S3 Mid	1000	300	700	S1	S3
S1 S3 High	1000	400	600	S1	S3
S2 S1 Low	1000	200	800	S2	S1
S2 S1 Mid	1000	300	700	S2	S1
S2 S1 High	1000	400	600	S2	S1
S2 S3 Low	1000	200	800	S2	S3
S2 S3 Mid	1000	300	700	S2	S3
S2 S3 High	1000	400	600	S2	S3
S3 S1 Low	1000	200	800	S3	S1
S3 S1 Mid	1000	300	700	S3	S1
S3 S1 High	1000	400	600	S3	S1
S3 S2 Low	1000	200	800	S3	S2
S3 S2 Mid	1000	300	700	S3	S2
S3 S2 High	1000	400	600	S3	S2

Table 8.4: Volume flexibility policy scenarios

Scenario	Ii	Ir	Iq	partial allocation	Partial allocation
S1 S2 Low	1000	200	800	S1	S2
S1 S2 Mid	1000	300	700	S1	S2
S1 S2 High	1000	400	600	S1	S2
S1 S3 Low	1000	200	800	S1	S3
S1 S3 Mid	1000	300	700	S1	S3
S1 S3 High	1000	400	600	S1	S3
S2 S3 Low	1000	200	800	S2	S3
S2 S3 Mid	1000	300	700	S2	S3
S2 S3 High	1000	400	600	S2	S3

Chapter 9

RESULTS

In this chapter the results are presented, the experiments setup in chapter 8 are used for the generation of the results, testing supply chain risk management strategies under high uncertainty for the Ministry of Defence case study. The relative effectiveness of the different strategies is presented through the use of performance indicators suggested in chapter 6.

9.1 Experiment 1: Base scenario without disruption events

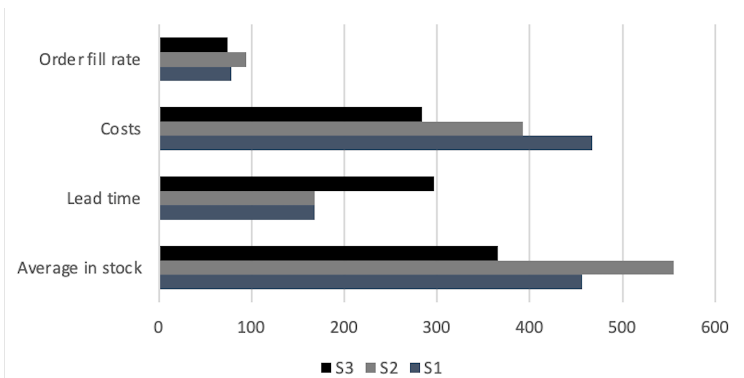

Figure 9.1: KPIs base experiment without disruptions

In the first experiment, nine scenarios are depicted, in the first three, supplier 1 is chosen and we see the reorder threshold set at 200, 300 and 400. During these scenarios, all the disruption events are turned off, but that does not mean there is no uncertainty left in the model. The production processing times are still drawn from a normal distribution so it can take longer to produce the finished goods. furthermore, the order frequency and quantity within the Defence organisation also introduce uncertainty, so demand peaks are still possible. Each scenario was run 100 times. In figure 9.2 the results are presented with regards to the main performance indicator, percentage order fill rate. Here the bars depict the 25% to 75% percentile of observations, divided into the upper and lower percentile,i.e., the middle having the highest chance of occurring and the yellow dot represents the mean value. It becomes clear that supplier 2's performance is the most stable with a high percentage of orders filled and not much variance. Supplier 1 had the highest order fill rate in a single observation but as you can see the variance is high. This was to be expected, as supplier 1 has a relatively low capacity compared to the demand it struggles when demand peaks hold for too long a period of time. Supplier 3 performs relatively stable but when the reorder point at the Defence inventory is set to low it becomes susceptible to demand spikes in rare cases (lower percentile). This is explained by the long delivery times. If large orders are placed before delivery they can not be fulfilled. When evaluating the impact of internal inventory it becomes apparent that this mainly had an impact on supplier 1, having too low of an internal buffer combined with a low capacity supplier means that the median order fill rate dropped significantly compared to the scenarios where supplier 1 was combined with a larger internal buffer.

Taking a closer look at the KPIs, in figure 9.1 they are presented for the different suppliers. The values of the scenarios with the reorder threshold of 300 are shown. Here it is seen that the costs and lead time are in line with the expected values from the supplier characteristics. Inspecting the average quantity in stock, supplier 3 scores the worst. This is a direct relation to the longer lead times. Where the longer time from order to delivery allows the internal inventory to deplete further.

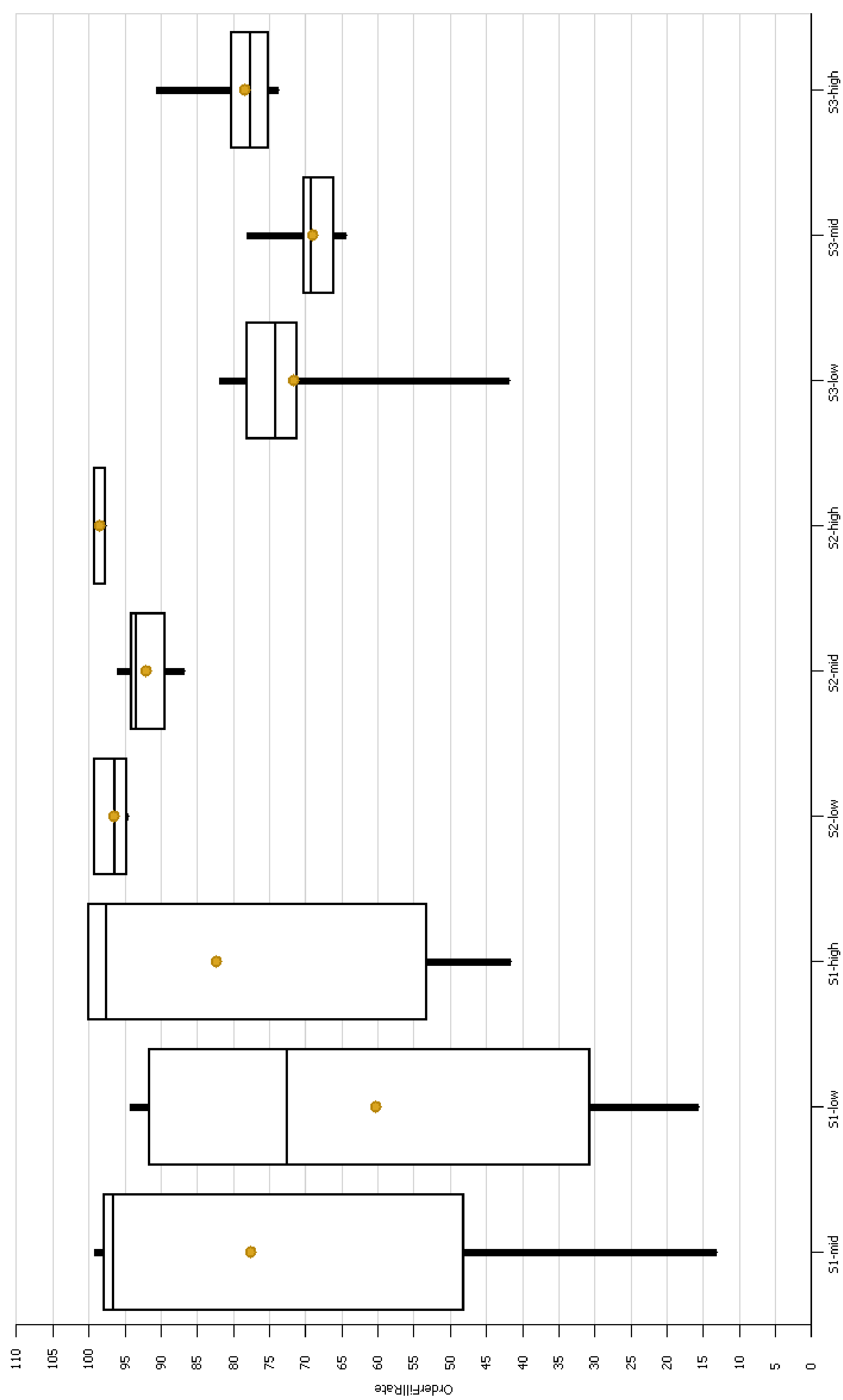

Figure 9.2: Base experiment without policy

9.2 Experiment 2: Base scenario with disruption events

In the military domain, being prepared for the worst-case scenario is standard practice. Escalation can create uncertainty, and with a domino effect, risks can pile up fast (de Wijk, 20219). To show the need for the strategies proposed in this thesis, the base scenarios have been rerun under disruptive risks to visualize the big impact these disruption events can have on the performance of a supply chain. Experiment 2 is the same as the first but the disruptive forces have been added to the model, see table 9.1. The suppliers have different ’uptimes’ when resupplying their finished goods stocks. When suppliers go into their downtime (see table 6.3). they are not resupplying their finished goods stock. The chance for an environmental disaster incapacitating supplier in that region to ship is between two and ten per cent depending on the region. Lastly, the price of raw materials varies between 0 and 22.

Table 9.1: Disruption variables

Disruptive event	Value
U_1: Uptime for supplier 1	X ∽ U(60,90)
U_2: Uptime for supplier 2	X ∽ U(30,60)
U_3: Uptime for supplier 3	X ∽ U(20, 60)
$P_{e,A}$ Chance of environmental disaster in region A	X ∽ U(2, 5)
$P_{e,B}$ Chance of environmental disaster in region B	X ∽ U(2, 10)
α_t The price of raw materials at timepoint t	$\alpha_t = \alpha_{t-1} + \mu$ Upper bound(22), Lower bound (0),

in figure 9.3 the results are presented with regards to the order fill rate. Each scenario shows the order fill rate at the Defence inventory with the confidence interval plotted. These results were generated over 100 runs. It becomes obvious that with a single supplier and no risk management strategies in place, the reliability of the supply chain falls quite drastically. none of the scenarios shows an acceptable percentage of orders filled. Supplier 1 or 2, with a high internal inventory score the best in this scenario, however, on average, they were only capable of satisfying around half of the incoming orders. Reviewing the confidence intervals between supplier 1 and supplier 2 it becomes apparent that capacity out-trades reliability under these heavy uncertainty scenarios. That being said, it does not hold when the reliability drops too far. As supplier 3’s performance is worse, this suggests there is an optimum in this trade-off. Reviewing table 9.2 the impact of the disruptive forces on the performance indicators is displayed. With, in the first column the mean value of experiment 1, the second column is the mean value of experiment 2 and the third column is the change in percentages. First, the average costs can be seen to decrease. However, this is not positive because it is due to fewer delivered orders. Furthermore, the average lead time only increases slightly. This is due to the rare occurrence of environmental disruptions. It will be

Table 9.2: Comparitive results experiment 1 and 2

Response	No disruption	Disruption	Effect
	Supplier 1		
AveregeQuantityInStock	456	227	-50%
AverageLeadTime	167	174	4%
Costs	467775	437675	-6%
OrderFillRate	78,07	37,52	-52%
	Supplier 2		
AveregeQuantityInStock	555	286	-48%
AverageLeadTime	168	174	4%
Costs	392840	347340	-12%
OrderFillRate	94,22	47,80	-49%
	Supplier 3		
AveregeQuantityInStock	365	182	-50%
AverageLeadTime	297	318	7%
Costs	284025	244440	-14%
OrderFillRate	73,87	32,52	-56%

interesting to see if policies can prevent this delay. Additionally, we see that the average quantity in stock and the order fill rate both drop around 50%, this suggests a close relation, which is logical because when the inventory is depleted because of incoming orders the quantity in stock average will fall.

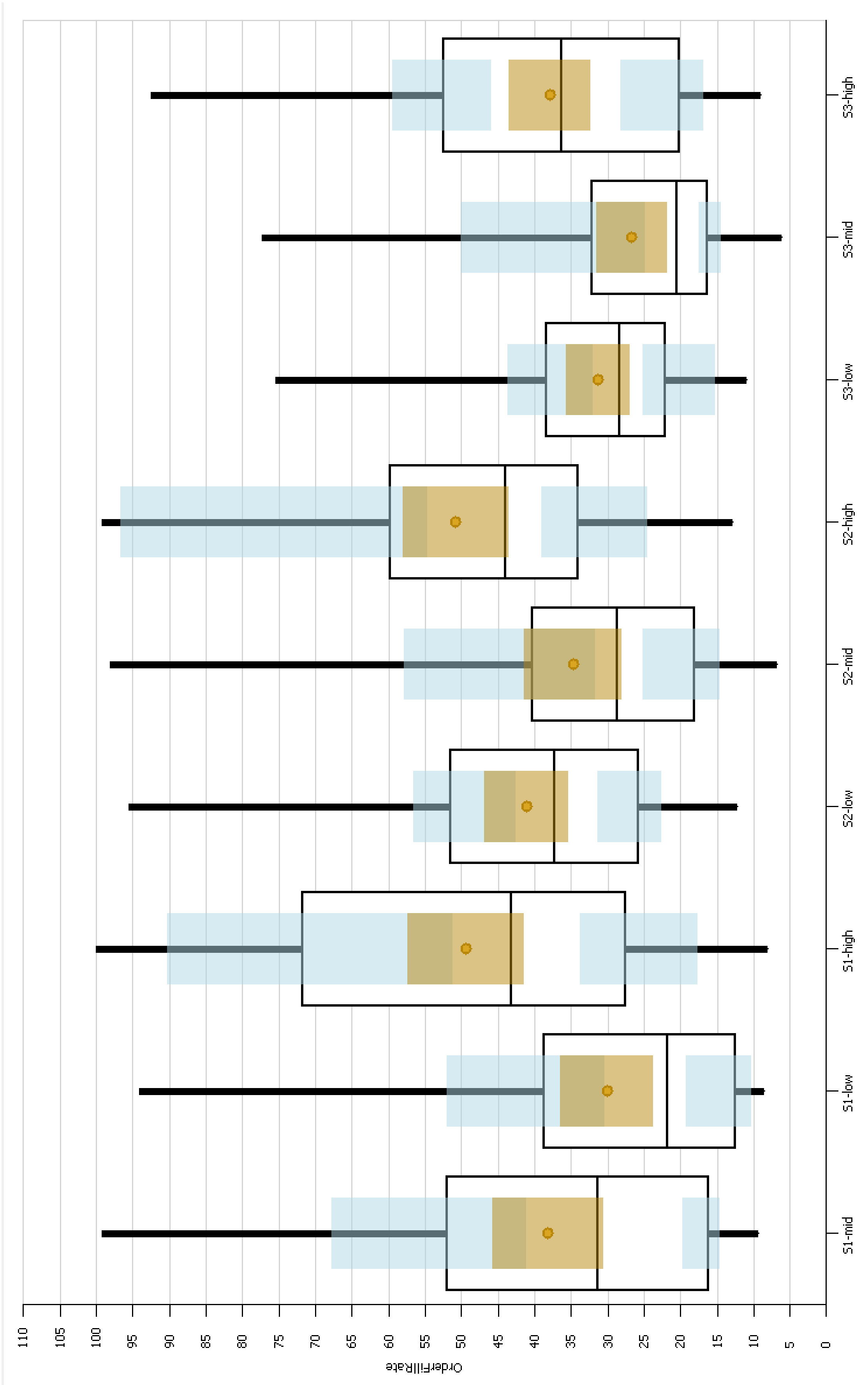

Figure 9.3: Base case with disruption events

9.3 Experiment 3: Backup supplier policy

When assortment managers opt for this strategy, there is one primary supplier and one backup supplier. This backup supplier is used when the primary supplier can not satisfy the order. At that point, the order is redirected to the secondary supplier. Afterwards, the next order will automatically first try the primary supplier. The experimental design for this strategy considers three different order points for the Defence assortment inventory I_r and tries all different combinations of S=1,2,3. A backup supplier has a minimal amount of costs, even when disruption does not occur. This is the difference between $C_{u,s}$ and $C_{uf,s}$ times 10% of the average total demand over five years, resulting in a value of $25.000. These costs are explained further in chapter 7. These increased management costs are like an insurance premium that pays out in worst-case scenarios (Kamalahmadi and Parast, 2016). the key performance indicators considered are in order of priority: Order fill rate, total costs, average lead time, average number back-ordered and the average quantity in inventory. The disruption variables have been set up as in table 9.1 and the scenarios have been replicated 100 times.

