Intra-organizational Supply Chain dynamics: An Agent-Based Modelling approach

A case study on the supply chain of bicycles within the Netherlands armed Forces.

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by

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https://github.com/ChrobGort/Master_Thesis

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Preface

This research finalizes my education at the faculty of Technology Policy and Management and the TUDelft. During my studying career I found out what goes into policy analysis from a combination of technical and social perspectives. Starting at the bachelor course ”solving complex problems” and to finish in master courses such as ”simulation masterclass” and ”advanced agent-based modelling”. I think I have chosen the right study.

Quite a journey it has been. During highschool, I went to 3 open days of the TUDelft. Other universities did not seriously come to mind and the TUDelft was always the dream. However, doubts arose; Am I good enough at math? What if I don’t make it? Well, here I am. But, I most certainly could not have done it alone.

Thank you Tina, for being my first supervisor and always quickly responding to questions I had. I remember when you made time for me even during your vacation in Norway. Thank you Jan, for being my second supervisor and providing valuable feedback.

Thanks to the persons at the Ministry of Defense for guiding me as well. Patrick, thank you for the many meetings we had and for providing me with exactly the contacts I needed within Defense. Eline, thank you for helping me start up this research project and being involved during the whole process. You also helped in being persistent in the beginning, while finding a suited project. Albert, thanks for your perspectives on my research and your insights into the complexity of policy within Defense.

Not only have I been helped content wise, but also mentally by my friends and family. I would like to thank my parents. Without your upbringing I would not have had the foundation from which I could finish this Thesis. I would like to thank my brother and sisters for always believing in me. I might have hided some struggles and the input from your perspectives might have seemed trivial, but your kind words always gave me the energy and confidence I needed. Not in the least I would like to thank my friends from the Adamshofstraat, highschool, C.S.R. and study.

I am grateful for having had the opportunity to follow this education and learning the things I did. Being born in the right country comes with its perks. I very much hope and look forward to contribute to society using the knowledge I gathered.

I hope you enjoy reading my thesis.

C. T. Gorter
Rotterdam, October 2021

Executive Summary

One of the sustainable development goals of the United Nations aims at keeping peace and achieving safety and security in the world. Defense organizations are key in achieving these goals. However, government spending on Defense within the Netherlands is lacking, which causes shortages in budgets. These shortages cause one of the goals of Defense to be: improve the logistical chain. Good supply strategy that can improve the logistical chain involves taking into account the complexity that a specific good is situated in. Such complexity can come from the heterogeneity between agents, even in the same organization, and subjective behavior based on imperfect information. This research takes bicycles as a use case in order to see how to improve the supply chain system. The following main research question is identified, which is central in this research.

> What are the effects of novel policies on the functioning of intra-organizational supply chain business processes, while taking into account the behavior and heterogeneity between key actors?

Aside from the goals for the use case of bicycles, the aim was also to fill the knowledge gap of analyzing an intra-organizational, multi-structural supply chain system. The method used to fill the knowledge gap and gain an answer on the research question is Agent-Based Modelling, combined with an exploration approach using the Exploratory Modelling and Analysis (EMA) workbench. To accurately conceptualize the model, multiple interviews were held with actors in the bicycle supply chain. Also, data was gathered on the current functioning of the supply chain. Policy documents helped in understanding the formal structure of the supply chain and the interacting processes.

The system consists of agents and interactions between those agents on the different interdisciplinary structures. The structures relevant in this research are the physical distribution structure, financial structure, information structure and management structure. The distribution structure is at the heart of the system, which is for the most part handled by the external supplier. Within Defense, the management structure keeps oversight and intervenes when necessary. Information is necessarily shared between structures and is defined as the information structure. Budgetary constraints are determined in the financial structure, which in turn limits the budgets of procurement.

The current bicycle supply chain is ”pull” focused in which the End-User have the initiative for order creation, and thus ”pulling” the bicycles through the chain. All information on orders is therefore ”pushed” from the End-User to the facility company or supplier, creating a loop of information and goods. The driver of the system is demand of the End-User, to which the End-User creates orders containing the most important information. This information entails standard order information, but also the amount of justification. Justification can shortly be defined as the argumentation behind the order, i.e. why the End-User needs the bicycles.

The concepts are implemented in an Agent-Based Model, using decision moments and order information. The most important KPIs were ”effort” of the different agents, which is calculated by adding effort ”points” for each action an agent takes. Effort in the end shows how much actions each agent has to take to ensure the whole supply chain keeps functioning adequately. Using this model, differences in process effort can be shown with varying policies and uncertainties.

The base case result, without any policy or uncertainty variation, shows a large variance in outcomes. Multiple dynamics are the expected cause of this variance, but primarily the sequential nature of the agent processes. If the processes are not aligned at every decision made by agents, such extra variance and unpredictability in the behavior is seen. A combination of high variance in base case and low amount of repetitions makes the results less robust.

The results of the model run via EMA workbench gave insight into promising policies and determining uncertainties. Both predictive replacements and willingness to share information were promising policies, but do require a trade-off. The uncertainty in demand and supply greatly influenced the effort required of the different agents.

Practical implications for practitioners are the following. Choices have to be made in what found important within the supply chain. Choices on effort distributions versus waiting time for end-users for

example. One must also take into account the long term visions of Defense with regards to the goals of the organization as awhole. If adaptability is most important, more investments must be made in opening up the processes ofDefense with regards to outsourcing. For example within Finance and Control, how can their processes be simplified and decrease their effort? The used simulation methodology in this research is a novel approach to investigate complex but practical problems occurring within Defense's processes. However, hurdles in using this methodology were encountered. Recommendations to overcome these are establishing a clear pragmatic goal and exploring all the processes involved before implementing a simulation model or looking to explain quantified performance indicators.

Theoretical implications are the following. Analyzing the intra-organizational supply chain within Defense showed that most of the intra-organizational system structures are on the financial and management levels. Only a limited amount of physical distribution was present within the use-case. This moved the supply chain problem space from a classic distribution network perspective to a more process oriented perspective. In general, intra-organizational supply chain research would benefit from a more process oriented perspective according to this research. True implementations of policy directions are required before the effectiveness of the method in a practical sense can be confirmed. Limitations of simulation approaches to business process analysis are found within the specific application of the Business Process Model Notation method conceptualization method combined with agent-based modelling. The main limitation originates from the use of agent-based modelling for business processes. The process oriented and order-centric nature required extensive modelling. Generalizing of the results goes as far as goods that have the same classification. For this, one can use sector specific or generic portfolio purchasing models that meet the requirements of the problem owner.

Limitations of this research consist of three points: Effort as KPI, run time and extrapolation. Effort is ambiguous which reduces clarity on what it represents, but it also facilitates comparisons between effort of different agents. Also, it can arguably facilitate the correct external view on the results. The relatively long run time of the model prevented extensive experiment testing and sufficient repetitions,reducing accurateness of the results. Extrapolating the findings to supply chain of other goods must be proceeded with caution, as the model is conceptualized towards that of bicycles.

Further research might investigate the possibility of extrapolation to other supply chains, as it is currently unclear how other supply chains within defense compare. Also, the structure considerations could be expanded, especially the geographical structure. Involving distances might make comparison to other goods easier as well. Finally, uncertainty considerations can be expanded past demand and supply. Geographical aspect implementation would for example facilitate the understanding of international uncertainty impacts.

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1 Introduction

One of the sustainable development goals of the United Nations is aimed at keeping peace and achieving safety and security in the world (United Nations, 2021). This goal requires resolving armed conflict by using peacekeeping military power. Military organizations in a broad sense do more than solely engaging in armed conflict, such as aiding in humanitarian disasters. Of course, one of the primary functions is protecting the homeland from which a military originates. Optimal functioning of a military power is therefore key for every nation. Especially with the tensions between superpowers the US and China rising and the Middle East being unstable. With these tensions, uncertainty about the NATO alliance has also increased significantly in the past years. The views on the future and goals that nations have of NATO are diverging (Heath, 2019).

The European Union focuses on achieving collaboration among its member states in order to be less dependent on external parties, such as the US, and foster own military integration efforts. The PESCO project is such an effort, which aims to increase collaboration between EU member states that are willing to participate. This way, capabilities are improved when executing worldwide missions in EU, UN or NATO context. However, the NATO alliance requests cannot always be fulfilled by the Netherlands armed Forces (from hereinafter denoted as "Defense"), which means we are mostly profiting instead of contributing accordingly (Boersema and Zuidervaart, 2021). Clearly, reforms between Defense capabilities and goals are happening and the Netherlands as a member state should not lag behind.

A report by the Algemene Rekenkamer (2018) shows how the Defense mission in Mali was executed and where problems arose. They conclude that there was to little attention to the actual preparedness for the Mali mission. To much reliance was consequently put on the improvisation capability of Defense to compensate for the lack of preparedness. The "can do" mentality of the Defense in this case became a liability instead of a strong point.

Flexible intervention capability is one of the main pillars of change in the Defense vision (Ministerie van Defensie, 2020). In this vision a greater flexibility and adaption power is wished for Defense by collaborating with non-military organizations and private partners to stay on top of current developments and be able to switch between parties quickly. A balance needs to be found between outsourcing activities and having the required knowledge in-house.

The current management of most of Defense's logistics is done through Assortment Wise Operations (AGW) which is a category-based supply management system. Within the AGW, goods are categorized according to market characteristics, needed expertise and the ability to recognize the product in the category. These decision rules of categorizing goods is quite arbitrary when viewed from the perspective of "supply strategy", as first described by Kraljic (1983). Supply strategy involves taking into account the complexity that the article is situated in.

One of the causes of a lack of preparedness lies in the budgetary constraints. The Dutch government has been investing below the NATO norm of 2% of BBP in the Defense force in the past years. The Dutch welfare state and Dutch constitution could explain why political parties prioritize welfare and social security over Defense investments (Roddenhof, 2017). As a result, Defense is struggling with a financial shortage. There is a shortage of 50 full-time equivalent (fte) in the "Defensie Ondersteuningscommando" (DOSCO) which is involved in supplying different kind of facilities to defense ranging from food to personnel services. Across the whole of Defense, only 72% of supplies was received in time and in the right quantity.

These shortages cause one of the goals of the Defense to be: improve the logistical chain. Improving on this area could go hand in hand with the Although logistics originates from the military, business actors have surpassed military logistics management in effectiveness since the second world war (Rutner et al., 2012). With insufficient budget and more demanding mission pressure, there is a growing pressure on the Defense to achieve more with less. Therefore, creative solutions within logistics management are required.