In appendix C the full results tables are presented, with the impact of internal inventory variations. In this section, results are presented with the reorder threshold I_r set at 300. Varying I_r had a small impact but a direct impact on performance (See appendix C.1). It becomes clear that reordering later and letting the internal stock run lower before reordering does have an impact but only of a few per cent. Additionally, with the right combination of suppliers, there have been no observations where this practice drastically failed. Considering the 30% decrease in the number of orders over the five-year contract period, it brings down the transportation costs and adds flexibility to the intra- organisational part of the supply chain, this should be considered by assortment managers accordingly. Looking at the order fill rate, a large improvement, compared to the base scenario with disruptions, is noticeable. In figure 9.5 order fills rate scores are inspected more closely by a graph chart with their mean, upper and lower percentile values with the respective confidence intervals. Looking at the first four scenarios where the primary supplier is located in region A, the confidence intervals of the results are all above 90%. This is an excellent improvement given the uncertainty levels. noticeable is that the combinations of primary supplier 2 and backup supplier 1 leave some vulnerability, being in the first 25 percentile range but still noteworthy. The small capacity supplier 1 as the backup supplier had some observations that were below the 50% order fill rate. This can be explained by the extra risk introduced by choosing two suppliers out of the same region. Primary supplier 1 with backup supplier 2 shows excellent results, but in the appendix, it is seen that it is susceptible to a lower I_r threshold, although these results are regarded as insignificant. However, seeing the costs with supplier 2 as primary and supplier 3 as backup is considerably lower, this is a more dominant strategy with the confidence intervals of the order fill rate overlapping almost completely (figure 9.4). Looking at the last two scenarios a drop in performance is noticeable, these are scenarios with a less reliable primary supplier and a reliable backup supplier. The decreased performance of these scenarios was initially unexpected. It turns out that the longer transport times do increase the susceptibility to risk significantly. We see this in the number of back orders too (figure 9.4). Where the performance can be considered very poor compared to the other scenarios. More back orders mean the ministry can manage the expectations of the end users less reliably. Assortment managers should note that the right primary and backup suppliers will allow them to order less frequently (30% decrease) without much-added risk, and the cost trade-off here seems worthwhile. Furthermore, the preference for a primary supplier should go to one with low transport times with at least moderate reliability. With a backup supplier, the capacity of the primary supplier has become less relevant. Additionally, preference should go to a backup supplier located in a different region than the primary supplier. Considering the most benefit for investment, in this scenario, an assortment manager should consider primary supplier 2 with backup supplier 3. For more extensive experiment results appendix C can be consulted.

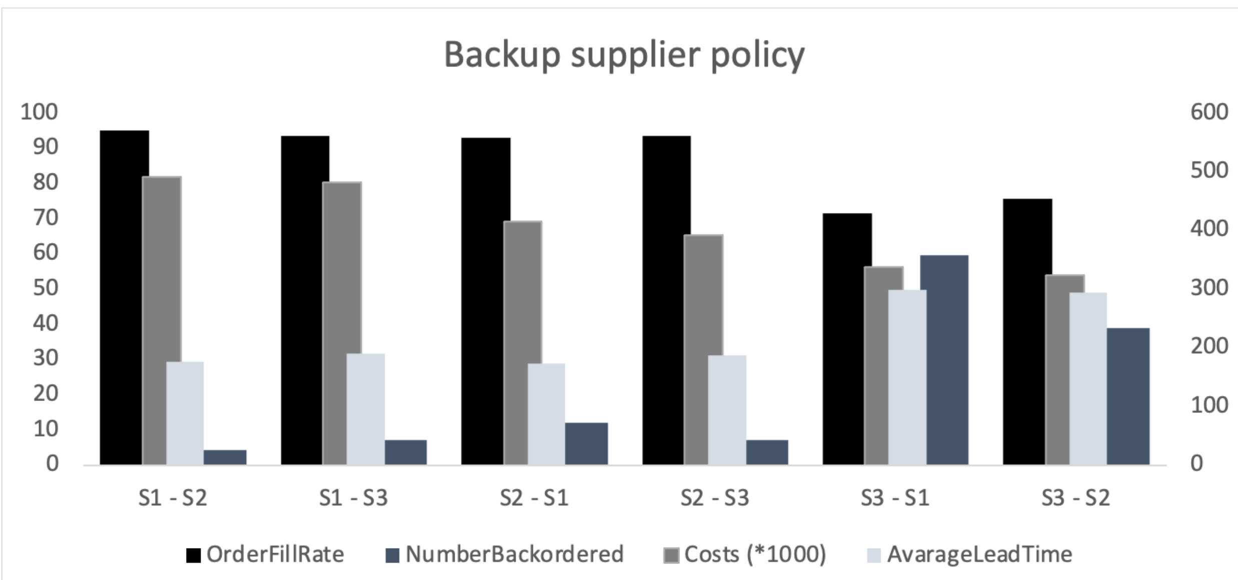

Figure 9.4: Model responses backup supplier policy

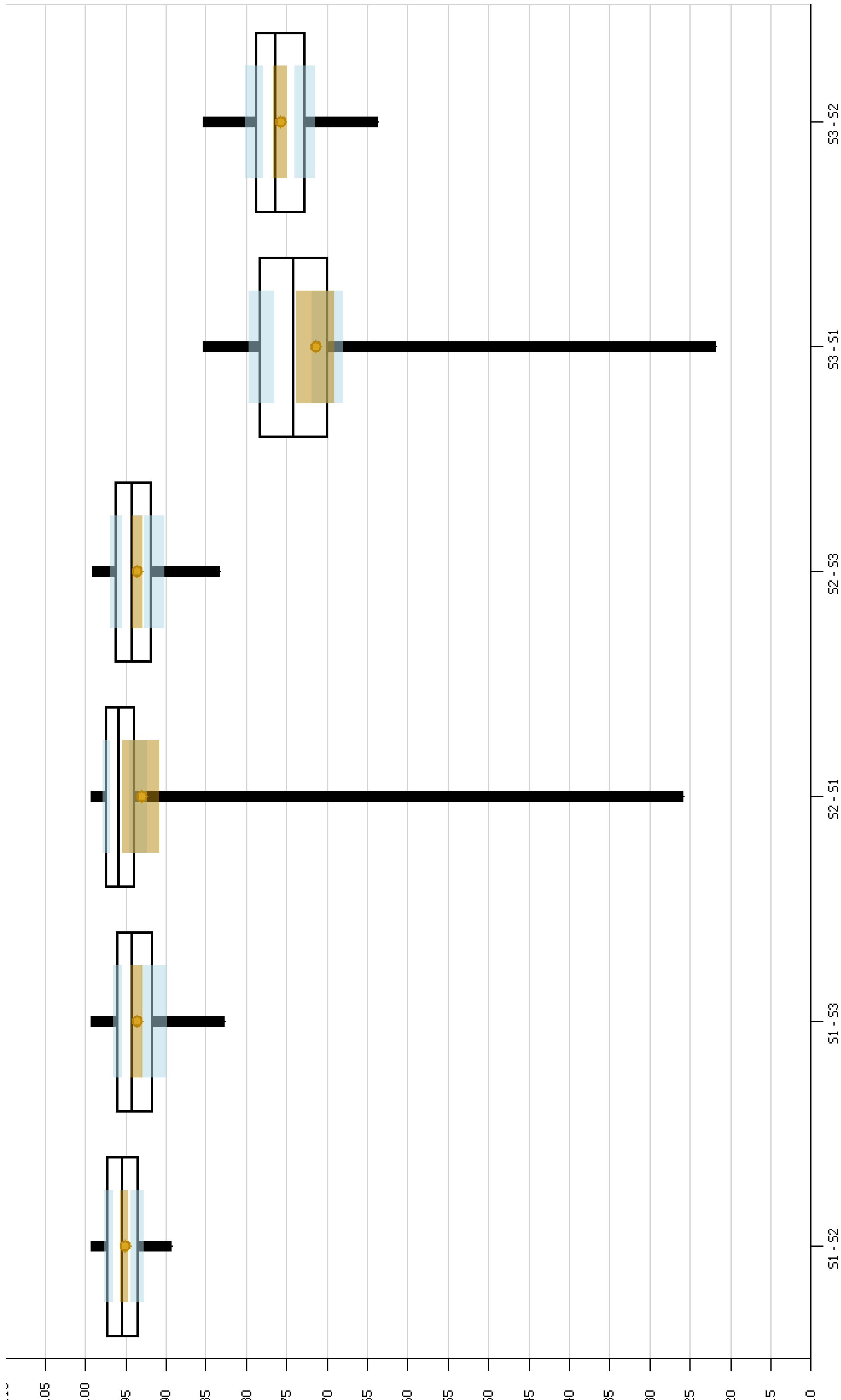

Figure 9.5: Backup supplier strategy, order fill rate

9.4 Experiment 4: Volume flexibility policy

When opting for this strategy, the assortment manager contracts two suppliers at the same time, dividing the demand allocation between them. If one of the suppliers has not had enough finished products in inventory the second supplier is requested to scale up the order quantity so the demand can still be satisfied. The design for this experiment considers three different order points for the Defence assortment inventory I_r and tries all different combinations of S=1,2,3. This results in nine scenarios. In appendix C all scenario results are presented, in this section, the variable I_r is held constant at 300 for a more direct comparison, but the main finding is that there is little benefit in increasing the reorder threshold. However, bringing it down does increase the variance as well as some performance loss in the supplier.

Figure 9.7 shows interesting performance on the primary performance indicator: order fill rate. It achieves the highest rate of all experiments with disruption events implemented. It achieves this in the scenario with suppliers 1 and 2. This does not come cheap as it is also one of the most expensive options within the possible strategies. When comparing the combination of supplier 3 with supplier 1 or 2, there is significantly less performance loss compared to experiment 3, this tells us that the volume flexibility strategy is lenient towards a drop of either reliability or capacity with a supplier. Furthermore, looking at the average overall performance of the flexibility strategy it becomes apparent that there is no really bad strategy with even the lower 25 percentile staying above 80% fill rate. This means the flexible strategy is more forgiving overall for supplier characteristics. But it must be noted that this strategy is harder to implement because it relies on better communication with the supplier and intensive use of information systems. Additionally, not all products are suitable for volume flexibility.

Inspecting the other KPIs in figure 9.6, it is seen that the costs decrease when working with the cheaper suppliers without much performance loss. The only downside here is the increased lead time but looking at the number of back orders from end-users this does not affect internal continuity.