To conclude, the problem central in this research is the following. Shortages within Defense regarding personnel and budgets call for a more efficient and thought trough design of the supply chain for different goods, in order to save money and effort. The design needs to be improved not only in the current circumstances, but also taking into account supply and demand uncertainties using novel policy implementations. Appropriate methodology providing insight in the current organizational complexities is required to anticipate the effectiveness of policy implementations.

2
Literature review

This chapter will explore the research gap in current supply chain literature and in the methodologies used for the analysis of supply chains. First the supply chain system is defined by its resolution, structure and accompanying worldview. After this, the intra-organizational resolution is explained and business processes perspective is used to define intra-organizational supply chains. Finally the research gaps are articulated that this thesis aims to fill.

2.1. The supply chain as a complex adaptive system

The ground laying work by Choi et al. (2001) identify modern supply chains as complex adaptive systems, in which the dynamics of the supply chain is seen as emergent behavior. They explain that supply chains are complex from a top-down point of view because, due to increased specialization, a myriad of heterogeneous companies are involved in a supply chain. However, these companies work together very efficiently through the use of economic incentives and trust. There is no central governing body that steers the entire chain into an efficient equilibrium. The individual choices of the companies maintain this equilibrium, thus this can be seen as bottom-up emergent behavior.

2.1.1. Resolution considerations

A supply chain system is often modelled on the macro resolution as an inter-organizational network through which goods are transported, e.g. supplier to manufacturers to retailer. However, Long and Zhang (2014) identify four conceptual resolution layers in their framework for Agent-Based Modelling (ABM) of production supply chains (see figure 2.1). In each layer, the agents are on a different resolution level within the supply chain. As stated before, most papers involve the top layer of the inter-organizational supply chain in which the agents represent organizations. Less research is done on higher resolution levels where intra-organizational agents are taken as the scope for the investigated system (Guertler and Spinler, 2015; Clausen et al., 2019).

2.1.2. Structural considerations

The interactions between agents within a supply chain can be divided into physical goods flows and information flows. We see this particular 2-fold division from the earliest of literature on supply chain management, for example by Ellram and Cooper (1990). Ivanov et al. (2010) however go a step further with their multi-structural framework of supply chains. Figure 2.2 shows an overview of the different structures that their framework consist of. These structures not only regard different objects of transfer between the nodes, but can also have an entirely different structure per layer.

2.1.3. Agent-based modelling approaches

What about used simulation methods? Mousavi et al. (2019) model the two levels of physical distribution and information flows within the supply chain using Discrete Event Simulation for the physical distribution aspect and ABM for the information flows. Kimbrough et al. (2002) have researched the possibility of simulating a distribution network using virtual agents with self-learning capabilities. They

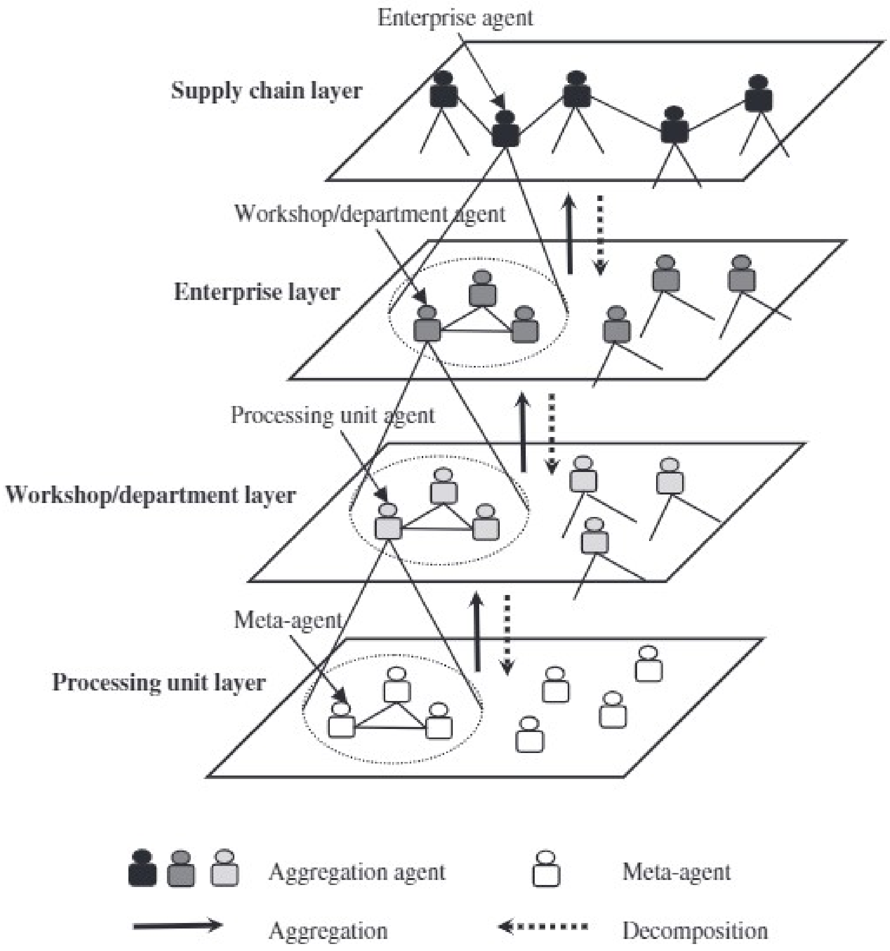

Figure 2.1: Four resolution layers in production supply chain modelling (Long and Zhang, 2014)

conclude that virtual agents *can* indeed manage a supply chain the same way, or in some cases better, than humans. Especially when analytical good policies are not available due to the complexity of the scenarios. Humans are not able to come up with analytical good policies in complex situations due to bounded rationality, information asymmetry and individual optimal policies that do not support the system-wide goals (Kimbrough et al., 2002), which is why simulation methods can prove valuable. Chen (1999) describe a concrete example of such behavior: The Misused Base Stock Policy. It originates from information delays within a supply chain. In the misused base stock policy, procurement managers do not take into account outstanding orders and therefore order more than is needed in order to satisfy customer demand.

Chu et al. (2015) use the ABM approach to model an order driven inventory network. Their vision on the network is that there is no central governing body that can determine the behavior of each facility in the network. The autonomous decisions made by each facility in the supply network is suited to be modelled using agents. Holweg and Bicheno (2002) use an agent-based approach for a case study regarding steel production. They find that information distortion and the lack of demand visibility for all agents are root causes in the poor performance of their specific case study. They are reluctant however to generalize these findings to supply chains as a whole due to the specificity of their simulation model design.

2.2. Intra-organizational supply chains

Aitken et al. (2016) mention two perspectives on the complexity of supply chains. One from a holistic perspective, in which the entire supply chain network is broadly represented as an inter-organizational network. Another from the single firm point of view (Aitken et al., 2016), or intra-organizational per-

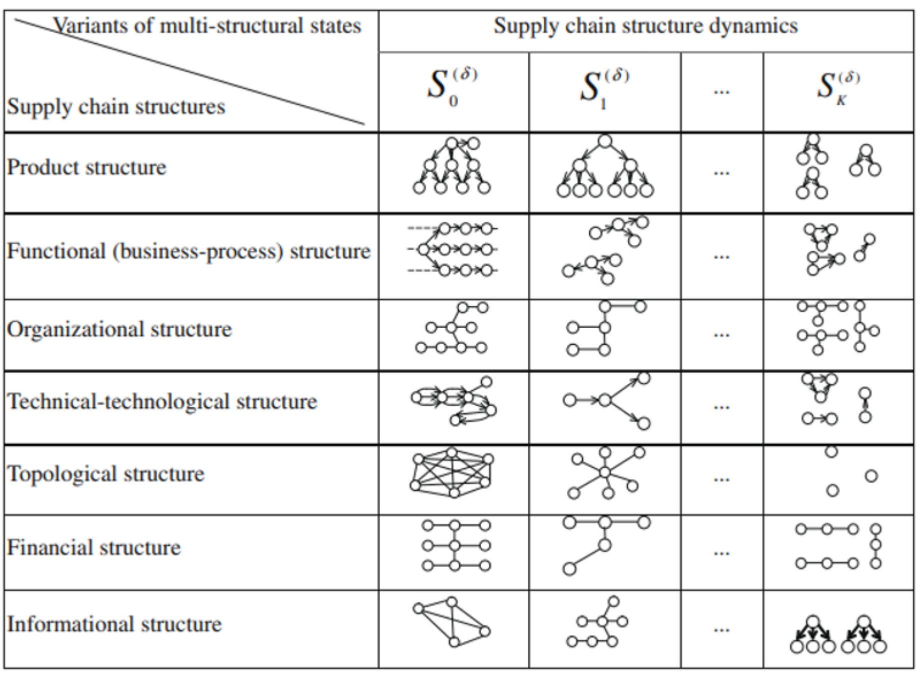

Fig. 2. Supply chain multi-structural composition and structure dynamics.

Figure 2.2: Multi-disciplinary structures in supply chains (Ivanov et al., 2010)

spective:

> *"From the BU [Business Unit, i.e. individual firm] perspective, the focus is not as much on understanding or measuring the degree of entropy characterized by a broadly defined supply chain network; rather, the interest is on how this complexity manifests itself within the BU and at its interface points with its external supply chain partners."*

In other words, they investigate how individual firms cope with the complexity of a supply chain in combination with the overall goals of the firm. They see two main directions to cope with complexity in the supply chain: absorbing and reducing complexity. Absorbing complexity of the supply chain can for example be done by increasing the use of information systems to allow more information processing. Reducing complexity is aimed at for example reducing the demand variability. Solely focusing on either will not give the best results, instead Aitken et al. (2016) opt for a hybrid approach in which both are combined.

2.2.1. Business process definition

Understanding the complexity of a business unit in a large organization, and how that unit manifests itself in the supply chain, can be a difficult endeavor. Firstly, the nature of an organization has to be understood. There are however multiple perspectives as to what defines an organization. In this research, an organization is defined as a set of business processes that interact with each other to fulfill the organizational goals. The ideas in the influential paper by Melão and Pidd (2000) form the basis of an holistic view on what business process are and how they can be accurately modelled. Through their 4 perspectives on business process they show the multi-disciplinary and social-technical aspects of business processes, going past the often mechanistic (meaning viewing a business process as a machine which can be captured in static formulas and controlled top-down) viewpoint that they identified from previous literature.

2.2.2. Research on business processes using simulation

A recent literature review by Rosenthal et al. (2018) on business process simulation shows that there is a lack of research on the practical applications of business process simulation. Also, they see a lack of descriptions of limitations that might occur when modelling a business process as a simulation model. A paper by Bisogno et al. (2016) does provide a practical case study and have used a novel methodology using Business Process Model Notation combined with simulation techniques for analyzing business process operations within a firm. They conclude that their method can help decision makers improve complex and dynamic business processes through using the simulation model in evaluating different policy implementations. They do identify that their single-case application of this methodology limits validity and generalization to other business sectors.