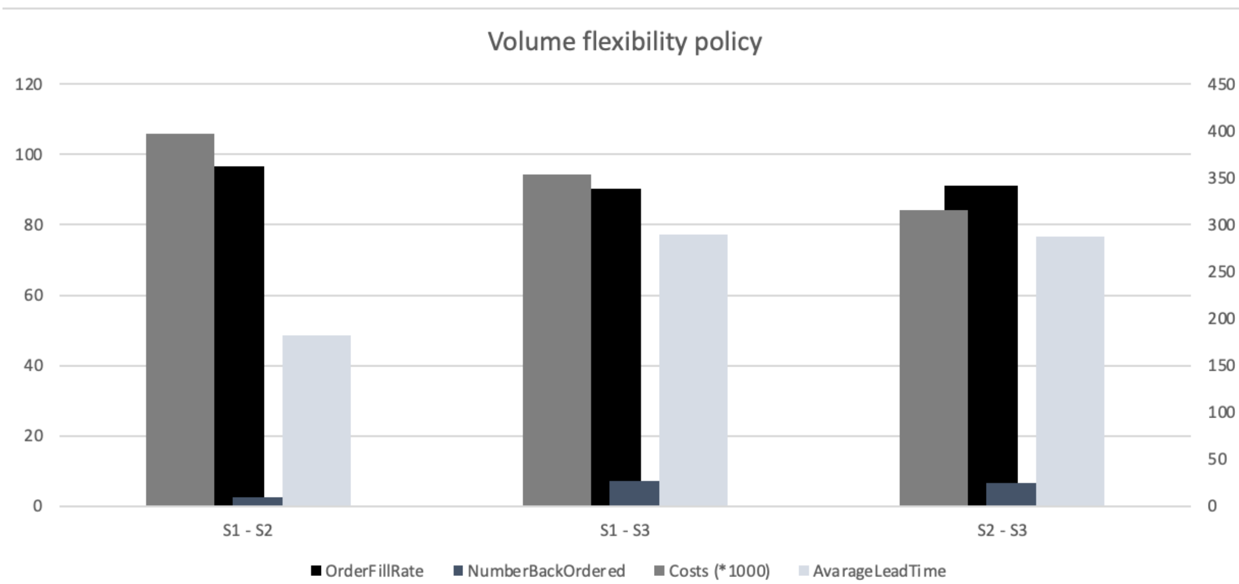

Figure 9.6: Model responses volume flexibility policy

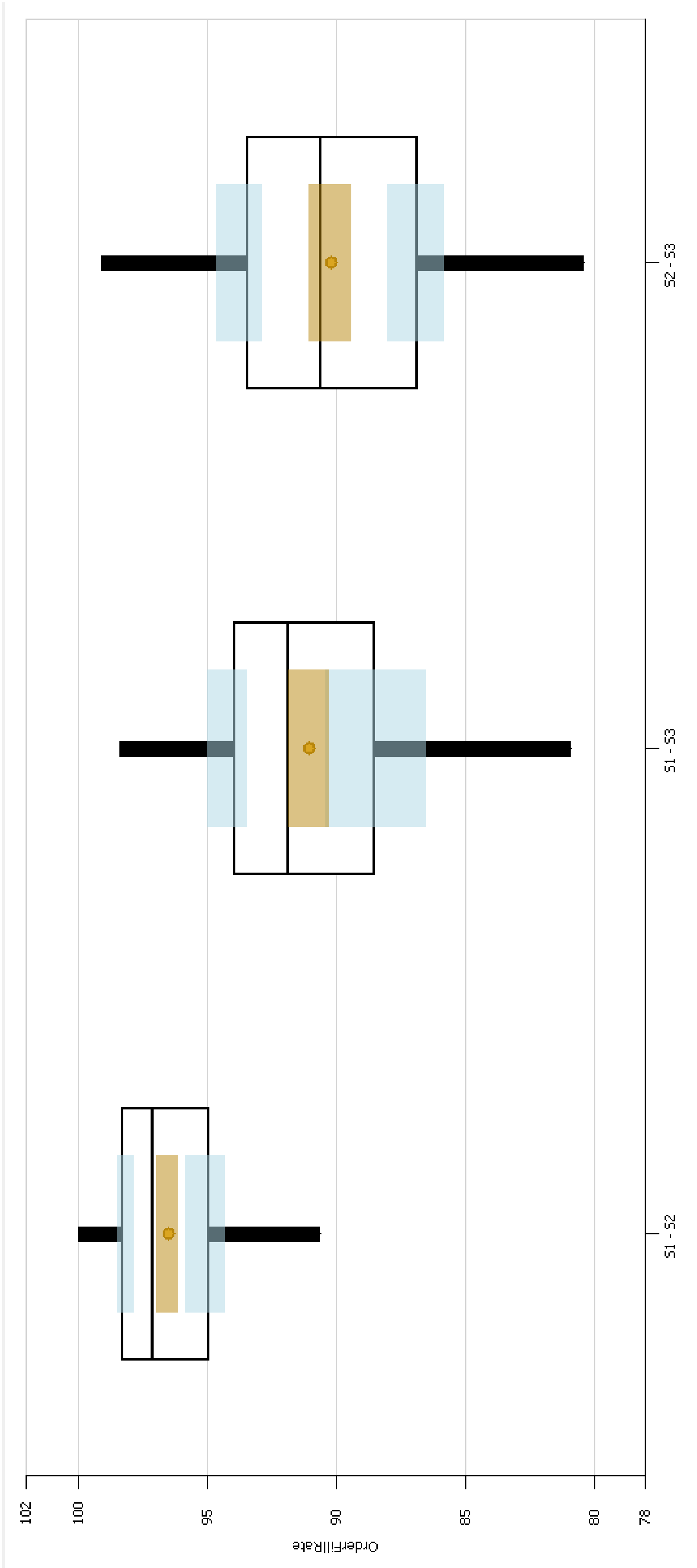

Figure 9.7: Flexible supplier strategy, order fill rate

9.5 Trade-offs

This section compares the two policies directly to each other and the base case. The recommended supplier selection scenarios are chosen from sections 9.3 and 9.4 and compared on KPI performance. For the base case scenario supplier, 2 is selected with a higher I_r threshold of 400, the policies can thus be compared to each other and no policy at all. The backup supplier with Supplier 2 as primary and supplier 3 as backup is selected. For volume flexibility suppliers 2 and 3 are selected as well. The I_r threshold for both is set at 300.

In table 9.3 it is seen that the order fill rate is drastically improved by implementing either policy. The backup supplier performing better by 2.9%. This is further improved if the confidence intervals are considered which are significantly smaller with the backup supplier policy (See appendix C.2 & C.1). This means it is a more stable policy.

The higher order fill rate comes at a cost, evaluating the costs of both policies it can be seen that the backup supplier policy costs on average $50.000 more compared to the volume flexibility alternative. This is quite a difference considering the number of products in a Defence assortment. The values are shown with their differences from the base case, however, this is not entirely fair because not the number of products paid for in this experiment is lower due to the order fill rate. This costs difference will be even greater if there are no disruptions because the backup supplier policy makes the same costs while the volume flexibility costs will recede further.

The number of backorders is again improved tremendously, which means end users will not have to wait longer than the estimated delivery times. Volume flexibility scores a little better but the differences are small.

Average lead time and average quantity in stock can be evaluated in unison, longer lead times result in internal stocks being depleted further before the order comes in. It is seen that the backup supplier policy performs better here, this is because the volume flexibility policy relies more on supplier 3 with its long delivery times. This makes the strategy more vulnerable to demand peaks from end users.

Table 9.3: Policy performances

	Base case	**Backup supplier**	**Volume flexibility**
Order fill rate	49,5	93.6%	90.7%
Difference	-	+44.1%	+41.2%
*Costs (*1000)*	354	393	343
Difference	-	+39	-11
Number back ordered	44,41	7.22	7.07
Difference	-	-37.19	-37.34
Average lead time	175	186	285
Difference	-	+11	+110
Average quantity in stock	298	546	443
Difference	-	+248	+145

Chapter 10

VALIDATION

In this chapter, the model is validated. The validation of the DES-Model in this thesis consists of a historical output validation, a face validation and an input sensitivity analysis.

10.1 Historical output validation

It is tough to perform this type of validation with much certainty because the uncertainties in the model, representing disruptive forces, are hypothetical scenarios based upon the frameworks of Christopher and Peck and Mackay et al. (2004; 2020). Therefore, the performance losses in disruption are compared to the severity of disruption discussed in literature reviews and other studies.

Comparing the severity of disruption with the securities found by Macdonald and Corsi (2013), who performed multiple qualitative depth interviews with practitioners it can be seen that a performance loss of 50% falls well within the expected range of a system under influence of disruption. It must be noted that most literature measures performance loss in financial terms instead of continuity which does complicate finding relevant data a bit further. However, turning to the works of Ivanov (2018; 2021), who (literally) wrote the book on modelling supply chain resilience models, The performance impacts are very comparable to the example models employed in his epidemic models.

10.2 Expert validation

In this study I had the opportunity to work with the Ministry of Defence enabling me to couple this research in a pragmatic sense to practitioners. After processing and analysing the results, the opportunity arose to present the findings to the management staff in the Hague. This inspired a discussion that resulted in an invitation to a Defence wide assortment coordinators meeting. Where the findings were discussed with the key actors who are controlling and approving the policy decisions being made at the assortment inventories of Defence. As part of this meeting the assumptions and findings of this research were discussed. This resulted into several insights, the most important discussed here:

Reviewing my simulation model, the practitioners agreed with my supplier archetypes and overall structural setup. Pointing out that in practice I slightly over estimated the organisation's ability to match supply and demand. Stating that intra organisational logistics only deliver about 10% of their orders in the allotted time, the rest either too early or too late. This is outside of the scope of this research but definitely worth exploring further. Some questions were raised about the viability

of these policies for products that have much smaller order quantities. Here, it was noticeable that within Defence organisations focus quickly shifts towards the flashy items such as weapon systems. Although the simulation model might be less applicable for these types of items, it was discussed how the same mindset could be applied. It is possible to create external buffers for such weapon systems by applying the same volume flexibility contracts in partnership agreements with allied countries.
The immediate adaptation of ideas and philosophies playing a large role in discussion with the coordinators, who compared my research with steps they are currently taking to improve their overall supply chain performance. Recommendations and findings I presented where noted as conformation, for example, the navy, who are trying to integrate the information exchange between purchasing and assortment management further; or representatives of the land forces who recognized the value of supplier management above its current level. Lastly, the expressed importance of information integration between purchasing and assortment management let to the idea of organizing expert consultation sessions between the departments to help aid this process.

The conclusion of this expert consultation was that the insights generated by my model were certainly relevant and point out the importance of information integration in an organisation, to improve the quality of decision making. However, scepticism persists as the buffer capacity placement outside the organisation can lead to vulnerability to strategic attacks. Furthermore, the implementability was questioned as suggested information integration can be difficult. This is in line with my findings that there is an issue with finding qualified employees for key positions. Overall, there was consensus with regards to how the model and suggestions can help improve decision making.

10.3 Input sensitivity analysis

To test the sensitivity of our model to the input variables, a response sensitivity analysis has been performed. In this analysis, all the input distributions are assessed on their impact on the model responses (outputs). To see how this works let's consider the meta-model for our simulation:

If there are L mutually independent input processes so that there is a collection of estimated distributions:

$$\hat{F} = \hat{F}_1, \hat{F}_2, ..., \hat{F}_L$$

So that the estimated distributions are represented by the vector . This vector estimates the unknown real-world distributions:

$$F^c = \mathrm{F}_1^c, \mathrm{F}_2^c, ..., \mathrm{F}_L^c$$

The model calculates the responses by using the input variables so that the output from replication j can be represented by:

$$Y_j = (\hat{F})$$

In our model, we perform multiple replications and use the average to approximate the real-world value. So, the results of the model are calculated by getting the average number of replications. This can be denoted as follows:

$$\bar{Y}(\bar{F}) = \sum_{j=1}^{n} Y_j(\bar{F})/n$$

With estimating the true mean of the output of the real system. We can define this by:

$$g(\hat{F}) = E[Y(\hat{F})|\hat{F}] = lim_{n\to\infty}\bar{Y}(\hat{F})$$

Where the expected output Y, given the set of estimated distributions provides a better estimate as the number of replications approaches infinity.

Now, to analyse how much impact the individual input variables have on the model responses we can describe the model as a function of the means and variances of the input variables. In mathematical terms: the relation between the input model (set of distributions) and the simulation output (g()) can be shown in terms of a linear function of the mean of the estimated distributions and the variance of the estimated distributions. Creating a meta-model for the simulation model providing a regression approximation of the relationship between the inputs of the model and the output of the model:

$$g(\hat{F}) = \beta_0 + \sum_{l=1}^{L} \beta_l \mu(\hat{F}_l)) + \sum_{l=1}^{L} \nu_l \sigma^2(\hat{F}_l))$$

based on the assumption that the sensitivity of the mean simulation output is largely captured by the mean and variance of the individual distribution of the input variables. By simplifying the model eliminating the variance effects and only observing the mean effects to approximate the simulation output we get the regression model:

Table 10.1: Input sensitivity base case with disruptions

KPIs	Order fill rate			Average lead-time		
Scenario's	alpha t	Pe	Us	alpha t	Pe	Us
S1 - Low inventory	84%	12%	2%	78%	15%	4%
S1 - High inventory	13%	84%	2%	4%	93%	1%
S2 - Low inventory	80%	15%	5%	69%	18%	7%
S2 - High inventory	81%	14%	3%	30%	62%	4%
S3 - Low inventory	86%	10%	3%	83%	11%	5%
S3 - High inventory	79%	13%	8%	95%	2%	1%

$$g(\hat{F}) = \beta_0 + \sum_{l=1}^{L} \beta_l \mu(\hat{F}_l))$$

This allows us to estimate the sensitivity of our simulation output to each input distribution of $\hat{F}$ This results in the ability to identify the sensitivity of our output by observing β_l. This value tells how much our output response would change if the input variable is increased by one unit.

The input sensitivity analysis is performed for the base scenario, where the change in the model response of one united is attributed to the disruptive input variables by percentages. The results are presented in table 10.1.

The base scenario with and without disruption events provides a good reference for a sensitivity analysis. Since the results of the simulation model are highly dependent on the variables inside the model it is good practice to analyse the relative weight of these variables to check if a model is not to depend on specific variables. Additionally, the relative impact of the risk-mitigating policies is discussed in the results section and discussion. To analyse which of the disruption events had the biggest impact on the drop of performance in the base case with disruptions, table 10.1 shows the relative influence of the disruption variables on two performance indicators. Only the scenarios with high and low inventory levels are shown to emphasize the contrast. What is interesting is that when the first supplier is contracted, the internal inventory levels play a significant role in what is the determining factor for the order fill rate. This means that a low-capacity supplier combined with low inventory levels results in a large dependence on material availability in the market. If the internal inventory levels are higher, environmental disruptions become the main concern. This effect is stronger when looking at the average lead times. This is interesting because long lead times have a more direct relation with environmental disruption but when the internal inventory is too low material scarcity becomes a higher priority. Reviewing the less reliable but high-capacity suppliers we see that material scarcity becomes a more dominant determent of the performance indicators. There is one exception, the combination of supplier 2 and high internal inventory is more dependent on environmental disruption as well. This means that in a single supplier scenario assortment managers must be weary of material scarcity and can achieve higher resilience if they opt for a reliable supplier combined with a heightened internal inventory..

10.4 Face validation

Using the results of the input sensitivity analysis, a face validation of the disruption parameters and the main KPI is performed as part of the face validation

Order fill rate, compared to the base case without disruptions where the median order fill rates were between 73% and 99% a very sizeable drop is noted to a median range of 22%- =44%. This performance drop of about 50% points is big but that is the point. In the military domain, strategic thinking commands assuming the worsts case scenario (de Wijk, 2019). In this case, high uncertainty in different places in the supply chain with no risk mitigating measures resulting in a 50% performance drop is along the lines of expectation.

Scarcity, material scarcity is simulated by rising material prices. It is assumed that high-reliability suppliers have a higher price tolerance and are therefore more capable of acquiring these materials. table 10.1 shows that this scarcity has a very high impact of up to 86% on the order fill rate. However, it is important to realize that a supply chain has a beginning and an end. Meaning, the processes in the model are not parallel but consecutive. Therefore, without risk-mitigating strategies in place, it is reasonable to assume that disruption at the source of the chain, has a high impact. Furthermore, 10.1 shows that under the right conditions other variables can become more important, thus suggesting the presence of mitigating possibilities. When considering a second performance metric: Average lead time, we can see a large spread in the sensitivity to material scarcity. This is along the lines of expectation seeing that when material shortage determines the critical path in the supply chain, lead times automatically become longer as it takes more time to prepare orders. When scarcity does not determine the critical path the impact on lead times decreases. This is logical model behaviour and therefore acceptable.

Environmental disruption, Note that the sensitivity to this variable has a large spread on both of the performance indicators. This suggests that it is not dominating results but is important only under the right circumstances. This behaviour makes sense considering that large delays in shipping times become increasingly important when the assortment inventory has a low average quantity in stock.

Uptime at suppliers, This is the only disruption source that is also a supplier characteristic. The performance indicators do not seem that sensitive to changes in the number of times suppliers are producing goods for orders. This does not mean it has little impact on the simulation, but that a shift uptime from for example 30 days to 40 days does influence the performance indicators dramatically. This can be explained by the way the system is modelled. A supplier only produces finished goods up to the capacity point. After that it stops producing, so those 10 extra days are not being utilized to build an extra buffer. Only in the critical moment do those 10 extra days determine if an order can be filled or not. For the most part, they are not necessary. This is a modelling choice and is not considered a problem. A supplier has to deal with limited capacity and other business processes. In this sense, the type of disruption event distinguishes itself from the other two which have a more direct effect on the primary supply chain processes. You can see the inventory of the supplier as a buffer against this disruption source. The low sensitivity compared to the other events is therefore not a problem.

10.5 Limitations

In this thesis, supply chain risk management strategies are considered to mitigate disruption threats in the supply chain of the Ministry of Defence. The strategies considered were volume flexibility and backup suppliers, both identified as antecedents of resilience. Their impact on the performance of a single-product supply chain exposed to three sources of disruption was measured. These considered sources were: the scarcity of raw materials upstream in the supply chain, Supplier downtime stopping them from producing goods and Environmental disruption delaying shipments. The simulation model showed that both practices had a significant impact on supply chain performance. That being said, a model is always an approximation of reality and therefore has its limitations. in this section, these limitations will be discussed which can suggest future avenues of research.

Data constraints, Models are restrained by the quality of data that is fed into them. In this simulation research, the data of Ruiz-Torres et al. (2013) and Kamalahmadi and Parast (2016) was used as a source for the supplier characteristics. This data is sourced from observing a manufacturer of appliances. Therefore it must be acknowledged that a more detailed dataset specifically tailored to military supply chains would have made the results stronger. Furthermore, because the high disruption chance scenarios are hypothetical situations there are limited options for statistically substantiating value assumptions. Additionally, the high-uncertainty situations in the military domain make it difficult to define the severity of the disruption. Disruption parameters are based on assumptions based on literature reviews and other studies. This all leads to a weakened model validity. It would be helpful to have more access to military data but this was not possible due to limited data clearance with the Ministry. Additionally, not only the clearance restrictions had an impact on data collection but the willingness to share was limited as well, during the interactions with the employees it became clear that there was a limited amount of information they were willing and/or allowed to share. As an outsider, I understand the hesitance to provide information regarding the vulnerabilities of the supply chain. However, it the impact on the significance of the results can not be neglected.

Model limitations, Choosing the Discrete event simulation approach has benefits as described in section 3.2. This does imply that the benefits other modelling paradigms boast are not obtained. For example, an agent-based model would have been able to take the human behaviour aspect more into consideration. For future research taking this approach combined with a focus on information sharing is definitely worth exploring. Other options such as mathematical optimization would have been able to provide exact thresholds for when to switch strategies. However, I think research aiming to find things such as 'optimal' allocation is not suited for high uncertainty scenarios and it is better to delineate broad categories where practitioners can make judgement calls building upon their experience.

The model could have been further improved by a more specific demand function. However, due to time constraints and insufficient data from the Ministry, this was left outside the scope of this thesis. Furthermore, the flexibility approach could have been improved by varying the order times between two suppliers which is currently not adopted in the model logic. Another limitation within the model is that suppliers cannot go bankrupt or discontinue product lines. It would be another study to explore the risks of bankruptcy upstream in the supply chain.

The key performance indicators in the model were: Order fill rate, Costs, the average number of orders back-ordered, average lead time and average quantity in stock. Although the simulation software also allows insight into much more result statistics, there could be other performance indicators implemented to reveal new insights.
A more practical limitation imposed by the model was the run time, for the risk mitigation strategies 100 trials were run per scenario, this meant that if a small change was implemented it would take over 3 hours to run all experiments again. This limitation was partly mitigated by experimenting with model changes and performing a single run in a single scenario, however, this does not always provide a complete image.
In the model, there are two geographical locations which each have individual chances of disruption. However, this does not consider systematic disruption as seen during the COVID-19 pandemic where all industries, irrelevant of their location, were affected. Furthermore, my locations fit very general archetypes a specification to a single product group could target real physical locations and

make a separate risk analysis for that specific environment.

The process for representing scarcity was coupled with a varying price function. This price had each day the same chance of going up as going down. However, it would be more realistic to have a function that takes the trend into account. Meaning that a price rises or declines often over a time period reacting to geopolitical development. However, a more complex price function should be accompanied by more strategic buying behaviour of the model entities so this requires much more complexity.

The use of three archetype suppliers is both a benefit and a limitation of the model. The benefit is that is generalizable, most products can find suppliers fitting these archetypes. However, it forgoes specificity that can provide tailored policy advice for specific products.

Chapter 11

DISCUSSION

11.1 Findings and interpretation

This thesis provides several insights into the implications of supplier selection under uncertainty and hopes to assist assortment managers of the Ministry of Defence with part of their decision-making and responsibilities. Furthermore, the findings can assist academics in further developing an understanding of supply chain risk management and resiliency. The data gathered from the simulation model and the important findings learned from that data will be discussed in this section. In the following section, the implications of these findings will be highlighted and translated into policy recommendations for the ministry of Defence case.

Experiment 1 and 2: the base case with and without disruption

The first step of the modelling approach was to determine a benchmark by simulating a base case. In this instance, this base case was split up into two separate experiments: The first without the presence of disruptive events and the second with these events implemented in the model. This was done to see the effects of not having risk mitigation policies in place. for this base case, there were three supplier options, generalized to the following archetypes: 1) high reliability, low capacity, high costs and close proximity in region A. 2) moderate reliability, moderate capacity, moderate costs and close proximity in region A. 3) low reliability, high, capacity, low costs and intercontinental distance. other than supplier selection assortment managers have control over the reorder threshold. with the three available options: 200 (low), 300 (moderate) and 400 (high).
In the base case without disruption events, the scenario's scored between 73% and 99% on average and upon reviewing the variance between observations a large spread was noticeable with supplier 1. After inspection, it was concluded that supplier 1 has too low of a capacity to reliably supply the assortment inventory during demand spikes. Therefore, in a single supplier approach assortment managers must be aware of how high the worst-case scenario demand is, so in times of demand spikes the assortment can scale up their orders without jeopardizing their own downstream reliability. The second supplier with its higher capacity showed to be capable of handling demand spikes and performed very reliably. Supplier 3 showed little variance and thus stable performance in this scenario. However, being the least reliable supplier this results in an order fill rate between 70% and 80% and in the scenario of a low reorder threshold, observations below the 50% mark were seen. This is caused by the combination of a long delivery time with a low threshold. Being

the cheapest supplier this could be a strategy for products that are not being pressured by a time constraint.

When adding the disruption events to the base case a significant drop of around 50% to a range of 22% - 44% order fill rate across all scenarios was noted. This means that under high uncertainty where raw material is scarce, environmental conditions are unstable and the supplier is unable to produce goods a percentage of the time; there should definitely be risk mitigation methods in place in order to maintain any form of reliability downstream in the intra-organisational supply chain. The following findings can be established after experiments 1 and 2:

Finding 1: Internal inventory levels act as a buffer against disruption
Finding 2: In a single supplier scenario, supplier capacity should match worst-case scenario demand
Finding 3: Supplier capacity acts as an additional buffer against disruptive forces.

Experiment 3: Backup supplier policy

To assist assortment managers in choosing the right risk mitigation strategies the second step of the modelling phase explored the redundancy strategy: Backup suppliers. The setup is the same compared to the base case except that when a supplier cannot satisfy an order at the moment it is being placed, that order is redirected to a backup supplier. with the same varying reorder thresholds and trying all possible combinations with the three suppliers this resulted in eighteen scenarios, which were observed 100 times each.

The results from this experiment indicated a preference for a primary supplier in region A. This is to be expected as the less reliable supplier 3 in region B struggled the most without a backup policy and a primary supply should capture as much of the demand as possible. In the set of scenarios, it is noticeable that half of the scenarios contain a few observations with very poor performance. In the cases where supplier 3 is the primary, this is explained by a demand peak during an environmental disruption event in region B and downtime at the supplier in region A. Note, that the scenario's where supplier 2 functions as a backup were only observed in one of the three scenarios. This can likely be explained by the larger capacity of supplier 2 functioning as an extra buffer. The other poor observations are caused by having a backup supplier in the same region, this creates an extra vulnerability for environmental disruptions. Here the lack of capacity of supplier 1 makes it less suitable as a backup in this very specific situation. Considering the all performance metrics it becomes clear that primary supplier 2 and backup supplier 3 is the most advisable combination. Boasting order fill rates that match supplier 1 as primary, combined with low variance and the lower costs of supplier 2, makes it the best choice in high uncertainty. It became clear that the function of a backup supplier is forgiving for supplier characteristics. This makes sense as the backup allocation is reserved, thus process downtime should not influence performance. The leniency towards transport time is interesting. If internal inventory spans the delivery time of the backup supplier the risks can almost be completely mitigated. This strategy could thus be very well suited for strategic inventory items and/or items vital to operational capabilities. The following findings can be established with regard to experiment 3:

Finding 4: A primary supplier benefits from shorter transport times, allowing for a higher average quantity in inventory and higher order fill rate.
Finding 5: Geographical spacing between suppliers helps mitigate supply chain risks.
Finding 6: The backup supplier policy is lenient to reliability and transport time characteristics of the backup supplier

Experiment 4: Volume flexibility

In the third and final step of the modelling phase, the flexibility strategy was implemented. More specifically, the volume flexibility strategy to mitigate supply chain risks. Here instead of shifting the entire order to a new supplier, the demand is split up over two different suppliers. With this smaller allocation per order, supplier capacity plays less of a role and can thus act more in a buffer capacity. When one of the suppliers cannot satisfy an order, the other supplier tries to take up the slack by increasing their order quantity. To account for all the different variations this experiment was set up with all the possible combinations of suppliers and the varying reorder thresholds of the assortment inventory. This resulted in nine scenario's which were observed 100 times each.
This strategy showed one important characteristic, which is that it scores very stable over all the scenarios. There are no observations recorded under the 70%. Furthermore, the highest order fill rate with disruptions implemented was recorded in scenario three, with suppliers 1 and 2 combined with a high reorder threshold. That being said, this is also one of the most expensive scenarios. What is interesting about this strategy is that the combinations with supplier 3 are performing really well with filled order rates between 85% and 94%. Considering that S3 is the cheapest supplier and in this strategy handles about half the allocation making it a very attractive option for dealing with uncertainty in the supply chain. The following findings are established with regard to experiment 4:

Finding 7: Volume flexibility is more lenient towards supplier characteristics
Finding 8: Due to little upfront costs, this policy is more cost-efficient albeit less effective.
Finding 9: Due to higher incoming order frequency, the environmental disaster disruption has less impact with this policy.

11.2 Implications, trade-offs and recommendations

Considering the results generated by the simulation model and the findings provided above, this section will aim to translate the results into pragmatic recommendations for supply chain managers, or in this case assortment managers. By discussing these implications for the practice of supply chain risk management the trade-offs between the different strategies, under varying circumstances, are highlighted.

In traditional competitive markets, supply chains should be designed with risk management in mind. The design should account for uncertainties that threaten the supply flow such as the reliability of the suppliers and external uncertainties that can cause disruption (Christopher and Peck). An entity can enhance its resilience to supply chain threats by incorporating strategies such as redundancy and flexibility into its supply chain design, which are known to improve overall resilience (Dubey et al., 2019). These strategies can help supply chain managers to redirect or replace the flow of goods when a disruptive force requires them to. In the introduction, the increased awareness of supply chain risk management was named. This might be the case, however, the most recent literature still suggests that firms are still coming up short with regard to implementation (Ivanov,2011). An important reason, businesses still have doubts about whether the gains of SCRM outweigh its implementation costs (Sáenz and Revilla, 2014). I believe this is caused by decision makers having difficulty with the justification on basis of statistical predictions, the known unknowns of Rumsfeld's uncertainty matrix (2002). Take the Evergreen as an example, prior to the ship running aground, it was known that a blockage of the Suez channel would have a big impact on the lead times of many supply chains. However, because it had never happened, practitioners did not know how to evaluate such a risk. Models such as the one proposed in this thesis should make these considerations more approachable. The simulation model was set up with three goals in mind: 1) provide insight into how redundancy and flexibility-orientated strategies influence supply chain performance given supplier characteristics. 2) research how risk appetite, costs and resilience determine the trade-offs when opting for the aforementioned strategies. and 3) embed pragmatic use in a model where multiple sources of uncertainty are incorporated, the individual suppliers are exposed to unique risks fitting their characteristics and enabling exploratory over-optimization.

The results of the model led to a set of implications that impact the way assortment managers should weigh decisions in several ways. First, both volume flexibility and backup suppliers resulted in a significant improvement in the reliability of the supply chain under heavy uncertainty. with certain strategies even surpassing supplier performance in the base case without the chance of disruptive events. This is in line with the work done by Ivanov (2020) and McKay (2019) where the strategies are conceptualized and suggested to improve resilience against external uncertainties. That being said, in the literature, there is not much stated about the relative value of both practices.

This study finds that employing backup suppliers, as a supply-side redundancy measure, is more effective than the volume flexibility alternative. The results of implementing a backup supplier showed less variance by being more stable with higher scores on performance. This low variance leads to higher predictability and therefore higher reliability. Volume flexibility should be regarded for product types that are considered less crucial or for entities that want to minimize expenses. Volume flexibility can be a good way to embed more resiliency in the supply chain and add a lower cost. This is due to the higher tolerance for less reliable suppliers while still maintaining decent performance. It should be considered that volume flexibility is not an option for all product categories and/or suppliers because last-minute order quantity changes can be difficult. Kamalahmadi and Parast (2021) name an example of supply chains that involves chemical processing, this would be undoubtedly the same for several of the products in the Defence assortments. That said, redundancy is not without its deficiencies either. Consider goods with a deterioration rate. By placing buffers in the supply chain you are exposing yourself to substantial write-off costs making it an expensive strategy. Relating to the reorder threshold for the assortment inventories, being able to operate with a lower reorder threshold would make an organisation more flexible. This is due to being less dependable on your own internal buffers. Therefore making it easier to adapt to changes in the market because fewer buffer zones in the infrastructure are making the organisation less sluggish. This can be reached with strategies placing the buffers at other places in the supply chain. For example, a backup strategy with a secondary supplier with a large capacity would allow an assortment manager to opt for a lower reorder threshold. This should be considered for strategies that had little variance in the results and an acceptable performance with the low reorder threshold. An oversight of the implications is provided in table 11.2

Concluding, I will make the recommendation that for product types that are of strategic importance, a backup supplier is the better choice. The redundancy method is considered more risk-averse which fits with an organisation such as the Ministry of Defence. However for product types where resiliency is needed but not crucial it would be more cost-effective to opt for the volume flexibility approach. Lastly, for the type of products where risk mitigation strategies are considered superfluous it would be advisable to opt for regional suppliers with a capacity large enough to satisfy peak demand. To make these recommendations more tangible, they can be coupled with the portfolio purchasing model suggested by Ekström et al. (2021) in a recent study of military organizations. Ekström's model is presented in figure 11.1.