2.3. Distribution network design

Researchers analyze the distribution network of a supply chain using optimization models that maximize the flow of goods. The goal is to distribute the goods from the supplier to the consumer accounting constraint by the goals of the specific organization. Depending on those goals, organizations need to make operational decisions regarding (Ambrosino and Scutell, 2004):

- Inventory
- Transportation
- Facility location

It is often impossible to invest fully in all of these factors, as resources will be insufficient or the objective is a least cost design. Trade-offs between these factors need to be made in order to reduce costs but also satisfy the consumer service demands. For example, having an inventory at every node in the network to combat uncertainty in supply will be too expensive to maintain, due to warehouse rent and operational costs.

A literature review by Mangiaracina et al. (2015) make two distinctions in distribution network design research: Network structure decisions and management policy decisions. Of the network structure research, the optimal *number of echelons* in the network is one of the mostly analyzed decisions. Echelons in a supply chain system are the amount of layers of distribution centers and warehouses between the supplier and the end-user. Mangiaracina et al. (2015) note that the number of echelons in a distribution network is often treated as a constraint, often in which the number of echelons is given. Most papers that do treat the number of echelons as a decision, see it as a strategic decision with only theoretical argumentation without using any quantitative methodologies.

In supply chain management policy research, the *inventory level*, *safety stock* and *inventory policy* decisions are among the mostly analyzed decisions (Mangiaracina et al., 2015). The safety stock decision often relates to the inventory level and the item fill rate. The goal of the safety stocks are to guarantee the service level that is required (Sourirajan et al., 2008). Inventory policy decisions are the decisions made in strategic aspects such as a push/pull inventory strategy and the item fill rate goal (Mangiaracina et al., 2015). Lean and agile strategies can cope with the type of inventory dynamic depending on the type of good (Payne and Peters, 2004).

2.4. Research gap

Overall, we see a clear body of literature that classifies a supply chain as a complex adaptive system, which is modelled and simulated for analysis using the ABM paradigm. Modelling such a system requires demarcation of the system boundaries. Two dimensions are identified which serve as a basis for the most important scoping decisions for analyzing the supply chain. The first dimension is the resolution level, where a distinction is made between intra and inter-organizational supply chains. The second dimension is on the multi-structural notion in which different disciplinary structures are identified within one supply chain.

Within the resolution level dimension, the intra-organizational resolution is less researched than the inter-organizational research stream. This can be explained by the more pragmatic direction of intra-organizational research which focuses on dealing with the complexity within organizations. It is more pragmatic because the decision-making advice given in those researches focus on an organization specifically and can then be actually implemented by that organization. Taking this path of an intra-organizational supply chain will be the scope of this research. On the multi-structure dimension, the focus will lie on investigating the cross-structural characteristics, relations and interactions that are the cause of the organizational complexity.

As this research identifies intra-organizational business units as a combination of different business processes, the business process simulation literature is examined as well. A second second knowledge gap is consequently identified. There are three aspects of the gap. Firstly, there is a lack in **practical applications** of the business process simulation methodology. Secondly, descriptions of **limitations** that might occur when implementing simulation methods for business process analysis is lacking. Thirdly, **generalizability** of the business process simulation method results is limited due to the low variety in sectors where business process simulation is used.

3 Methodology

The literature review in the previous chapter identified a knowledge gap that entails the understanding of multi-structural intra-organizational supply chains, by using the business process perspective. There is insufficient knowledge on the dynamics and effects of policy implementations on the behavior of the system. This research will use the case study of Defense's bicycle supply chain as subject of analysis, providing us with an intra-organizational supply chain system embedded in a complex multi-structural organization. Multiple business processes of Defense's intra-organizational supply chain will be modeled and simulated, in order to also add to the business process simulation knowledge gaps on practical applications, limitations and generalizability. For this, the main research question is posed, along with sub questions that explore the aspects needed to answer the main research question.

3.1. Research questions

The main research question is the following.

> *What are the effects of novel policies on the functioning of intra-organizational supply chain business processes, while taking into account the behavior and heterogeneity between key actors?*

This question focuses on how the effects of certain policies manifest themselves in intra-organizational supply chain systems. For this, understanding of the dynamics within such a system is key. This research will be a search for understanding how to analyze such complex intra-organizational supply chains, and how policies can alter the behavior of such a system. The analytical perspective will be from an Agent-Based Modelling (ABM) worldview, where heterogeneity between agents and their behavior is key. To fully answer the main research question, the following sub questions need to be answered in which the case study of Defense is key.

1. *Which actors, business processes and relations between the processes are most important in the functioning of the bicycle supply chain of Defense?*

   The first question revolves around understanding the processes and actors that make up the supply chain of bicycles. The case study of Defense will provide us with a complex and large organization, different from typical commercial organizations in its goals and approaches. The main method used to answer this question is by interviewing key actors which will be represented as a digital agents in later stages of the research. Through interviews, insights are gained from different perspectives on the supply chain of bicycles and how it currently functions. Also, potential policy areas can be identified through the ideas of the interviewees. Unstructured interviews are used in order to gain exploratory knowledge.

2. *How can the complex supply chain of bicycle distribution and the underlying processes be conceptualized and implemented in an ABM simulation model?*

   Using the answer on the previous question, a conceptual model on the supply chain of bicycles can be constructed using the Unified Modelling Language (UML) and the Business Processing

Model and Notation (BPMN) methods. These conceptual models visualize the complexity between the business processes and agents. The full answer to the question will be provided by elaborating on key mechanisms and decision rules used by the agents.

3. *How do different policies influence the processes of the agents and thereby influence the average waiting time, budget and effort, under varying demand and supply scenarios?*

   The third sub question revolves around the implementation of the conceptualization into an Agent-Base Model. The system of the bicycle supply chain of Defense can be quantified using this model. Different supply and demand scenarios i.e. uncertainties can be simulated and the effects of these uncertainties will become clear. Different policy options can be tested to influence the key performance indicators. These policy options are implementations of the answer on the first question or from literature on supply chain management. Conclusions on the usefulness and promising policy options will be discussed as well.

3.2. Methods

Multiple steps will be taken in order to answer the sub questions. First, *data* is gathered on the functioning of the supply chain system as it stands now. Then the system is conceptualized and implemented in an ABM model. Using the model the experiments can be run and the results are analyzed and interpreted. This section will describe the methods used.

3.2.1. Data and conceptualization

Data gathering is essential in the understanding and conceptualization of a complex system such as a supply chain. The main methods to gather data will be literature, interviews and quantitative data. The data will need to give insight into how the orders flow from the actual demand creator to the supplier and which steps are taken in between. This way, relevant actors that play a role and impact the distribution of orders can be identified. Interviews with these relevant actors will provide descriptions of the tasks that are executed and which tasks are relevant. Important in these interviews is gaining an insight into the decision rules that the different actors use when processing the orders. Some tasks might be implicit and are not written down in policy documents. These unwritten decision rules are suited to implement in an ABM model and are the most important for understanding the potentially inefficient behavior. Quantitative data will be needed to model the current quantities of demand and distribution of order quantities among the end-users.

The conceptualized system as a whole can be visually structured using a Business Process Model Notation (BPMN) and Unified Modelling Language (UML) diagram, both adding to each others weaknesses. Onggo (2012) make a strong case for using the BPMN for conceptualizing an ABM model, instead of the often process-oriented simulation formalism, because the BPMN helps in visualizing the processes that are executed by the different agents. A weakness of the BPMN lies in the lack of options to provide detailed attribute information for each agent (Onggo, 2012). This is where the UML supports the BPMN. The UML diagram visualizes the different objects with detailed attribute information and shows the simplified relations between the objects. Another weakness in using BPMN for ABM lies in the variation in model structure that can occur in an ABM model (Onggo, 2012). In this research, the BPMN will describe the processes holistically, meaning that every key structure is represented.

3.2.2. Simulation model

The complexity of Defense as an organization and the supply chain systems in its current form, along with future uncertainties on developments, make the case complex and difficult to analyze. A simulation model can provide insight into the stochastic nature and dynamics of the system, which cannot be grasped in static formulas (Fayez et al., 2005). The literature review in chapter 2 already showed that a supply chain can be analyzed using an ABM simulation approach, given the plethora of literature with proposed frameworks and conducted case studies using this method. The system of Defense in which we find the problems on process synchronization, matches with the strengths of ABM. It is important to explain why this is the case, especially because ABM is relatively novel as a tool for supply chain analysis. Also, supply chains found in manufacturing and planning problems are often analyzed using discrete-event simulation, not ABM. This also makes motivating and evaluating the use of the ABM simulation paradigm important.

ABM is especially suited for the analysis of systems that contain heterogeneous agents, individualistic behavior, imperfect information and decision rules based on this information. The actors in the supply chain within Defense can be represented as agents, along with the bicycles themselves as agents. They form the dynamic network on which order information and budgets/expenditures is exchanged. The cause of dynamics among the agents will originate from their attributes, decision rules and information on relevant states of other agents. Using these aspects, the supply chain system within Defense can be conceptualized, modelled and simulated including multiple uncertain future scenarios. Using the simulation model, uncertainty in future scenarios can be taken into account when analyzing policies.

3.2.3. Exploratory analysis

After the model is constructed, the Exploratory Modelling and analysis (EMA) workbench is used for experimentation. Multiple uncertain parameters can be taken into account using the EMA workbench. First, the parameter space will be defined by setting the ranges on the input parameters that the scenarios will be sampled of. Latin Hypercube sampling will provide a good representation of all the uncertainty and policy dimensions within the parameter space, even though the sample size is small. It does this by stratifying the parameter ranges and only sampling one value per dimension bin.

The sampled policies will be run with each of the scenarios and the experiments will be repeated a number of times, due to the stochastic nature of the simulation. Only with multiple replications per run the behavior of the model can be analyzed with sufficient certainty. The results will be visualized using graphs and compared to the base case. Also, a feature scoring test using the extra trees algorithm will be executed, giving insight in the global sensitivity of the model. The values in the feature scoring test will show how much the uncertainty and policy parameters declare the variance in the Key Performance Indicators. The higher the value, the more influence a parameter has on the outcomes.