Considering Ekström's model, supply goods can be classified into four categories based on the limitation they impose on operational capability and the uncertainty in which the supplier market finds itself. **Strategic supplies**, with high supply uncertainty and disastrous limitations on operational

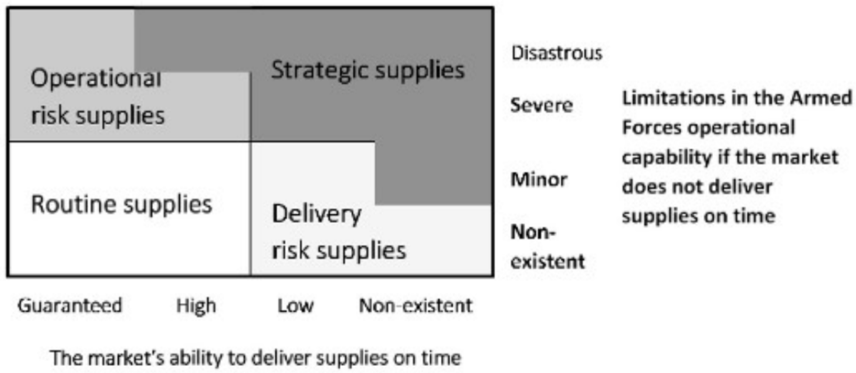

Figure 11.1: Portfolio model of Ekström, used to classify military goods

capability, should have the highest certainty risk mitigation strategy in place. Strategic supplies should have a backup supplier, a primary supplier with high reliability and a backup supplier with high capacity, making sure to geographically distance between the two. **Operational risk supplies**, here assortment managers could consider two approaches, the risk-averse backup supplier strategy or the more cost-efficient volume flexibility. **Delivery risk supplies**, could be managed with volume flexibility, saving on implementation costs but still increasing the resilience of the supply chain significantly. **Routine supplies**, for routine supplies assortment managers, should consider risk-mitigating strategies if order quantities are very high, this would mean that the implementation costs would be more worthwhile and increase overall resilience.

Policy	***Factor***	***Outcomes***	***Managerial insights***
Backup supplier	Material Scarcity	Material scarcity can be mostly negated by a backup supplier as the capacity is reserved at the backup supplier. This policy provides benefits from high internal inventory but with added flexibility due to the buyback contract.	Knowing when to opt for a backup supplier is as important as the effects the policy has. Assortment managers should be able to classify the strategic importance of the product. And relate it to the external environment. Where increased strategic importance and high uncertainty are determinants of choosing this strategy. Finally, assortment managers should be aware that the efficiency of the cost trade-off is finite. And that extra investment in backup suppliers does not linearly create extra certainty.
	Environmental disruption	By geographically spacing suppliers this risk is almost completely negated. The risk of both environments being struck remains a threat but much more unlikely.	
	Process disruption	The backup allocation is reserved in advance, so the supplier should not need to produce goods, this negates this risk.	
	Internal inventory	By outsourcing internal inventory to a backup supplier you receive the same benefits of high internal inventory while remaining flexible. The drawback is that if a disruption does not occur, the higher costs are fixed.	
Volume Flexibility	Material Scarcity	Material scarcity is a greater threat to the volume flexibility strategy as there is no fixed allocation reserved in advance. Therefore, a increase in scarcity does impact this policy, it can be partly negated by selecting suppliers with high capacity and reliability. These characteristics both have a buffer effect on scarcity.	Volume flexibility is a good alternative if upfront investment is not preferred. Additionally it is fitting for less strategic goods as it can also suppress costs. Assortment managers could benefit from actively monitoring external developments such as increasing material scarcity. Than this risk can be mitigated by increasing internal inventory levels.
	Environmental disruption	By geographically spacing suppliers this risk is almost completely negated. The risk of both environments being struck remains a threat but much more unlikely.	
	Process disruption	Assuming there is always a trade-off between reliability and cost, the deciding factor here is capacity. For low reliability can be offset by high capacity as the policy is lenient to some ’bad’ characteristics	
	Internal inventory	For this policy, it can be said that higher internal inventory decreases the impact of material scarcity.	

Figure 11.2: Managerial implications

Chapter 12

CONCLUSION

This thesis employed a simulation modelling approach to supplier selection strategies, testing different antecedents of resilience in their capability to embed resilience in the supply chain of the Ministry of Defence. The simulation model was subjected to three different disruptive events that represented environmental and supply risk in supply chains (Kibli et al., 2010; Sheffi and Rice, 2005). The proposed model created a better understanding of supply chain risk management practices and trade-offs between redundancy and flexibility orientated strategies. The results of the model were discussed with regard of how contingency planning can mitigate the negative effects of disruptive forces on the supply chain. The discussion led to the recommendation that in high uncertainty environments, products, that can be classified as strategic according to Ekström's portfolio model, would benefit from having a backup supplier in place. The volume flexibility approach is suited for products that are less vital to the operational capacity, where a good performance can be achieved with less costs. The volume flexibility strategy proved to be more forgiving towards supplier characteristics but can also be harder to implement depending on the specific product.

Returning to the main question in this thesis:

" What are the trade-offs between flexibility- and redundancy-orientated strategies for supply chain risk management, considering the supply- and environmental risks?"

Both flexible and redundancy strategies prove useful, the trade-off between both strategies is predominantly determined by the risk appetite of the entity looking to implement the strategy. A more traditional organisation such as the Ministry of Defence can be considered to be risk averse, this attitude towards risk steers more towards a redundancy approach. In this case, backup suppliers proved to perform more consistently under heavy uncertainty and although the approach has higher implementation operating costs, it is better equipped to secure strategically important products. That being said, in an environment where all available suppliers are considered to have low reliability, the flexible approach can outperform redundancy as it is more lenient towards unreliable suppliers. Therefore, it can be concluded that there are two planes on which trade-offs can be identified. First, there is a trade-off between cost and performance between both strategies. With redundancy being more reliable but more expensive as well. Second, there are trade-offs based on the supplier characteristics, and how they interact with the chosen policy method. It was observed that in with a backup supplier policy in place, the primary supplier needed to have at least moderate reliability for the policy to achieve good performance. Contrastingly, the backup supplier characteristics are less important under this policy. With the volume flexibility policy, a different relationship was noticeable towards supplier characteristics. Although, combining the most reliable suppliers did boast excellent results, it was more lenient towards the supplier characteristics. Meaning, that the combination of the least reliable suppliers did still result in relatively good performance.

Considering the supply- and environmental risks, the choice was made to decompose these risks further into 1) material scarcity risk, 2) production risk and 3) environmental risk. First, material scarcity is considered the biggest threat to the supply chain, and the backup supplier policy proved more effective in mitigating this risk because it acts as buffer capacity outside the organization. Volume flexibility was less capable of dealing with this risk. Although the capacity of the suppliers themselves acted as a buffer too it was less effective as a dedicated buffer. Therefore, it would be recommended to increase internal inventory sizes if material scarcity is anticipated. Second, both policies showed great capability of dealing with production risks. This is because these risks work independently on all suppliers, so the ability to shift product flow towards a second supplier almost completely mitigates this risk. This is a capability of both strategies, only volume flexibility cannot always redirect the complete flow but is dependent on the flexibility rate. Third, environmental risk poses a threat mainly to the lead times, which have an effect on the number of backorders. Both policies can adequately deal with this risk by geographically spacing their suppliers. This, effectively mitigates the risk although it must be stated that some environmental risks are system wide and not regional (For example, covid). This is not considered in the model but could be a potential liability leaving the internal capacity as only buffer.

This leads to the finding that both policies are worth considering and can be preferred dependent on the context, with both having their own supplier characteristic recommendations.

If opting for the backup supplier strategy: The primary supplier should meet at least moderate reliability constraints and with a strong preference for a close location. Backup suppliers are subject to fewer constraints, although geographical spacing and moderate to high capacity are advisable for further improved resilience.

If opting for the volume flexibility strategy: Both suppliers should be geographically spaced, due to higher tolerance for less reliable suppliers this approach can save costs by choosing cheaper suppliers. That said having at least one moderately reliable supplier is advisable when possible. Furthermore, anticipated material scarcity should be countered with an increase in the internal inventory

To conclude, In the literature, there is an increased awareness of the important role uncertainty plays in the ability of inputs to steer supply chains to their elected goals, thus challenging the regular mechanisms of order and control (Mackay et al., 2020). The relevance of proper supply chain risk management by implementing risk mitigating strategies exists in societal interest's organisations and competitive markets alike. Much of the literature emphasizes competitive markets and their underlying drivers with academics such as Ivanov, Hosseini and Kamalahmadi producing much reputable work. But beyond these markets, the horizon of SCRM has expanded with Day et al. (2012) exploring the benefits in humanitarian relief supply chains and with this thesis the military domain as well. Therefore, it can be stated that improved supply chain performance under uncertainty can yield not only financial benefits but social benefits as well by avoiding the negative impacts of disruptions (Mackay et al., 2020). Studying supply chain risk management and resilience is therefore a contribution academics can make towards preparing our organisations for the uncertainties the future brings in this increasingly complex world. Helping become less vulnerable to the adverse effects of globalisation and exogenous forces that would disrupt our society.

12.1 Recommendations for future research

There are several avenues that might be interesting for further study. First as shown in figure 5.1, the supply chain can be split up into the demand side, intra-organisational side and supply side. In this thesis, the emphasis was on the supply side but it would be very interesting to expand it towards the whole supply chain where there are more alternatives for both flexible and redundancy policies. With regard to this case, a model targeting demand forecasting would be interesting for the ministry and could be coupled with this model to create a more holistic approach. Looking at intra-organisational model expansions it is interesting to see how information spreads through the organisation and how it impacts decision-making. In Chapter 4 it became apparent that the formal policies describing the process of contracting suppliers are not made very explicit, from informal discussions it became clear that assortment managers are not entirely satisfied with current procedures. An avenue for further research could thus be an exploration of these practices and what the effects of alternatives would be. Another suggestion would be to look at multiple products, in this model a single product supply chain was analyzed. In a more holistic approach where multiple product categories, for example, all of Ekström's (2021) classifications, were considered in an assortment. This would allow exploration into tracking the operational capacity of the organisation where strategic products are more important than operational products. Adding, for this case it would also be interesting to study the effects of decentralization and maybe for products used by operational units what the effects of local sourcing would be.

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Appendix A

UNIQUE CHARACTERISTICS PRESENT IN DEFENCE ORGANISATIONS

As an extension to chapter 4, the unique characteristics that differentiate military supply chains from the ones present in competitive markets are described here.

Supply Chain Risk Management (SCRM) poses a challenge for all large organisations. When looking specifically at the Ministry of Defence, due to different system characteristics, traditional SCRM might not transition seamlessly into the military domain. This is due to the differences between military- and competitive market supply processes. Military logistics differ in several ways. For example, the fact that the ability to efficiently handle supply chain operations is decisive for the capabilities of operational units that are tasked with vital safety and security duties (Acero et al., 2019). Furthermore, it is unique in the sense that the required resources are part of varying geographical supply chains, specifics such as maximum lead times, unpredictable quantities and variable locations of deployment are all possibilities (Cohen, 2015). Lai (2003) identified five main characteristics where military supply chains differed from consumer supply: (1) A large number of different item types, (2) variable demand (3) supply management considering priority matters (urgency of need), (4) necessity of equipment and supply readiness and (5) different divisions with individual targets characterized by non- fixed locations. Lastly, I propose two additional, related, factors that play a distinctive role in the military domain. The first one, available funding, varies heavily per nation and determines what kind of policies are viable. Second, a different perception of competition is present in military organisations compared to traditional markets. In this section these characteristics are discussed and how they influence SCRM notions for the purposes of this thesis.

Wide variety of different item types in military inventory there is a very wide variety of different item types. Maintaining operational capacity is one of their key priorities. Therefore, items ranging from everyday necessities such as clothing and rations to specialized equipment are part of the organization's inventory. This led to the creation of an intricate classification system where all items are registered under specific categories (assortments). These different assortments still can carry well over a thousand different item types. In the case of the department of industrial substances, there are over 6000 articles held in inventory for which various supply strategies are employed, i.e., push or pull systems. Further complications can arise through legislative necessity because transporting industrial substances is bound by strict rules. Especially substances that are exclusively reserved for military use tend to have strict shipping procedures further complicating supply lines.

Variable demand Even though competitive market supply chains struggle with demand volatility as well. Military supply chains can experience even less predictable demand depending on geopolitical stability. For example, a car manufacturer can relatively accurately predict consumer demand on a timescale of a few months. In contrast, military demand for supplies can wildly change overnight in a far less predictable manner (Elvira et al., 2015). Military units can be called into operation in reaction to conflicts and/or calamities at a moment's notice. In this situation, more supplies will be required than anticipated. Furthermore, due to technological advancement, military equipment has grown far more complicated over the last decades. As a result, the number of maintenance and repair goods has increased immensely and the demand for them has become less predictable (Nour, 2017).

Priority matters within the military there is a standardized level of priority assigned to supplies. Priority is assigned by considering the 'urgency of need' which is determined by the appropriate military officer. This ability, potentially changing priorities, is something traditional supply chain management does not have to consider.

Maintaining operational capacity The great military powers must prepare their inventory for wartime demand. This is not the case in the Netherlands, or most of Europe. However, in a recent report, the Dutch Defence organisation has stated a preference for expanding their striking capabilities and to that end scale-up their inventory levels (Bijleveld, 2020). This overstocking requires a unique form of inventory management. As an example, the field rations held in inventory are far greater than the expected usage and due to expiration dates, operational units usually eat rations nearing the end of their shelf life.

Non-fixed locations within Defence organisations the location of operations can shift rapidly, when needed, units need to be able to get to an operation-ready level anywhere in the world in a relatively short time span. This means that supplies need to be capable of mobilization for those locations without having prior notice. This is mainly the distribution side of the logistic process. However, it overlaps with the supply side because of the benefits of alternate sourcing. As an example, the Dutch military has contracts with allied nations that allow them to source fuel in many places of the world. This has an obvious advantage over transporting fuel from a single source to all operation locations in the world.

Intra-organizational structure a characteristic in which military organisations differentiate themselves, is in the tendency to incorporate as much of the supply chain within their own organization. This is due, to their preference for independence. However, due to the complex nature of specialized equipment and some manufacturers that are too big to avoid, partners in the supply chain are inevitable. Another complication that arises due to the vast nature of the organisation, is that the visibility over the supply chain decreases. Meaning, that it becomes increasingly difficult for individuals within the organisation to keep track of the many processes related to the supply chain as it increases in size.

Competition In supply chain risk management literature, competitiveness is often named as driver for implementing policies (Shishodia et al., 2021). In traditional markets, the firm that handles the threat of disruption the most efficiently brings down its cost more and, therefore, has an edge over other firms in the market space. In the military domain, competition works differently, two military organisations do not compete in the same market space. That would be like the Dutch government hiring a foreign military because they can do the job at a better price. The price competition of regular markets does not hold for the military domain. The size of the budget is a political decision instead of being determined by supply and demand. The government assigns the tasks that the Ministry of Defence must be able to carry out and allocates a budget. the Ministry has the responsibility to perform those tasks to the best of its ability within the budget constraint. That is not to say that competition does not exist. On the contrary, technological and/or equipment competition is very important. Having the most advanced equipment is definitely a large advantage. However, that enters in the concept of deterrence. deterrence plays a big role in military thinking but for the purposes of this research, it is out of scope.
So, if competition is not the driver for supply chain risk management in the military domain, what is? And does it change the way the relevant SCRM literature should be interpreted? To answer these questions, the values underlying the driver must be reviewed. In a regular marketplace, firms can only exist if they generate income, to do so they must be competitive. the military branches exist because they safeguard values such as security and freedom. From this perspective, SCRM is important because it enables the military to better safeguard its values. The way this alters how the literature should be interpreted is thus a shift in the priority of values. Where literature values cost efficiency above continuity, this changes for military organisations because running on a budget deficit does not remove the need for the institution as it would do for a regular firm.

Funding uncertainty Within The Military domain, there is little visibility with regard to Return On Investment (ROI). This is because a big responsibility of the organization is being prepared for undefined events. Furthermore, militaries generally do not generate income and are completely dependent on government funding. A situation arises where the size of the budget as well as the location with the highest ROI are, to some extent, uncertain. This leads to circumstances that experience the same threat as common goods in liberal market models: 'tragedy of the commons.

Where divisions within the organisation start to behave strategically to safeguard their requirements at the expense of others. The result is that there are buying waves the moment funding becomes available instead of efficiently distributing resources.

Appendix B

DISCRETE EVENT SIMULATION MODEL IN SIMIO

In this appendix, the Discrete event simulation model used is introduced. The program used for the simulation is the SIMIO software package. Here a glimpse is given into the setup of the model. However, if understanding the model is the goal I recommend downloading it from the GitHub page (https://github.com/jvanwalsum/simio) and experimenting with the model yourself. This would provide a much better understanding of the model than an explanation in a text could. The intuitive nature of the program makes it easy to understand a pre-build model. Building a model from scratch in the software has proved more challenging.

Facility view In figure B.1 the facility view of the SIMIO model is shown. Here you see a front-end view of the simulation model. There are two model entities used in the model. The shipping entity travels across the time paths to the nodes which represent physical locations. The shipping entity contains the order quantity passed on to it by the different reorder processes. This same entity is thus used for the orders of the assortment inventory as well as the suppliers ordering raw materials. The product entity is a single unit of a product. In the EndProductionProcess suppliers turn raw materials into finished products, every unit is produced individually and the production time is drawn from a normal distribution.

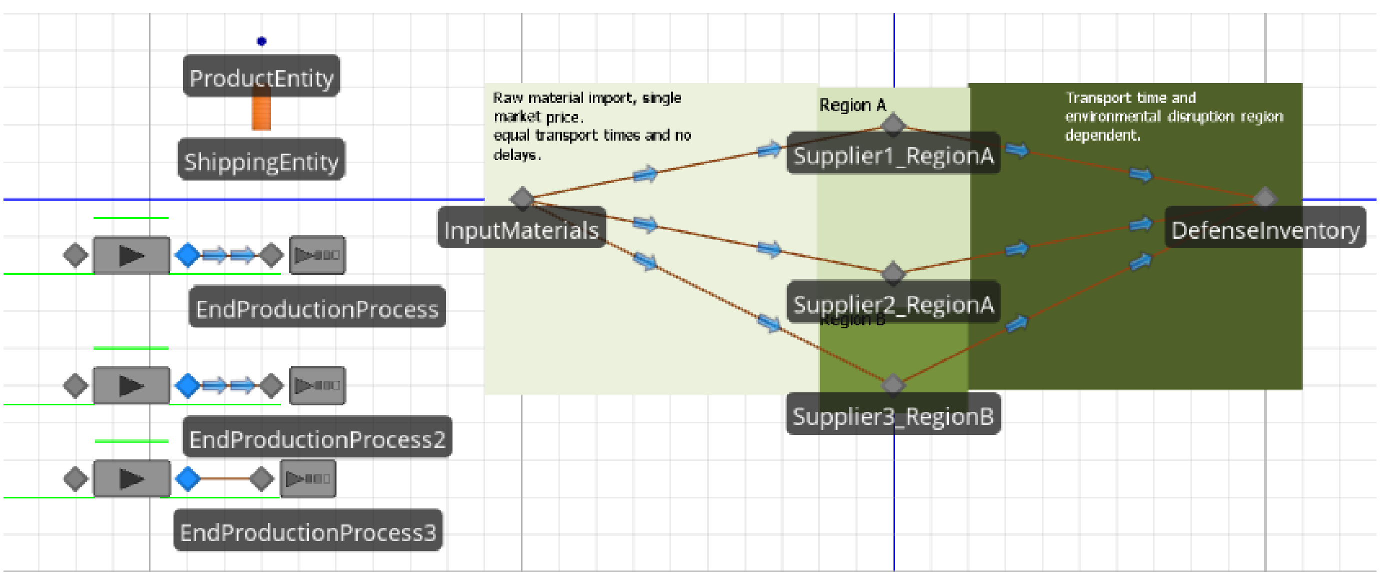

Figure B.1: Facility view SIMIO model

Definitions The nodes that are seen in the facility view each have material inventories linked to them. In figure B.2 this is seen in the definitions tab of the software. It can be seen that all nodes have inventories that can store ’finished goods’ or ’raw material’. The state statistic elements are used to determine the price of raw materials and keep track of how many times an order was not placed due to high prices. The timer elements are used to set off scheduled events.

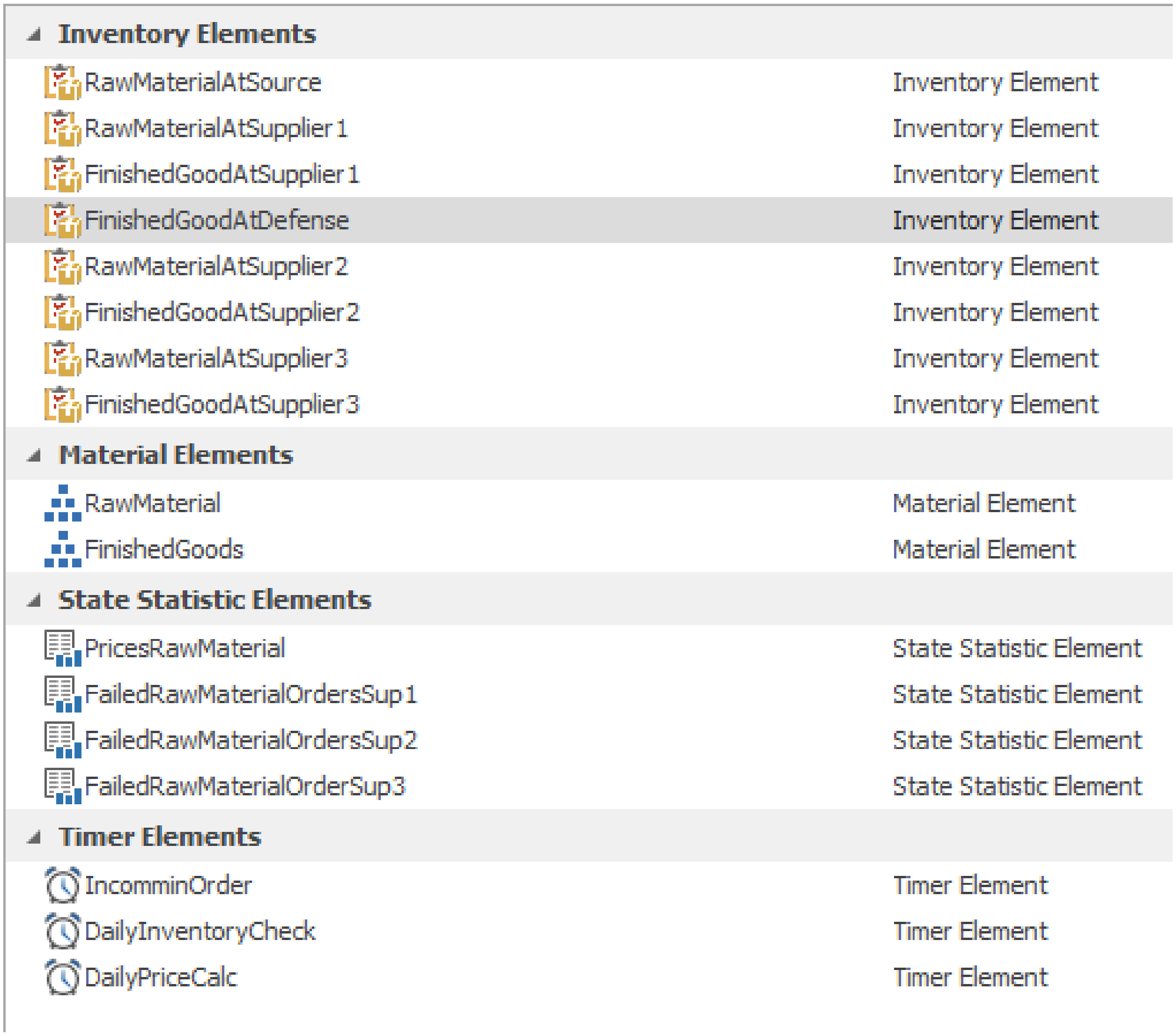

Figure B.2: Defined definitions in SIMIO

States In figure B.3 the model states are shown. These states are variables where information is stored either for response tracking or for the model to save values later needed in processes.

Name	Object Type
State Variables (Inherited)	
State Variables	
NumberOrders	Integer State Variable
OrderQuantityStorage	Integer State Variable
DefenseOrderCounter_supplier_1	Integer State Variable
ProductionOrderQuantityStorage_1	Integer State Variable
RawMaterialOrderQuantityStorage_1	Integer State Variable
RawMaterialPriceCalc	Real State Variable
FailedOrderRawMaterial1	Integer State Variable
DefenseOrderCounter_supplier_2	Integer State Variable
ProductionOrderQuantityStorage_2	Integer State Variable
RawMaterialOrderQuantityStorage_2	Integer State Variable
FailedOrderRawMaterial2	Integer State Variable
SplitOrder	Real State Variable
FailedOrderRawMaterial3	Integer State Variable
RawMaterialOrderQuantityStorage_3	Integer State Variable
ProductionOrderQuantityStorage_3	Integer State Variable
DefenseOrderCounter_supplier_3	Integer State Variable
OutstandingOrder	Boolean State Variable
EnvironmentalDisruptionA	Boolean State Variable
DisruptionChance	Real State Variable
temperoraryState1	Real State Variable
TotalUnitExpense	Real State Variable
DisruptionChanceB	Real State Variable
EnvironmentalDisruptionB	Boolean State Variable
Scarce1	Real State Variable
Scarce3	Real State Variable
Scarce2	Real State Variable

Figure B.3: Model states in SIMIO

Processes An example of a process in the model can be seen in figure B.4. This is the process which determines to which supplier an order placed by the assortment inventory goes. The three "decide" steps check which supplier is the primary and if they are able to deliver the ordered goods. If not, the backup supplier is selected. The "Consume" step then removes the finished goods from the supplier's inventory. Then a shipping entity is created, assigned a number of goods corresponding to the consumed amount and placed on the time path with destination assortment inventory.

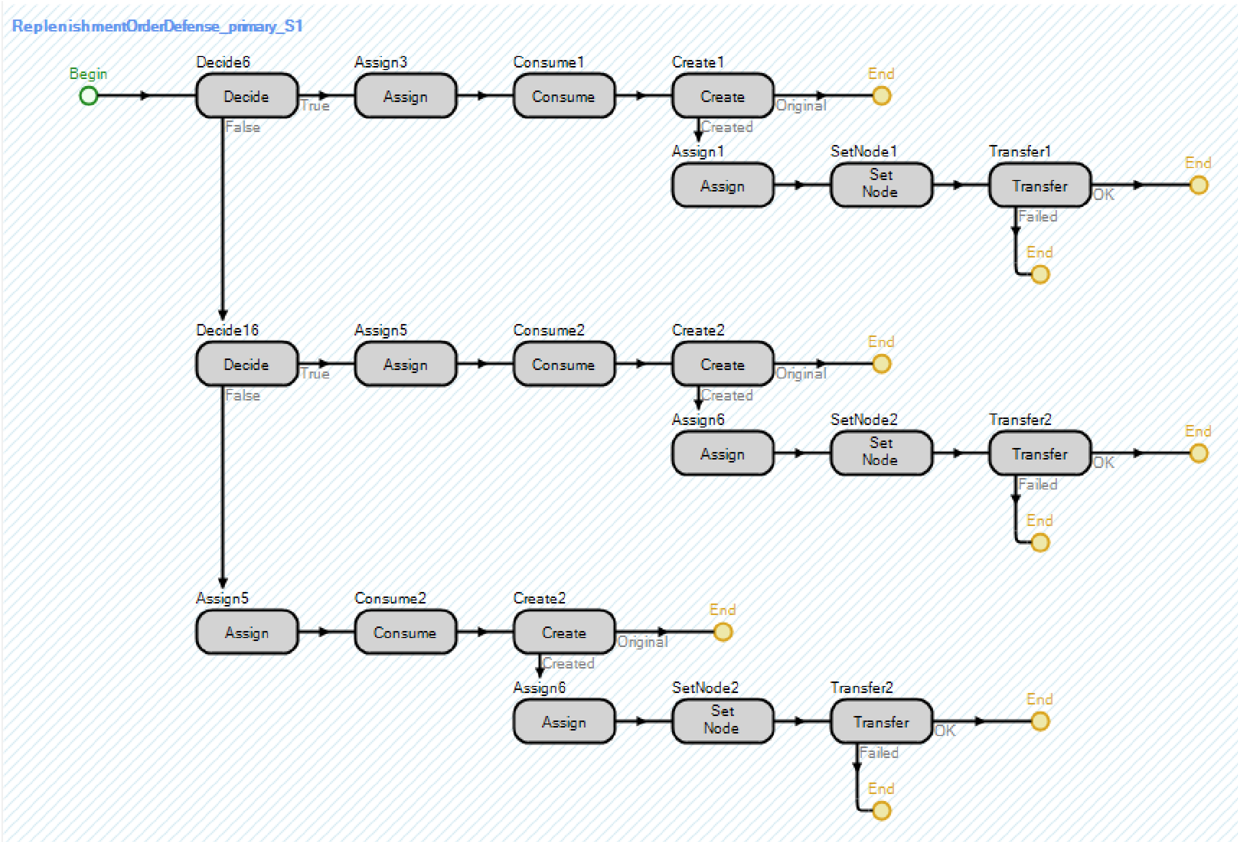

Figure B.4: Supplier selection process backup policy

Appendix C

EXTENSIVE RESULTS

Table have been reduced to crop for pdf, the full results can be found on my GitHub page (https://github.com/jvanwalsum/simio). The simulation model is uploaded as well for even more extensive data exploration.