4

Supply chain design for the Netherlands Armed Forces

The knowledge gap from the literature is clear as described in chapter 2.3; Understanding and analyzing a complex intra-organizational multi-structure supply chain through the use of the agent-based modelling paradigm. Defense as a case study provides a complex organization which has an extensive supply chain system. It is also one of the core activities in a well-functioning military force as it facilitates the organization as a whole in achieving its goals. As without even the most basic supplies, a military force cannot function properly.

In order to accurately conceptualize the supply chain system of bicycles, multiple unstructured interviews are held with key actors (see appendix A for extensive notes on these conversations). These interviews were more conversation like, getting to know the complex Defense organization and exploring which systems and processes are used. Also, internal policy documents that guide the business processes are taken as a source. The information gathering in this chapter is guided by the following sub question:

> *Which actors, business processes and relations between the processes are most important in the functioning of the bicycle supply chain of Defense?*

4.1. Defense as an organization

The Dutch Defense organization as a whole is an enormously complex organization. Providing a large range of goods to a large number of different military bases and service branches proves a difficult endeavor, as seen by the two logistics and service oriented service branches that support the four main branches of Navy, Air Force, Land and Marechaussee. These two are the *Defensie Ondersteuningscommando* and *Defensie Materieel Organisatie*. Before 1996, the different service branches within the Netherlands Armed Forces worked independently, each providing their own needs with entire separate infrastructures and contracts with suppliers. After 1996, the two service and logistics branches were added to provide facilities and goods for every branch of Defense.

Assortment management is implemented to facilitate the distribution of goods across Defense. The goal of having Defense-wide assortments is to prevent the duplication of contracts and logistical chains for the same good, which was the case before each of the 4 main Defense branches fell under the same organization. This assortment way of working required a different mindset from the Defense branches. From "own Branch first" to more "purple thinking", in which individual branches put the goals of Defense as a whole first. This is not an easy change and individuality among branches is still present, although this improved a lot over the years.

4.2. Information exchange and coordination

The sub-optimal coordination between Defense branches shows. In a conversation with the assortment manager it was brought up that different systems are used for different goods. DigiInkoop (a government broad system of procurement) is used for the sub-assortment bicycles, but the army uses SAP for almost all of their goods. This makes that the assortment manager cannot easily gain access to data on similar goods, such as mountain bikes, which are registered using SAP. The other way round, employees at the Army branch working with SAP are used to that system and therefore will not jump to use DigiInkoop for procuring the city bikes from the assortment central in this research.

Implementing state-of-art techniques within an organization that has a long and rich history could prove to be difficult due to path dependency. For example, in the facility at the Royal Military Academy they administrate incoming and outgoing bicycle quantities by hand on paper. To the question; do you think a digital administration system would improve the workflow? Employees responsible for the distribution of the bicycles responded along the lines of: *"We work in this manner for decades. Do you think we can learn to work with a new digital administration system?"*. Making the estimation that this is a rhetoric question, it cannot be expected from these employees to learn to use a fully digital and complex tool such as SAP. Therefore, other policies need to be searched for.

Different parts of the registration system of bicycles are executed in different ways which means that there is hardly any centralized data on how many bikes are at which base at a certain point in time. There only is data on how many bikes are supplied from the supplier to the end-user. The facility company head talked about how there is no data or knowledge about precise bicycle counts at each military base. There is also no record of the state of these bikes and whether they need maintenance soon. At some point in time, the facility company head received a bulk order of 100 bicycles due to lagging maintenance. However, it can be assumed that it is impossible for 100 bikes to need replacement at exactly the same time. One reason for this is that the demand comes from a local employee that likely has little time and incentive to investigate the state of each bike. He or she then orders entirely new bikes because it is the way of least resistance, without consequences.

4.3. Physical distribution

Every Defense Department (Defensie Onderdeel) is responsible for their own distribution of bicycles at the different military bases at which Defense Departments are situated. For example at the Royal Military Academy in Breda, there is a high and constant demand of bicycles due to the yearly incoming students that require a bike. To this end, the facility provider at that military base is concerned with the distribution of bicycles. The bicycles that are returned for maintenance due to failures are repaired once a week by a mechanic that will come if there are 5+ bicycles in need of repairs. However, in general the bicycles are delivered from the Supplier *directly* to the End-User, without any stocks in between. Except for the Supplier, who does keep a stock and produces bicycles for only a certain time a year at a continuous pace.

4.4. Management

The assortment manager is responsible for managing the the supply chain of multiple different assortment groups. From the internal policy document we can see that the primary task of the assortment-based operations is quality control, supplier procurement and limiting expenditures if expenditures reach budgetary limits. The assortment manager physically tests the bikes on quality and checks this quality with what is expected from the end-users that will use the bike. Also, the manager constructs and closes the contract with adequate suppliers. However, an important responsibility is the limiting of expenditures through declining demand requests if they are not supported adequately.

Finance and control management needs information from the end-users which is essential in evaluating the justness of the demand in light of the work that the end-users need to do; is the demand justified by the actual proposed need of the end-user? Right now, the Facility company receiving the demand order from the end-user does not receive adequate information to evaluate and create sufficient arguments to justify the demand. As a result, the Facility Company is required to go back to the end-user and verify the arguments behind the demand order. This is not the primary task of the Facility Company but it does cause them to spend working hours which they cannot spend on processing the order immediately, probably causing delays in the entire bicycle supply chain. More elaborate and standardized way of information exchange between the different departments and their processes can improve the argumentation behind demand orders and therefore streamline the ordering process.

Finance and control also plays a role in the management of the supply chain for bicycles. They keep an eye on the match between on one side the contract and the allocated budgets and on the other hand actual aggregate demand that is placed within that contract. If the demand is exceeding the contract by a large margin, intervention needs to take place in either scaling down demand or closing a new contract. If the demand is exceeding the allocated budget, that budget needs to be raised by looking at other budgets within the Facility Company region in case. If there is no available budget within the region, budget will be asked inter-regional. If that does not work the demand for budget is escalated a level higher still.

4.5. Policy ideas

After sharing their insights on the functioning of the supply chain of bicycles, interviewees were asked to come up with policy ideas on how to improve the service level or efficiency of the supply chain. These ideas are valuable for this research, as they can eventually be tested and quantified in the analysis.

Within the European procurement procedure, multiple suppliers can offer their services to a public institution. The same goes for the bicycle provision and maintenance demand of Defense. At the beginning of the current contract, which runs for two to four years, multiple bicycle suppliers applied in order to get an agreement. One of these suppliers was chosen for the current agreement because it was the most inexpensive of all options. However, the assortment manager had a preference for another supplier. This supplier could provide an ”OV-fiets” type of bicycle which could easily be registered digitally when lending out. This option was more expensive per purchased bike, which is why it was not preferred by the financial department. The initial investment costs were leading in the procurement decision for the bicycle contract. However, aside from the initial investment costs, costs of time spend administrating and gaining information on the outstanding bike orders needs to be taken into account when making an investment decision. The man hours a more expensive but less administrative intensive ”OV-fiets” type bike could save might change the overall cost picture of the procurement offer.

Another idea on bicycle supply chain improvement involved digitizing the registration of the purchased bicycles using the ”Defensie pas” (a Defensie pas serves as an identification pass of each employee). Bikes can easily be lend out using a scanner that collects the information needed from the identification pass. Relevant information is uploaded to a central database, through which the Facility company can see who lends which bicycle and where. On top of this, more information on the quantity of bicycles at different locations can be collected meaning more insight in current availability of bicycles. This system would save man hours in administration which can be spend elsewhere; not only saving money but also precious hours. Increased available time from employees is valuable as there are 9000 vacancies across Defense.

There also was an idea on pro-activeness of the Facility Companies in predicting demand. The Facility Companies can visit the End-Users once a year to inventorize where and how much bicycles are present. Also, the state of these bicycles can be investigated. When the total amount of bicycles would be very low compared to last year, or to the current demand of the End-Used, the bicycles can be ordered in advance. This would mitigate the need for End-Users to order bicycles and make the demand trough out the year more predictable and lower.

The switch from independent branches to a unified Defense Force still shows its traces in information processing, budget distribution, data collection and agility in using modern techniques. Experienced employees bring path dependency and although ideas on supply chain improvement were identified, implementation can prove difficult. The rest of this research needs focus on these policy ideas and show what lessons we can learn, not only for this use case on bicycles specifically, but for Defense as a complex organization as a whole.

4.6. Conclusion

Concluding on the central question in this chapter, *Which actors, business processes and relations between the processes are most important in the functioning of the bicycle supply chain of Defense?*, is done using the information from this chapter. To summarize, the following actors and accompanying processes are identified:

- End-Users
    - Order creation based on demand and justification.

  - Information sharing on justification
- Facility companies
  - Order analyzing on costs and justification
  - Information sharing on budgets
- Supplier
  - Manufacturing bicycles
  - Distributing bicycles to End-Users
- Manager
  - Monitor expenditures
  - Reduce demand
- Finance and Control
  - Order analyzing on justification
  - Budget analyzing of Facility Companies
  - Budget gathering from other Facility Companies
  - Justification gathering from End-Users

The above processes are not executed in a vacuum. On the contrary, they often serve as inputs to each other, creating feedback loops throughout the entire system. Order creation is at the heart of all processes, as the orders contain essential information as inputs to other processes present in different actors. Orders provide costs, budgets and justification information which are required in the analysis of the orders and monitoring of budgets. A more detailed overview of the conceptualization made can be found in figure 5.1 in the next chapter 5 on the conceptualization.

5 Conceptualization

This chapter will show what the supply chain system of bicycles within the Netherlands Armed Forces conceptually looks like and how its performance can be measured. The dynamics between the different concepts are stipulated to create a coherent complex model. Using literature frameworks and interviews, the concepts and relations are defined. The conceptualisation will result in a conceptual model that forms the basis for implementation in the simulation model. The research question which will be **partly** (as denoted by the vertical bar: **|** in the question) answered in this chapter and partly in the implementation chapter 6 is the following.

> **How can the complex supply chain of bicycle distribution and the underlying processes be conceptualized** (chapter 5) | and implemented in an agent-based simulation model? (chapter 6)

Figure 5.1 shows a schematic system diagram, containing the agents, processes and their relations. It represents the complete system and acts as a visual guide when reading the subsequent paragraphs. The structure of this chapter follows the different concepts that are relevant. Demand is important to conceptualize, as there is no clear-cut answer to the origins of demand. Then, the different structures concerning physical distribution, finance, information and management are explained. Finally, policy implementations and expected effects are conceptualized. The UML diagram in figure 5.2 shows the objects and their relations as conceptualized in this chapter in a schematic kind of way. The Business Process Model Notation (BPMN) model in figure 5.3 visualizes the decisions and actions of the different agents. See appendix B for more information and an enlargement of figure 5.3.