Table C.1: Experiment 2: base scenario with disruptive forces

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S1 Low	AveregeQuantityInStock	202,261876	164,097596	278,301279	102,9367339
S1 Low	AverageLeadTime	172,0281718	171,5779961	176,2983144	166,00439
S1 Low	Costs	421400	420000	440000	400000
S1 Low	OrderFillRate	32,86329237	23,75	44,35483871	16,17647059
S1	AveregeQuantityInStock	227,295208	182,51617	303,9994498	116,4887192
S1	AverageLeadTime	174,5492229	173,1990361	180,1621887	168,4182517
S1	Costs	437675	437500	455000	420000
S1	OrderFillRate	37,51952683	30,21582734	49,6350365	18,24817518
S1 High	AveregeQuantityInStock	308,669508	282,3495449	446,7311789	157,9435329
S1 High	AverageLeadTime	174,4273187	174,5646174	178,6089203	168,7086916
S1 High	Costs	445050	450000	480000	420000
S1 High	OrderFillRate	51,88648244	46,08695652	77,69784173	31,2
S2 Low	AveregeQuantityInStock	224,2398005	198,8391528	310,3750221	127,7471907
S2 Low	AverageLeadTime	173,7064524	172,894835	180,3108935	166,9062892
S2 Low	Costs	338880	336000	352000	320000
S2 Low	OrderFillRate	37,29873136	34,19354839	52,25225225	18,75
S2	AveregeQuantityInStock	286,3875419	245,5832844	402,3351509	174,2524363
S2	AverageLeadTime	174,3301218	173,2441328	180,7415015	168,626897
S2	Costs	347340	350000	364000	336000
S2	OrderFillRate	47,79606198	45,57823129	66,66666667	29,16666667
S2 High	AveregeQuantityInStock	297,8774103	259,1566893	387,6408312	170,188301
S2 High	AverageLeadTime	175,4466653	174,8785283	180,4683942	168,9044744
S2 High	Costs	354000	360000	372000	336000
S2 High	OrderFillRate	49,51787853	46,77419355	64,46280992	29,03225806
S3 Low	AveregeQuantityInStock	166,7417924	149,0089908	221,8570409	108,8485715
S3 Low	AverageLeadTime	301,9894826	301,5038712	309,4565376	292,9151803
S3 Low	Costs	240600	240000	252000	228000
S3 Low	OrderFillRate	29,35583006	24,26470588	37,6	17,6
S3	AveregeQuantityInStock	182,0138062	155,0162931	217,8090418	122,5397967
S3	AverageLeadTime	318,2280718	315,5548297	328,8618532	306,9933138
S3	Costs	244440	241500	252000	241500
S3	OrderFillRate	32,51750364	27,77777778	41,37931034	20,51282051
S3 High	AveregeQuantityInStock	211,9732077	193,9746502	279,7853335	131,3691694
S3 High	AverageLeadTime	334,7805423	334,682234	344,6189677	325,0122585
S3 High	Costs	247950	252000	252000	243000
S3 High	OrderFillRate	38,74739488	34,84848485	51,35135135	25,19083969

Table C.2: Experiment 3: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S1 - S2 Low	NumberBackordered	10,93081576	4,656068106	6,698323464	2,738041351
S1 - S2 Low	Costs	484640	488000	516000	464000
S1 - S2 Low	AvarageQInStock	510,9427374	516,0363721	534,2965457	500,7676035
S1 - S2 Low	AvarageLeadTime	173,7541968	172,5543592	180,2387099	167,6210069
S1 - S2 Low	OrdersS3	0	0	0	0
S1 - S2 Low	OrdersS2	2,81	3	4	2
S1 - S2 Low	OrdersS1	20,98	21	22	20
S1 - S2 Low	OrderFillRate	90,68878021	92,59259259	94,26229508	89,74358974
S1 - S2	NumberBackordered	4,224813506	2,849534798	6,010944673	1,510234001
S1 - S2	Costs	491050	497000	528500	458500
S1 - S2	AvarageQInStock	559,7524665	554,5911541	575,990932	545,6407592
S1 - S2	AvarageLeadTime	176,5712799	175,4147748	182,3008095	171,0690567
S1 - S2	OrdersS3	0	0	0	0
S1 - S2	OrdersS2	2,72	3	4	2
S1 - S2	OrdersS1	24,91	25	26	24
S1 - S2	OrderFillRate	95,14911766	95,41984733	97,2027972	93,52517986
S1 - S2 High	NumberBackordered	1,887670102	0,83504051	2,338371317	0,213634083
S1 - S2 High	Costs	488130	486000	522000	456000
S1 - S2 High	AvarageQInStock	615,1708455	613,946281	631,5644312	601,5180062
S1 - S2 High	AvarageLeadTime	175,5340398	174,1186143	180,6779698	170,4337279
S1 - S2 High	OrdersS3	0	0	0	0
S1 - S2 High	OrdersS2	2,31	2	3	1
S1 - S2 High	OrdersS1	29,92	30	31	28
S1 - S2 High	OrderFillRate	97,72951018	98,30508475	99,17355372	96,92307692
S1 - S3 Low	NumberBackordered	11,82177061	10,71010721	15,78881628	6,134406873
S1 - S3 Low	Costs	471600	480000	500000	440000
S1 - S3 Low	AvarageQInStock	496,380781	494,140315	514,7937167	479,3139316
S1 - S3 Low	AvarageLeadTime	187,0731088	185,9194031	195,1435416	178,9958778
S1 - S3 Low	OrdersS3	2,64	2	4	1
S1 - S3 Low	OrdersS2	0	0	0	0
S1 - S3 Low	OrdersS1	21,01	21	22	20
S1 - S3 Low	OrderFillRate	88,94165815	89,3129771	92,1875	86,33093525
S1 - S3	NumberBackordered	7,241971175	5,522769487	10,10909581	2,951460764
S1 - S3	Costs	482125	472500	507500	455000

Table C.2: Experiment 3: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S1 - S3	AvarageQInStock	540,2390896	543,8033836	559,2261025	519,6363476
S1 - S3	AvarageLeadTime	190,0303539	189,9012038	198,6201669	180,8575165
S1 - S3	OrdersS3	2,65	3	3	2
S1 - S3	OrdersS2	0	0	0	0
S1 - S3	OrdersS1	25,07	25	26	24
S1 - S3	OrderFillRate	93,59131604	94,24460432	96,06299213	91,59663866
S1 - S3 High	NumberBackordered	3,322567887	2,406676076	5,040694809	0,477975189
S1 - S3 High	Costs	481350	480000	510000	450000
S1 - S3 High	AvarageQInStock	598,1714748	598,9740136	613,4708246	578,8448124
S1 - S3 High	AvarageLeadTime	186,0450937	185,4298175	191,2286855	178,009557
S1 - S3 High	OrdersS3	2,35	2	3	1
S1 - S3 High	OrdersS2	0	0	0	0
S1 - S3 High	OrdersS1	29,91	30	31	28
S1 - S3 High	OrderFillRate	96,7101555	97,54098361	98,51851852	95,04132231
S2 - S1 Low	NumberBackordered	10,89278852	4,714762739	7,950446671	3,024926283
S2 - S1 Low	Costs	409640	412000	436000	376000
S2 - S1 Low	AvarageQInStock	514,6392496	521,4778296	537,0794984	500,2197097
S2 - S1 Low	AvarageLeadTime	173,1649354	171,7921344	177,3791304	167,4689789
S2 - S1 Low	OrdersS3	0	0	0	0
S2 - S1 Low	OrdersS2	21,25	21	22	20
S2 - S1 Low	OrdersS1	2,63	3	3	2
S2 - S1 Low	OrderFillRate	91,0827262	92,48120301	94,57364341	90,4
S2 - S1	NumberBackordered	11,96931829	2,162652437	5,14109065	1,02866689
S2 - S1	Costs	415135	409500	451500	374500
S2 - S1	AvarageQInStock	549,9434175	564,4036674	582,2395219	543,2691183
S2 - S1	AvarageLeadTime	173,6815626	172,5384856	179,8306408	168,0417764
S2 - S1	OrdersS3	0	0	0	0
S2 - S1	OrdersS2	24,99	25	26	24
S2 - S1	OrdersS1	2,8	2	4	1
S2 - S1	OrderFillRate	93,0819374	95,83333333	97,34513274	93,83561644
S2 - S1 High	NumberBackordered	5,954038604	1,009720594	4,062444236	0,453823802
S2 - S1 High	Costs	413250	414000	444000	381000
S2 - S1 High	AvarageQInStock	597,4886247	613,8522298	625,9595245	597,6579677
S2 - S1 High	AvarageLeadTime	175,5511602	174,2664547	180,6442364	169,5163358

Table C.2: Experiment 3: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S2 - S1 High	OrdersS3	0	0	0	0
S2 - S1 High	OrdersS2	29,88	30	31	29
S2 - S1 High	OrdersS1	2,76	3	4	1
S2 - S1 High	OrderFillRate	95,58367239	97,65625	99,06542056	96
S2 - S3 Low	NumberBackordered	10,90632287	9,568713287	15,34343924	5,953771567
S2 - S3 Low	Costs	390000	392000	416000	372000
S2 - S3 Low	AvarageQInStock	499,4309725	502,1117303	518,5343019	480,3206908
S2 - S3 Low	AvarageLeadTime	184,4773447	183,3836145	189,8900626	178,3841519
S2 - S3 Low	OrdersS3	2,59	3	3	2
S2 - S3 Low	OrdersS2	21,35	21	22	21
S2 - S3 Low	OrdersS1	0	0	0	0
S2 - S3 Low	OrderFillRate	89,6626758	90,51094891	92,30769231	86,66666667
S2 - S3	Costs	392700	388500	416500	367500
S2 - S3	OrdersS3	2,63	3	4	1
S2 - S3	OrdersS2	24,84	25	26	24
S2 - S3	OrdersS1	0	0	0	0
S2 - S3	AvarageQInStock	546,3131624	547,1916294	566,2705893	530,402888
S2 - S3	NumberBackordered	7,216306118	6,354581073	9,646023287	2,724283515
S2 - S3	AvarageLeadTime	186,4293749	187,4437819	193,187169	179,7373236
S2 - S3	OrderFillRate	93,57926517	94,24460432	96,21212121	91,85185185
S2 - S3 High	Costs	390870	390000	423000	363000
S2 - S3 High	OrdersS3	2,57	2	4	1
S2 - S3 High	OrdersS2	29,56	30	31	28
S2 - S3 High	OrdersS1	0	0	0	0
S2 - S3 High	AvarageQInStock	593,0039351	594,9095049	615,2073592	570,7683459
S2 - S3 High	NumberBackordered	4,096611865	2,593840156	5,761090006	1,335912177
S2 - S3 High	AvarageLeadTime	187,8236347	186,2025587	195,5933458	178,9411952
S2 - S3 High	OrderFillRate	95,93422842	96,32352941	97,95918367	94,21487603
S3 - S1 Low	Costs	336880	336000	368000	296000
S3 - S1 Low	OrdersS3	20,54	21	21	20
S3 - S1 Low	OrdersS2	0	0	0	0
S3 - S1 Low	OrdersS1	3,47	4	5	2
S3 - S1 Low	AvarageQInStock	347,7556243	353,0138144	374,729113	335,6745694
S3 - S1 Low	NumberBackordered	65,31827286	56,92042108	70,20221868	44,02908245

Table C.2: Experiment 3: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S3 - S1 Low	AvarageLeadTime	283,0265484	279,8389404	293,1891985	271,6000373
S3 - S1 Low	OrderFillRate	68,09967211	68,53146853	72,95081967	65,2173913
S3 - S1	Costs	337050	336000	374500	301000
S3 - S1	OrdersS3	23,49	24	24	23
S3 - S1	OrdersS2	0	0	0	0
S3 - S1	OrdersS1	4	4	6	2
S3 - S1	AvarageQInStock	368,3291523	383,016809	403,3336563	362,5514548
S3 - S1	NumberBackordered	59,5710326	39,80950554	52,06074409	31,03576607
S3 - S1	AvarageLeadTime	298,3381292	296,1265216	310,5754509	287,7580461
S3 - S1	OrderFillRate	71,40301923	74,10071942	78,4	70
S3 - S1 High	Costs	331350	327000	366000	303000
S3 - S1 High	OrdersS3	28,06	28	29	27
S3 - S1 High	OrdersS2	0	0	0	0
S3 - S1 High	OrdersS1	4,05	4	5	2
S3 - S1 High	AvarageQInStock	415,7329174	422,5307822	440,744279	405,0671388
S3 - S1 High	NumberBackordered	32,27148028	26,63390696	34,57111678	20,16971169
S3 - S1 High	AvarageLeadTime	315,1394117	315,8929221	327,0834239	306,1378801
S3 - S1 High	OrderFillRate	79,27669206	80	83,33333333	76,59574468
S3 - S2 Low	Costs	329640	324000	360000	288000
S3 - S2 Low	OrdersS3	20,45	21	21	20
S3 - S2 Low	OrdersS2	3,68	3	5	2
S3 - S2 Low	OrdersS1	0	0	0	0
S3 - S2 Low	AvarageQInStock	348,471732	353,068085	371,5218369	334,4110243
S3 - S2 Low	NumberBackordered	59,67435054	56,42912808	65,39543919	42,79179045
S3 - S2 Low	AvarageLeadTime	283,0624232	282,5001805	293,6845066	270,6404452
S3 - S2 Low	OrderFillRate	68,49923694	68,46153846	72,79411765	65,44117647
S3 - S2	Costs	324135	336000	367500	294000
S3 - S2	OrdersS3	23,67	24	24	23
S3 - S2	OrdersS2	3,88	4	5	2
S3 - S2	OrdersS1	0	0	0	0
S3 - S2	AvarageQInStock	388,4157338	387,4297442	404,0589054	372,7359381
S3 - S2	NumberBackordered	38,88460883	36,89794454	44,58570855	30,4581996
S3 - S2	AvarageLeadTime	294,7135715	293,0246668	303,8967403	282,8492974
S3 - S2	OrderFillRate	75,73306747	76,33587786	78,86178862	72,78911565

Table C.2: Experiment 3: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S3 - S2 High	Costs	317250	315000	342000	288000
S3 - S2 High	OrdersS3	27,82	28	29	27
S3 - S2 High	OrdersS2	4,01	4	5	2
S3 - S2 High	OrdersS1	0	0	0	0
S3 - S2 High	AvarageQInStock	421,9706539	422,9326928	438,2428339	404,9917099
S3 - S2 High	NumberBackordered	27,53804119	26,21201269	34,47820846	20,64129829
S3 - S2 High	AvarageLeadTime	316,0411644	317,5226547	325,4809797	306,4956799
S3 - S2 High	OrderFillRate	80,41358965	80,14705882	83,33333333	76,77419355