5.1. Demand

The demand of the *end-users* comes from two different sources. First, the bicycles in possession of the end-user deteriorate over time. Bicycles eventually will reach such a poor state, that the end-user renders the bicycles unusable for the purpose they are needed. He then orders new bicycles to replace all bicycles in possession, not just the unusable ones, to prevent the bicycles braking down completely and having to order small batches of bicycles throughout the year. This type of demand is called *maintenance demand*. Second, recruits/employees or other might need new bicycles because they did not have a bicycle in use yet. We call this *new demand*. Making distinction between these two types of demand is important as they need different approaches in the policy construction in paragraph 5.3.

Maintenance demand can be predicted if the state of bicycles would be known, which is not the case currently. New demand is harder to predict, but the nature of the location - e.g. the location of the military base is easily reachable by bicycle because most employees live nearby or there is a city in the proximity of the base - and the amount of new recruits/employees each year at that location can be promising indicators.

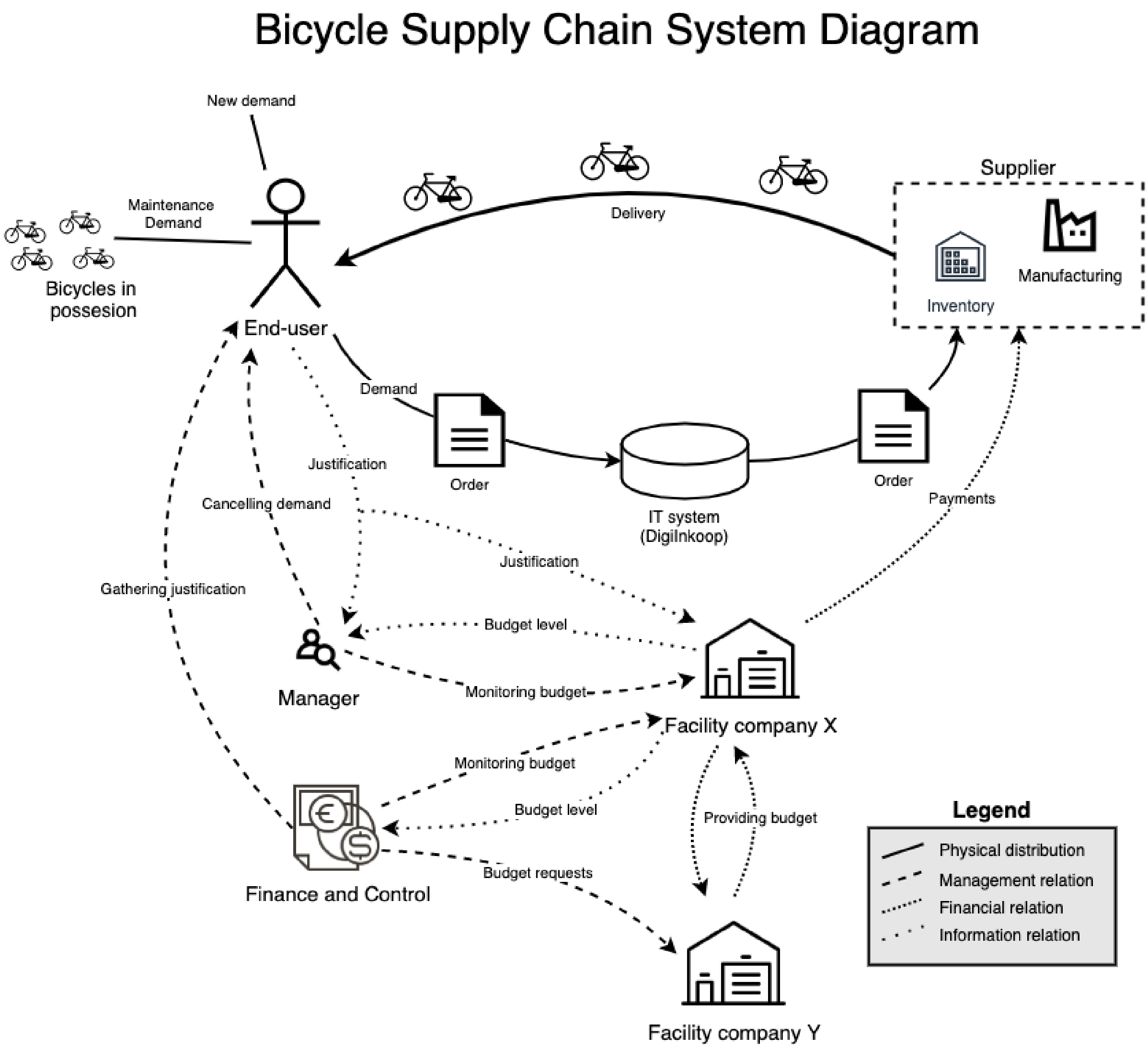

Figure 5.1: Conceptual model of the intra-organization, multi-structural Supply Chain system within Defense

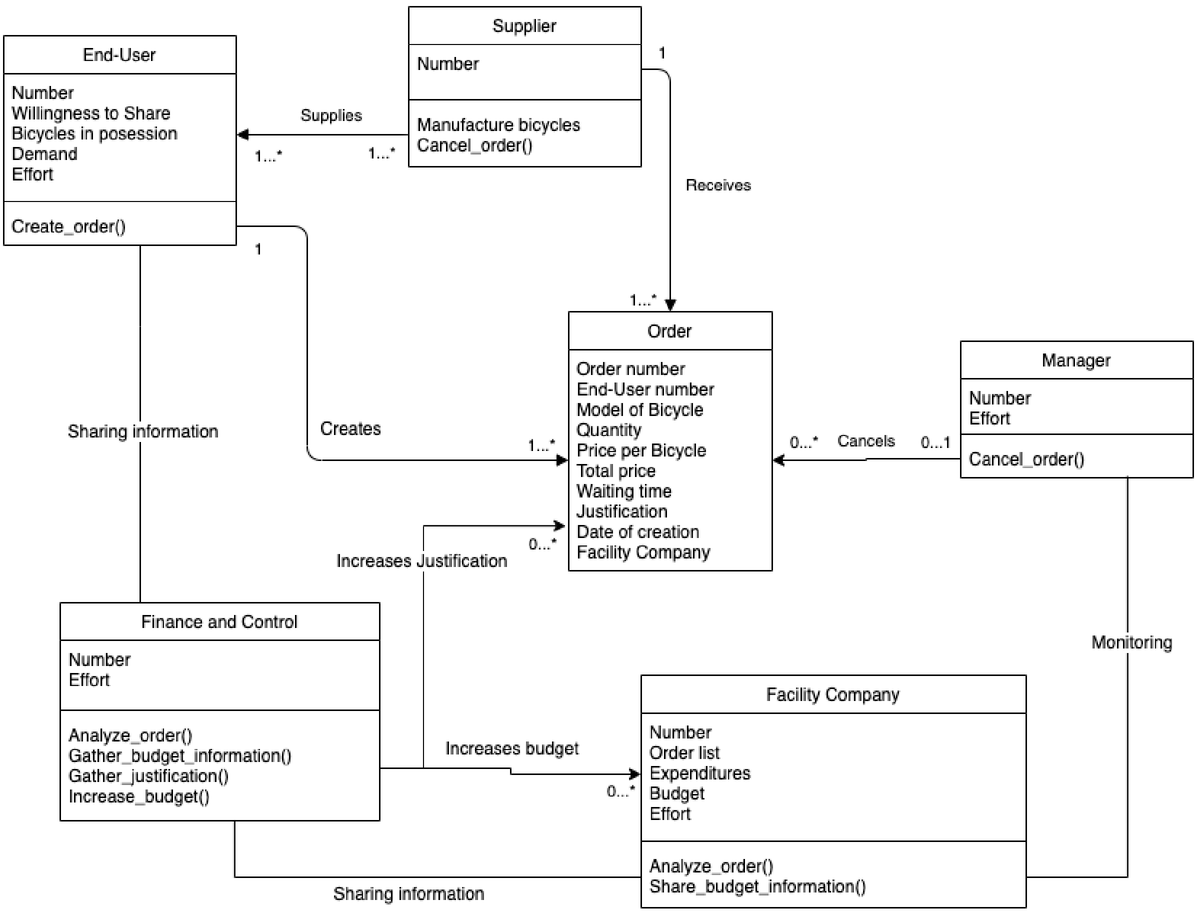

Figure 5.2: Unified Modelling Language model of the supply chain system

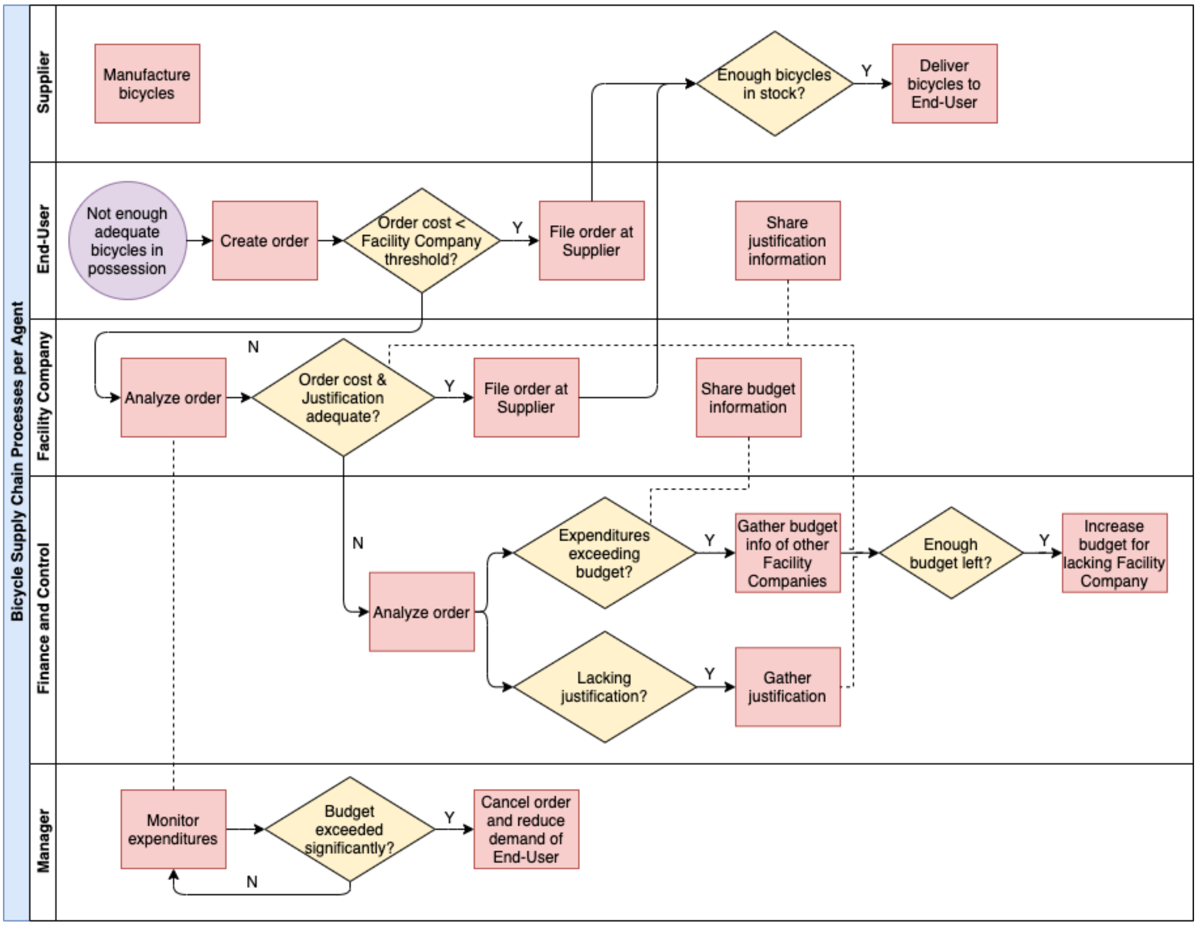

Figure 5.3: Business Process Model Notation (BPMN) of the processes within the bicycle supply chain for Defense (see appendix B for an enlarged image)

5.2. Multi-structural system

The concepts that will be elaborated relate to the different structures that are present in multi-structural systems such as supply chains, as described by Ivanov et al. (2010). The structures relevant for this research are the physical distribution structure, financial structure, information structure and management structure. These do **not** directly correspond to the structures identified by Ivanov et al. (2010), but are base on them. Together, these structures also scope the system. The distribution structure is at the heart of the system, which is for the most part handled by the external supplier. Within Defense, the management structure keeps oversight and intervenes when necessary. Information is necessarily shared between structures and is defined as the information structure. Budgetary constraints are determined in the financial structure, which in turn limits the budgets of procurement.

5.2.1. Physical distribution

The physical distribution structure encompasses the distribution of the bicycles themselves. It is conceptualized as the flow of bicycles between the different end-users and the external supplier. The physical distribution is not complicated, as the distribution happens directly from the external supplier to the end-users. There are no central or decentral stocks within Defense present. Specifics on transportation modes are left out due to the intra-organizational scoping. Uncertainty of supply is taken into account in order to see how the internal processes of Defense react to supply shortage or surplus. The supplier is therefore defined as a manufacturer with a certain inventory of bicycles, who will always fill incoming orders if his inventory is adequately filled. Figure 5.1 shows the *supplier*, consisting of the *inventory* and *manufacturing* elements. The supplier is not manufacturing the bicycles year-round. Instead, the supplier produces the bicycles only a certain period per year. The manufacturing line of the supplier is rigid and limited in switching to the production of other models, which is why the bicycle model for Defense cannot be produced continuously.

Whenever an order is filed in the DigiInkoop system, the external supplier starts processing the order by taking the required bicycles from its stock and transporting the required amount to the next node in the supply network, which in this case is the end-user. The time it takes from sending the order by the facility company to the actual delivery at the end-user is the lead-time. The supplier is assumed to be almost perfect in its order processing, as focus lies on the internal business processes of Defense. The variation in lead-times will therefore occur in the inefficiency or hurdles found in the intra-organizational processes or shortage of supply, but not the transportation time.

5.2.2. Financial structure

The budgets which can be used for the procurement of bicycles are ultimately determined by the investment that the cabinet makes in the Defense force. This whole trickle-down process is too elaborate to conceptualize and therefore the total budget for the bicycle supply chain procurement is externalized. The budget does trickle down to specific budgets for each facility company region, of which there are 7 across the Netherlands: Havelte, Schaarsbergen, Breda, Den Helder, Den Haag, Soesterberg and Oirschot. The budget determines the amount of bikes the end-users within a region can procure and is scaled to the amount of end-users present in that region initially.

A key aspect in the financial structure is the monitoring of expenditures and redistribution of budgets. The end-users and facility companies themselves are not that strict in monitoring the expenditures, as they are not responsible if expenditures exceed the budget. The facility company does test the justification behind an order and monitors the total cost of the order. If the justification is too low, or the total costs exceeds predetermined limits, finance and control comes into play. The facility companies will not process the order further.

Finance and control *is* responsible for this and should intervene when necessary. They do this by keeping track of expenditures which are registered in the financial register. If expenditures are exceeding budgetary limits by a large amount, finance and control will visit that facility company physically and gather information on the argumentation behind the orders. If the arguments are sound, which they often are as the arguments are hard to verify, the finance and control agent will try and gather budgets from other regions. This way, actions of end-users in one region will impact the end-users in other regions indirectly.

5.2.3. Information structure

The most important structure for the functioning of the whole supply chain is the exchange of information among agents. The flow of information in the information structure is defined as order sharing between multiple agents. Orders are in essence information bits that are shared among the agents containing essential information on who, what, where and when needs bicycles. The order also contain information on the reasons given by the end-users on why the bicycles are needed. This is captured in the *justification* behind the order. One such reason could for example be that employees in a team moved to a new location, at which some can cycle to and from their home or most facilities are at bicycle distance.

This is quite an abstract number, as justification is very hard to quantify in real life. How can the weight of a certain argument be evaluated? This mostly depends on the perspective and interests of the people involved. The evaluation of the justification behind an order is also prone to subjectivity by the facility company or finance and control.

The justification for an order is pushed from the end-user to the next link in the chain, meaning that the end-user determines the amount of justification he deems necessary for the order he makes. There is no elaborate standardized way in which end-users are required to share their initial argumentation behind the order and the quantity. More on standardization of information provision in paragraph 5.3, where the policy directions on standardization are investigated.

Currently, the supply chain of Defense is a pull focused system in which the end-users initiate the demand. The end-users are responsible for monitoring their own needs (the needs of their own or for employees which the end-user orders on behalf of, but this is not relevant for the scope of this study). Every process in the chain is subjected to the whims of the end-users. As a result, the facility company is functioning sub-optimally (see appendix A) because large orders can unexpectedly occur. Unexpected large orders require time and effort to process, as information and argumentation needs to be gathered.

The end-users create orders depending on their needs and send these to either the supplier directly or the facility company if the amount is too high. If the amount of the order is too high, the facility company needs to determine whether it fits the budget, as the budget is determined per region and not per end-user. The facility company can even request help from finance and control if the order amount is extraordinary high. From end-user to facility company to finance and control to supplier is the way in which order information is ”pushed”, but the actual bicycle need is ”pulled” from the supply chain. As a result the orders received by the different processing agents is hardly predictable on a monthly, let alone daily, basis.

5.2.4. Management structure

The management structure can be described in the broadest sense as guiding the business processes effectiveness towards the organizational goals. Management needs to control and guide the resources in such a way that the outcomes of the supply chain are on the required level. Assortment managers are key structures in the supply chain network. They manage the different assortments present within the supply chain with regards to procurement, quality, costs and monitoring. The scope of this research is confined to the managing of costs and the monitoring thereof. If expenditures are surpassing the budgets of Facility Companies, the manager will step in and try to reduce the demand and confine the expenditures. This should happen after Finance and Control has tried to increase the budget for the exceeding Facility Company.

5.3. Policies

As said, the current bicycle supply chain is ”pull” focused in which the end-user have the initiative for order creation, and thus ”pulling” the bicycles through the chain. All information on orders is therefore ”pushed” from the end-user to the facility company or supplier, creating a loop of information and goods. There is of course some standardization that the information in orders need to comply to, but information on for example the justification of the order is dependent on the willingness of the end-user in his sharing of information. This willingness to share information is viewed as a policy lever. Willingness to share mostly depends on trust and positive gain for both parties (Lee and Whang, 2000), which can be influenced by Defense’s decision makers. This can be done by for example convincing the actors on why information is beneficial for each of the actors.

The facility company might omit some of this subjective information by preventative maintenance demand. Predicting the maintenance demand will require some information gathering initiative from the facility companies themselves, as there is no centralized and accurate view on the bicycle locations, quantities and states. The facility company can collect information on the conditions and quantities of the bicycles. Using this information they can predict incoming demand, or even order bicycles in advance. Preventive maintenance is a well-known technique for improving the functioning of complex systems. In the bicycle supply chain, preventive replacement of poor state bicycles has the great advantage of making the demand more predictable. The supplier and facility companies can predict large orders and optimize their processes accordingly.

To better coordinate their processes with the needs of end-users, information is needed on which bikes need maintenance soon or need to be replaced or even some bicycles may be lost due to unforeseen events. As it is now, the system is purely order-driven and there is zero predictive maintenance or replacements happening. In an interview with the Facility Company, the interviewee mentioned that a complete overview of bicycles is lacking. There is no information on the quantity, location and state of bicycles in the current system. Therefore, the Facility Company is not able to predict what the demand will be in the short-term (coming year).

To test an implementation of better bicycle monitoring, a database can be kept on which bike is where and at which time. Each processed order of more than one bicycle will be tracked in a database. The idea is that once a year the database is compared to the actual bikes at different locations. For this, an employee travels to all the bike locations and checks their quantity and state. If there is a discrepancy between the database and the bicycles the employee will speak to the end-user for reasons. After the check, bicycles in poor condition can be replaced preventative and alleviate the number of large orders made in the coming year, smoothing out the workload and causing less delays in the provision cycle.

6 Formalization and implementation

This chapter will make the translation from conceptualization to a formalization that is suited to be modelled in the agent-based modelling tool Netlogo. Netlogo is a widely used tool that allows for construction of varying agents with heterogeneity in their behavior due to simple decision rules that are based on interaction with other agents and the environment. The tool is easy-to-use and due to the graphical user interface also visually aiding in understanding a system and the emergent behavior trough its agents. The central question to be answered in this chapter is:

> How can the complex supply chain of bicycle distribution and the underlying processes be conceptualized (chapter 5) | **and implemented in an agent-based simulation model?** (chapter 6)

The following sections will discuss each of the agents and their behavioral rules which are to be implemented in the model. The dimension and specification of time will also be elaborated because coordination, or lack thereof, between the processes of the agents will determine part of the performance of the system. To measure the performance of the system, Key Performance Indicators are specified in the final section. The framework by Chatfield et al. (2006) will act as a guideline in this chapter. Their view on an order-centric supply chain is consistent with what is found within Defense: Dynamic behavior from relatively independent and decentralized agents causing information and material flows on a static distribution network.