Table C.3: Experiment 4: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S1 - S2 Low	FailedRawOrder3	0	0	0	0
S1 - S2 Low	FailedRawOrder2	1,84	2	3	0
S1 - S2 Low	FailedRawOrder1	0,55	0	1	0
S1 - S2 Low	OrdersS3	0	0	0	0
S1 - S2 Low	OrdersS2	23,85	24	26	22
S1 - S2 Low	OrdersS1	23,85	24	26	22
S1 - S2 Low	Costs	427180	432000	450000	396000
S1 - S2 Low	NumberBackOrdered	4,362702006	3,13155675	5,466249912	1,555709501
S1 - S2 Low	AvarageQInStock	512,5414904	514,6276965	537,1693169	491,5265948
S1 - S2 Low	AvarageLeadTime	181,544399	180,2239323	188,5972713	172,2087266
S1 - S2 Low	OrderFillRate	92,95696472	93,49593496	95,57522124	91,09589041
S1 - S2	FailedRawOrder3	0	0	0	0
S1 - S2	FailedRawOrder2	1,44	1	2	0
S1 - S2	FailedRawOrder1	0,45	0	1	0
S1 - S2	OrdersS3	0	0	0	0
S1 - S2	OrdersS2	27,54	28	29	26
S1 - S2	OrdersS1	27,52	28	29	26
S1 - S2	Costs	431742,5	441000	456750	409500
S1 - S2	NumberBackOrdered	2,483802679	1,298576721	3,376077082	0,569311773
S1 - S2	AvarageQInStock	555,4625456	556,2717936	572,8158208	538,3761809
S1 - S2	AvarageLeadTime	181,6433195	182,1097272	189,4222486	171,4662331
S1 - S2	OrderFillRate	96,536053	97,10144928	98,27586207	94,92753623

Table C.3: Experiment 4: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S1 - S2 High	FailedRawOrder3	0	0	0	0
S1 - S2 High	FailedRawOrder2	1,6	1	2	0
S1 - S2 High	FailedRawOrder1	0,36	0	0	0
S1 - S2 High	OrdersS3	0	0	0	0
S1 - S2 High	OrdersS2	32,39	32	34	31
S1 - S2 High	OrdersS1	32,39	32	34	31
S1 - S2 High	Costs	435705	432000	459000	405000
S1 - S2 High	NumberBackOrdered	1,809479825	0,711898917	2,377064142	0,177940807
S1 - S2 High	AvarageQInStock	605,4000738	608,2270903	619,7581393	584,2517964
S1 - S2 High	AvarageLeadTime	184,6738969	184,6812584	192,4639241	176,4101632
S1 - S2 High	OrderFillRate	97,94431187	98,36065574	99,23664122	97,14285714
S1 - S3 Low	FailedRawOrder3	3,99	4	6	2
S1 - S3 Low	FailedRawOrder2	0	0	0	0
S1 - S3 Low	FailedRawOrder1	0,36	0	1	0
S1 - S3 Low	OrdersS3	23,88	24	25	22
S1 - S3 Low	OrdersS2	0	0	0	0
S1 - S3 Low	OrdersS1	23,88	24	25	22
S1 - S3 Low	Costs	378360	378000	400000	352000
S1 - S3 Low	NumberBackOrdered	11,74719703	9,615667296	16,14535189	6,506097155
S1 - S3 Low	AvarageQInStock	399,893773	399,6587714	417,5842583	378,0499073
S1 - S3 Low	AvarageLeadTime	278,2166185	277,5804104	286,4271094	269,8334644
S1 - S3 Low	OrderFillRate	85,71484597	86,50793651	89,6	83,05084746
S1 - S3	FailedRawOrder3	4,34	4	6	2
S1 - S3	FailedRawOrder2	0	0	0	0
S1 - S3	FailedRawOrder1	0,44	0	1	0
S1 - S3	OrdersS3	27,72	27	29	26
S1 - S3	OrdersS2	0	0	0	0
S1 - S3	OrdersS1	27,72	27	29	26
S1 - S3	Costs	384947,5	378000	400750	364000
S1 - S3	NumberBackOrdered	6,541338733	5,279092399	8,727875216	3,447091017
S1 - S3	AvarageQInStock	447,5877803	446,1174324	465,3156386	429,7033984
S1 - S3	AvarageLeadTime	286,4584459	286,399375	294,8758149	278,6752825
S1 - S3	OrderFillRate	91,0644831	91,8699187	93,93939394	88,52459016
S1 - S3 High	FailedRawOrder3	4,09	4	6	2

Table C.3: Experiment 4: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S1 - S3 High	FailedRawOrder2	0	0	0	0
S1 - S3 High	FailedRawOrder1	0,52	0	1	0
S1 - S3 High	OrdersS3	32,34	32	35	30
S1 - S3 High	OrdersS2	0	0	0	0
S1 - S3 High	OrdersS1	32,34	32	35	30
S1 - S3 High	Costs	384525	384000	415500	360000
S1 - S3 High	NumberBackOrdered	4,024096464	3,196544856	5,629955696	1,718876356
S1 - S3 High	AvarageQInStock	487,7927055	486,6019181	509,2297811	471,5279171
S1 - S3 High	AvarageLeadTime	298,3377824	297,831983	306,4532039	289,2705296
S1 - S3 High	OrderFillRate	93,98046329	94,20289855	96,42857143	91,60839161
S2 - S3 Low	FailedRawOrder3	3,96	3	6	2
S2 - S3 Low	FailedRawOrder2	1,65	1	3	0
S2 - S3 Low	FailedRawOrder1	0	0	0	0
S2 - S3 Low	OrdersS3	24,25	24	26	22
S2 - S3 Low	OrdersS2	24,25	24	26	22
S2 - S3 Low	OrdersS1	0	0	0	0
S2 - S3 Low	Costs	335420	336000	364000	308000
S2 - S3 Low	NumberBackOrdered	12,84924651	11,87115842	16,40495074	8,616725146
S2 - S3 Low	AvarageQInStock	402,8926216	404,0936925	423,1398189	381,8952921
S2 - S3 Low	AvarageLeadTime	276,0309271	276,5047701	283,4931317	267,2434501
S2 - S3 Low	OrderFillRate	85,31364576	85,81560284	88,46153846	82,17054264
S2 - S3	FailedRawOrder3	3,98	4	5	2
S2 - S3	FailedRawOrder2	1,94	2	3	0
S2 - S3	FailedRawOrder1	0	0	0	0
S2 - S3	OrdersS3	28,3	28	30	27
S2 - S3	OrdersS2	28,3	28	30	27
S2 - S3	OrdersS1	0	0	0	0
S2 - S3	Costs	343437,5	343000	362250	325500
S2 - S3	NumberBackOrdered	7,068822583	5,83623351	9,848616843	3,458755062
S2 - S3	AvarageQInStock	442,7271674	447,9144833	465,7874892	420,3323918
S2 - S3	AvarageLeadTime	285,209754	285,1398347	294,3394367	276,7169624
S2 - S3	OrderFillRate	90,6889066	91,21621622	93,43065693	88,4057971
S2 - S3 High	FailedRawOrder3	3,96	4	6	2
S2 - S3 High	FailedRawOrder2	1,81	2	3	0

Table C.3: Experiment 4: Extensive results

Scenario	Response	Mean	Median	Upper Percentile	Lower Percentile
S2 - S3 High	FailedRawOrder1	0	0	0	0
S2 - S3 High	OrdersS3	32,2	32	34	30
S2 - S3 High	OrdersS2	32,2	32	34	30
S2 - S3 High	OrdersS1	0	0	0	0
S2 - S3 High	Costs	334905	331500	357000	315000
S2 - S3 High	NumberBackOrdered	3,802537045	3,220291321	4,534106508	1,789482212
S2 - S3 High	AvarageQInStock	490,0047665	492,4660857	512,5588416	467,9154857
S2 - S3 High	AvarageLeadTime	297,5948704	296,8800962	304,9842628	289,2817577
S2 - S3 High	OrderFillRate	94,27691575	94,65648855	96,2962963	92,59259259

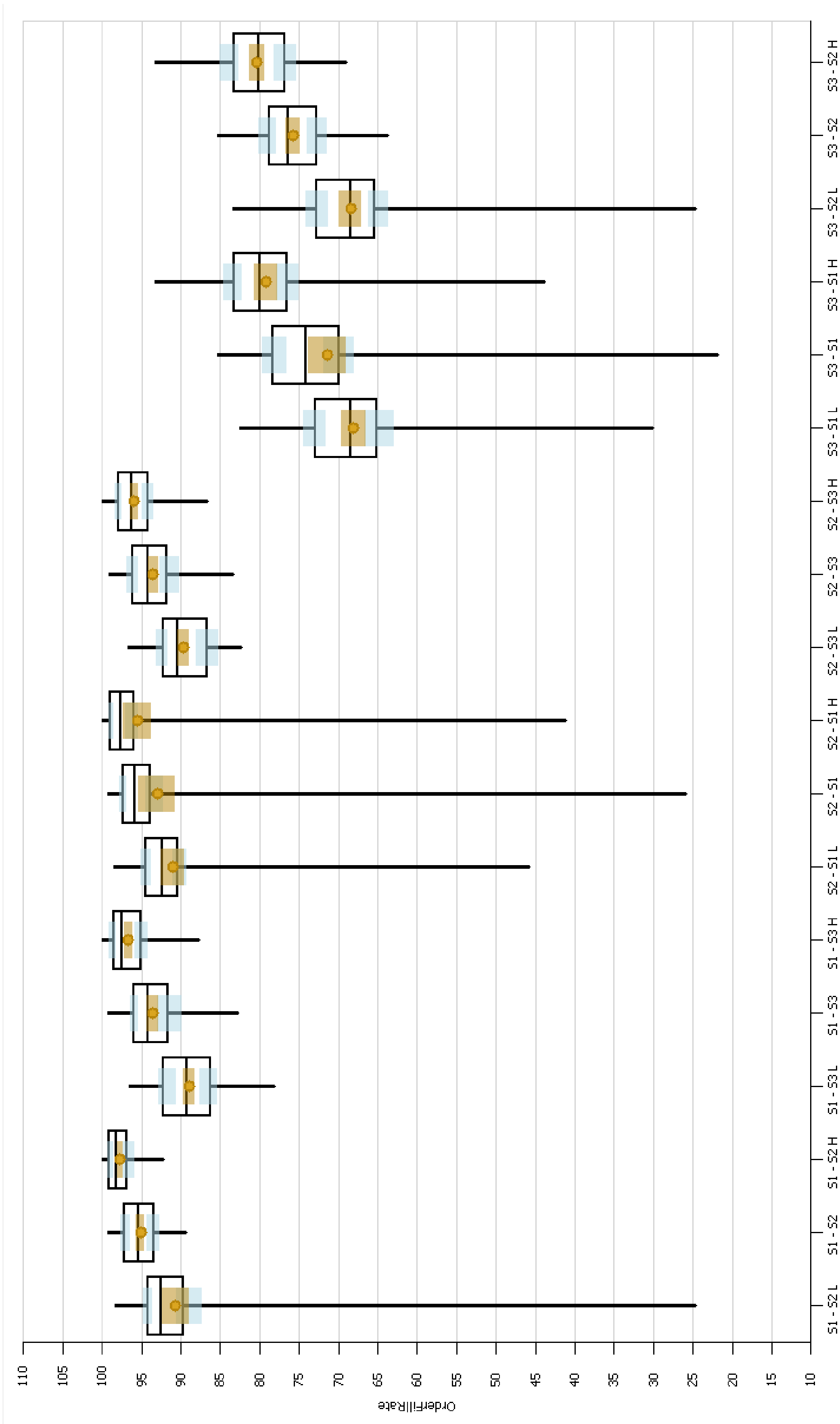

Figure C.1: Experiment 3: Order fill rate all scenarios

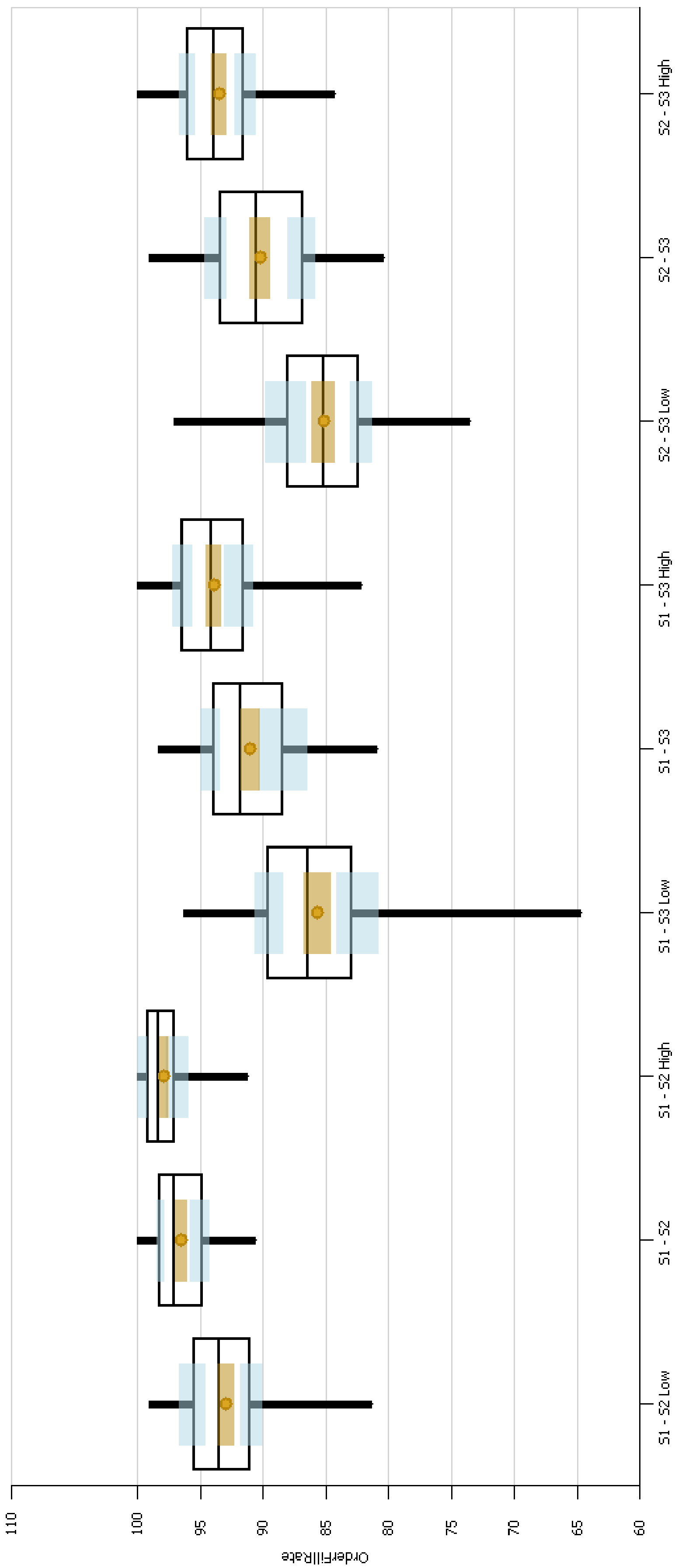

Figure C.2: Experiment 4: Order fill rate all scenarios