6.1. Agents

The agent central in the model are the *End-Users*, *Facility Companies*, *Supplier*, *Finance and Control* and *Managers*. Three layers of interaction are present, as described in the conceptualization; The financial layer, information layer and physical distribution layer. The flow within the information layer mainly consists of order exchanges. Orders are lists that contain crucial information on the demand, finances, planning and timing within the bicycle supply chain.

6.1.1. End-User

The End-User is defined as the demand ”creator” which in the end receives the physical bike and uses them. In case of a bike lending system, the facility company present in the specific military base is the end-user. End-Users have two attributes concerning demand. *Demand* and *new demand*. Demand is generated according to the probabilities as described in table 6.2 in paragraph 6.3. These attributes differ in the causes that determine their values. There are two causes, hence the two attributes. Demand concerns the degradation of bicycles already in possession. Demand is compared to the amount of bicycles in possession and the state of these bicycles. If the average state of the bicycles in possession drops below 50, including the disappeared bicycles which count as state 0, the End-Users will demand all their bicycles in possession to be replaced. Even if these bicycles are still usable. The same goes for the demand that is created when a new contract is closed and the bicycle model is modernized. End-Users will prefer the newer bicycles over their older ones if they are over a year old.

Table 6.1: Order list structure

List entry	information description
0	order number
1	number of the End-User that created the order
2	model number of the bicycle ordered
3	quantity of bicycles needed
4	price per bicycle
5	total price of the order
6	waiting time
7	justification of the order
8	date of order creation
9	Facility Company number that the specific End-User falls under

End-Users can either be an individual requiring 1 bicycle or a Manager that requires multiple bicycles for a grouped need. The End-Users always operate in a certain military base, therefore in the model the End-User can be seen as the military bases in which the demand is created. When an End-User is created a connection is made to the nearest Facility Company through an *information link*. He then sends an *order* with information on the bicycles he requires according to its internal demand attribute. Motivation and arguments on why that specific End-User needs the bicycles, is required as well. This is captured in the variable *justification*, ranging from 0-100. Geographical location of the order is irrelevant because the transportation time (which depends on the geographical location) is outside of the scope of this research. The focus lies on processes in the supply chain of Defense instead of the physical distribution of the Supplier.

6.1.2. Facility Company

After the Facility Company receives the order information from the End-Users, they start processing that order. The process begins by evaluating the information of the order; what is the *quantity* of demand, what is the wanted delivery *time* and what are the reasons (*justification*) behind the demand? Varying decisions rules are implemented, depending on the information provided:

- If the quantity of demand is under the Facility Company threshold, there is no further check and the order is made at the Supplier. Such a small order is important for that individual End-User because it probably is a bicycle for own use. Also, the impact of a single bicycle purchase on the total expenditures of the Facility Company will not be large.
- If the costs of bikes (amount of bikes * cost per bike) exceed a total of 5 thousand euros, or another defined threshold, the justification from the End-User needs to be high enough. If the justification is inadequate, action is taken by the Facility Company in which more information on argumentation behind the demand is gathered.
- If the total order value is above 30 thousand euros, or another defined threshold, the order information is provided to the Finance and Control agent for further investigation.

Each action will count towards a global variable, *effort points count*, that keeps track of the amount of effort required in executing the different processes within the supply chain. Also, each Facility Company will have an *expenditure* variable which tracks the sum of fulfilled orders. There is a max to the amount of demand one Facility Company can process. This is captured in the variable *max capacity*. Max capacity is the amount of End-User order the Facility Company can process at one point in time.

6.1.3. Bicycles

Bicycle agents represent bicycles and their corresponding attributes. The attribute *state* keeps track of the condition of the bicycles and is reduced with -1 every tick. When state reaches 0, a bicycle is assumed to be unrepairable and dies. Bicycles are created by the Supplier according to the orders the Supplier needs to fulfill, at the location of the End-User that originally created the order. The bicycles present at the exact location of an and-users are owned by that End-User through the attribute *bicycles in possession* that keeps track of the agent set of bicycles at his location. There also is a random chance that a bicycle dies, as some bicycles disappear without any information on what caused the disappearance (get lost or vandalized, but no-one knows exactly what happens which is why more accurate and updated information is needed).

6.1.4. Finance and Control

One agent represents the Finance and Control department. Finance and Control is responsible for processing the large orders that have a costs above a threshold set by the analyst (the one running the model and setting up scenarios). With these orders they analyze the justification behind the order. Does the End-User that created the order made enough valid arguments for why he/she needs those bicycles? Finance and Control is also also responsible for keeping track of the expenditures and budget of the facility companies. The budgetary allocation is outside of the scope of the model, but the actual budget distribution among facility companies can be altered by Finance and Control.

Expenditures and budget The aggregate expenditures are summed with every order above a threshold set by the analyst. This aggregate expenditure is compared to the *budget* of that specific Facility Company. Intervention of the Finance and Control agent happens when the budgetary limit of a Facility Company is reached. If the budget will be exceeded by a large order, Finance and Control will look for excess budgets at other facility companies. Information on expenditures and budgets at other facility companies will be gathered by Finance and Control, through which they can negotiate a redistribution of budgets. If this negotiation succeeds, meaning the other Facility Company agents have enough budget left, the budgets are redistributed to allow the big purchase for the lacking Facility Company.

Justification analysis Justification on orders starts with the End-Users that have an initial justification value, set by the model analyst. This justification comes into play with large orders above the threshold mentioned before. If the justification is adequate, the order may be filled. If the justification is inadequate, Finance and Control is involved. They will do so without an oversight as to where to jump into the process. Therefore, Finance and Control will ”visit” one of the 7 facility companies randomly every tick. Once at a Facility Company, they will check if an order is still in the Facility Company order list. If an order is still in that list, it means that the justification is lacking in relation to the order amount. The Facility Company will then proceed to ”gather” justification from the End-User that created the order. They can only do so at the rate at which that End-User wants to share its information, which is contained in the attribute willingness-to-share of the End-User.

6.1.5. Supplier

The Supplier is concerned with processing the orders they receive. The Supplier has a stock of bikes in order to compensate peaks in demand. Their manufacturing process is not flexible meaning that there is a certain period in a year in which the bicycles for Defense are produced. The other time during the year, different models are produced for other clients. The stock needs to be adequately filled in the production period to ensure continuity of supply in the non-production period. If the stock can satisfy the incoming demand, the Supplier will immediately do so, assuming no delay in delivery time as the processing time and details of the Supplier are outside of the scope of this research. Full focus is placed on the internal processes of Defense itself, mitigating the need for including elaborate external processes of the Supplier in the model.

6.1.6. Manager

The Manager is responsible for monitoring how the expenditures develop, taking into account the budgetary limit. Each tick he will scan the facility companies with open standing orders. Open standing orders means that some conditions for sending the order to the next agent (Supplier) are not met. If Finance and Control is not able to provide sufficient budget when the budget limit is reached, then the Manager has to intervene by cancelling the demand of the End-User. This way, expenditures should not exceed the budget limit. The downside is that some of the demand of End-Users will not be satisfied, thus negatively impacting the service level of the supply chain.

6.2. Time

The aspect of time in an agent-based model is not as easy specifiable because of the event-scanning worldview that the agent-based modelling approach is constructed with. Events are triggered by processes that track the state of the model. When the conditions for the event are met trough the relevant states of the model parts, the event is triggered. There is no determined ”real-life” time in seconds or minutes in-between activities, as with an event-scheduling world view. However, time is an important aspect in supply chain analysis, as delivery times are of the utmost importance in the functioning of the system. To overcome the lack of time specificity, progress of ”time” is tracked using ticks that occur after every agent has executed its defined procedures. The ”real-life” execution time depends on the calculation power of the computer and complexity of the code.

It is assumed that each tick is two days, so the procedural load of the agents per tick needs to correspond to what an agent could actually do in real life in two days as well. Delays in the delivery, thus simulating varying delivery times, are simulated with conditions that are not met. For example, an order is filed by an End-User totaling above 20.000 euros. This triggers the Finance and Control agent to look at the order and evaluate the justification. If the justification is insufficient, the control agent will ”gather” more justification, but only at a slow rate with a number of justification points per tick. It will then take a few ticks to gather enough justification points and allow the Facility Company to file the order at the Supplier. The ticks required for gathering the justification then cause an increase in the waiting time time for that specific order.

6.3. Parametrization

Multiple initial attribute states and decision thresholds are assigned to every agent, some of which are external and are not determined by the model interactions itself. Table 6.2 on the next page shows an overview of all the parameters in the form of distributions or constants. The source indicates how the value was determined. For more information on the interviews see appendix A. The current contract that Defense currently has with its supplier containing the price per bicycle is not publicly available.

The parameters are set on the values of the base case, which initially represent the current real-life situation and assumes a steady and predictable future scenario. This includes no shortage of supply, no extreme demand scenario and broad budgets that will be able to facilitate all the bicycle demand. This delivers a benchmark scenario which is important in understanding how the processes will differ under varying initial values in further exploratory analysis (Bisogno et al., 2016).

The Supplier has 3 production parameters, which will be set maximum for the base case, as in normal situations the supply is sufficient for the demand of Defense. The *price per bike* is the price Defense pays for bicycles in their current contract.

The *demand D* of End-Users is formed trough a manual distribution, as this is most easily implemented in the NetLogo code. The distribution that the initial demand is based on is shown in figure 6.1. The parameter D is multiplied with the *initial demand* factor which scales the initial demand. If the scale slider is at 1, the new demand will most accurately portray the data of 6.1, although differences between total amount of bikes can vary a lot due to spread of the distribution.

Medium orders are defined as orders that fall between the *order value limit* of facility companies and the order value limit of Finance and Control. In the base case this comes down to orders between 5,000 and 30,000 euros. Large orders are orders above the 30,000 euro limit of Finance and Control.

The *share demand malfunctioning* is the percentage of bicycles from the total demand that either have to be in poor shape or broken down completely (the agent ”died” and is erased from the model). Say that the demand for a particular End-User is 100, then the End-User will create an order when he only has 75 good functioning bicycles left.

6.4. Key Performance Indicators - KPIs

This section will elaborate on the chosen key performance indicators by which the behavior of the model will be analyzed. These indicators are *average order waiting time, effort End-Users, effort facility companies, effort Finance and Control, effort Manager, budget exceedance* and *demand End-Users*.

The average order waiting time measures the time between order creation and bicycle delivery per order. In the creation process of an order, the current tick is saved in one of the order bits. When the bicycles are delivered to the End-User this creation tick is subtracted from the then current tick. The

Table 6.2: Overview of important parameters and their values for the base case.

Agent	Parameter	Value	Source
Supplier	*restock rate*	20 bicycles per day	assumption
	max stock capacity	2,000 bicycles	assumption
	manufacturing cycle	9 months	assumption
	price per bicycle	260 euros	current contract
Facility Company	*order processing capacity*	5 orders	assumption
	order value limit	5,000 euros	interview
	total yearly budget	500,000 euros	interview
	justification limit for medium orders	50	assumption
	justification limit for large orders	100	assumption
End-User	*initial amount of bicycles*	4.0 factor	historical data (see figure 6.1)
	new demand, D	$P(D = 1) = 0.3$ $P(D = 2) = 0.3$ $P(3 \leq D \leq 5) = 0.2$ $P(6 \leq D \leq 30) = 0.15$ $P(30 \leq D \leq 200) = 0.05$	historical data (see figure 6.1)
	willingness-to-share	low (1)	interview
	initial justification	30	interview
	share demand malfunctioning	25%	assumption
Finance and Control	*order value limit*	30,000 euros	interview
	critical budget left share	10%	assumption
Manager	*budget exceedance limit*	5%	assumption
General model parameters	*demand growth*	5% per year	(Visser, 2020)
	bicycle average lifetime	Normal distribution mean = 4 years standard deviation = 1 year	assumption*

* The Weibull distribution is better suited here in representing the lifecycle, but NetLogo does not easily support implementation of the Weibull distribution. This is why the Normal distribution is choosen.

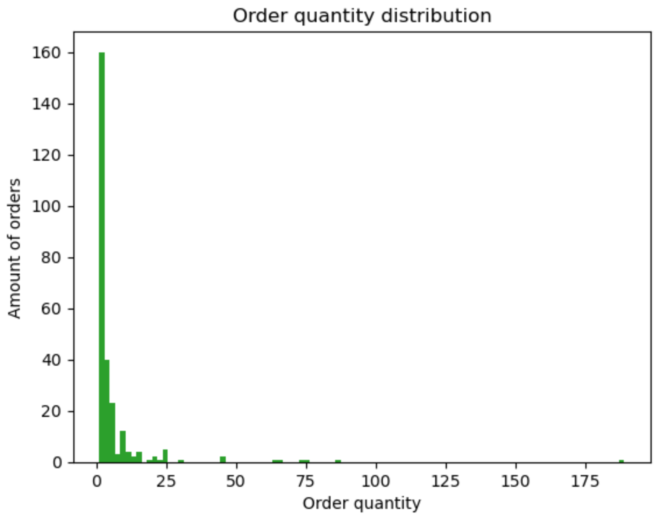

Figure 6.1: Order quantity histogram displaying the amount of orders with a certain quantity of ordered bicycles.

total waiting time of all orders is then divided by the number of fulfilled orders to retrieve the average delivery time across all orders. A high average order waiting time indicates if processes in the supply chain are experiencing difficulties.

The effort of agents show how much actions each agent has to take to ensure the whole supply chain keeps functioning adequately. By measuring the effort of each agent, the distribution of effort among the agents can be shown and analyzed. The specific effort performance indicators per agent are counted and monitored in the following way. It is **assumed** that each important action takes +1 effort, except for providing justification as this is an important aspect in the business process of End-Users and one needs to distinguish the effect of the amount of information sharing to accurately describe differences between scenarios.

- Effort End-Users
  - Checking which bicycles need replacement; +1 effort
  - Providing justification; +(justification / 10) effort
  - Creating an order; +1 effort
  - Sending an order to either the Supplier or the Facility Company; +1 effort
- Effort Facility companies
  - Sending order to Supplier; +1 effort
  - If policy predictive replacements = True, ordering replacements; +1
- Effort Finance and Control
  - Looking up budget information of facility companies; +1 effort
  - Gathering excess budgets from other facility companies; +1 effort
  - Gathering justification on deficit orders; +1 effort
- Effort Manager
  - Canceling an order; +1 effort

The effort for the End-Users in providing justification scales to the height of the justification they are providing. The more justification they provide, the more effort it requires from the End-Users. This effort lies for example in the time they spent on formulating the justification. It might seem as though the effort of facility companies and the Manager will always be less than the other agents. However, they have less tasks to execute in their processes. Also, it is important to remember that the comparisons between effort values will not be based on exact height of values, but rather the **delta** between different scenarios.

The budget exceedance KPI is monitoring the cumulative value of each expenditure that goes over the budget limit of the Facility Company in question. For example, if in total 12,500 euros are spend on bicycles, but the budget for that year and that specific Facility Company is only 10,000 euros, the budget exceedance at that moment is 2,500 euros. The budgets get redistributed at the end of the year, setting budget exceedance also back to 0.

The demand of end users is the cumulative value of all the demand attributes of the End-Users at one point in time. This value will give an indication of how high the demand is at any point in time, and what trajectory that demand value has. Is the demand increasing or decreasing over time? This KPI will show if the supply chain can fulfill most of the demand or if it has to scale down, indicating the performance or the presence of any bottlenecks in the system.

6.5. Policies

Most policies are the variations in parameter values of specific variables. These variables being: *initial justification*, *order processing capacity*, *critical budget left share*, *Facility Company budget yearly total*, *general willingness to share*. More on these specific variable ranges and the policy designs in section 6.3 experimental design. There is one policy, predictive replacments, that requires structural change to the model. The facility companies are the agent that will execute this policy yearly. Facility companies will go round every End-User in their region and count the amount of bicycles, along with their current states. Facility companies can then compare these quantities and states to the actual demand of the End-Users. The difference in bicycles can then be ordered by the Facility Company and delivered to the End-Users.

6.6. Implementation

The agent-based Bicycle Supply Chain Model is programmed in NetLogo software created by Uri Wilenski in 1990. NetLogo version 6.2.0 is used. Jupyter Notebook with Python 3 is used to run the EMA workbench experiments on the NetLogo model. The model, data and accompanying Jupyter Notebook python scripts can be found online at: `https://github.com/ChrobGort/Master_Thesis`

7

Verification and Validation

This chapter will discuss the verification and validation of the constructed model. Verification entails the comparison of the conceptualized model with the implemented model. Does the model accurately portray and behave as the formulated conceptual ideas from chapter 5? Validation is concerned with the accurateness of the model behavior with regards to representation of real world behavior. Does the model behave the same as the system in the real world? Verification and validation steps will be taken to show the degree in which the model is verified and validated. However, a model is always a simplified version of reality and all models are wrong, but some are useful (Box, 1979).

7.1. Verification

Verification is an important step in determining the value of the model. Often, the working of the model in relation to the expected behavior is taken for granted (Crooks et al., 2008). Therefore, the concepts as portrayed in the conceptualization will be compared to the actual implementation in the model logic and to the output of the model. These concepts relate to the information, financial and physical distribution structures within the system. The information layer encompasses mainly the the flow of orders between agents. The financial layer concerns the distribution of budgets among facility companies and the interactions happening due to lacking budgets. The physical distribution layer is the layer in which the bicycles are distributed to the end-users, based on states from the information and financial layer. Then finally, the policy implementations are verified as well, since they are focused on structural changes in the model and require logical coding. The verification is done through asking questions on key mechanics within the model, such as; Does x not ever exceed y?

End-user In the model, end-users are at the beginning of the supply chain cycle for defense. They are responsible for the demand articulation according to their needs. Orders are created as lists, which are then sent to other agents that read-out those orders and make decisions accordingly. Verifying the exchange of orders happened during the modelling process, as the desired behavior was known (partially). The desired behavior of the order transferring between agents is step-wise, beginning at the end-user. The end-user creates an order according to his/her demand and the actual amount of bicycles in possession. Important checks include: Does the order quantity equal the same quantity that makes the replacement share? Does an end-user create only one order at a time? Does the end-user wait for the placed order to be fulfilled before creating another order? Do the values within the order correspond to the end-users attributes? Are costs added correctly to the expenditures of the facility company which the end-user falls under? Are bicycles delivered to the end-user when the order is processed by the supplier? Does the possession of bicycles change accordingly when bicycles are delivered? Is effort increased for each action in the process of the end-user? All these questions are checked and answered yes during the modelling process.

Facility company The main function of the facility company is keeping track of aggregate expenditures and processing orders with high costs through checking justification or requesting help from finance and control. Each end-user falls under a facility company, so that that facility company is responsible for the actions of the end-user. Important checks include: Does the order list attribute only contains unique orders with different order numbers? Does the length of the order list never exceed the capacity of that facility company? Are high value orders only send to the supplier if adequate justification is provided? Are orders above a certain amount always investigated by the finance and control agent? Are orders within the order list of the facility company correctly changed by the finance and control agent with respect to justification? Are the orders send to the supplier if conditions are met?

The facility companies also plays a large role in one of the structural policies; predictive maintenance. This structural policy happens once a year and all poor state bicycles are replaced. This can be verified by looking at the expenditure plots. This graph line dips significantly immediately at the beginning of the year, which without this policy does not occur. This is a strong indication of the bicycles being replaced.

Supplier The supplier tasks are quite trivial: Delivering the bicycles using the orders they receive from the facility company or end-users. Again, no duplicate orders should be received by the supplier. The supplier cannot deliver more bicycles than he has in his stock. The stock is resupplied during a specified period per year and only then. When bicycles are delivered, the supplier must ensure the poor state bicycles are removed from the model and replaced by new ones. Also the supplier removes the satisfied order from the facility company and end-users order lists. All these conditions are met, thus we can say the supplier functions as intended.

7.2. Validation

The aim of validating a complex system model is to establish how accurate the model represents reality. Charnes et al. (1996) distinguish validation in three ways: conceptual validation, data validation and operational validation. Conceptual validation concerns the assumptions and theories underlying the conceptual model. Data validation is ensuring adequate and correct data that is used in the model.

The operational validation is important for this section, as it is concerned with the accuracy of the simulation model itself, with regards to the goal of the model. Charnes et al. (1996) define operational validation as:

> *...determining that the model's output behavior has sufficient accuracy for the model's intended purpose over the domain of the model's intended applicability.*

The behavior as a product of the model needs to contain that what is needed for answering the research question, and do so in a sufficiently accurate manner. Then, what is the goal of the model? In this research it is not optimization, but rather exploration of intra-organizational dynamics and performance under varying conditions and policies. There is also a methodological aspect to the goal of the model, which is understanding if agent-based modelling, and the accompanying worldview from a complex adaptive system perspective, is useful in the analysis of intra-organizational supply chains.

Davis (1998) identify three different kinds of validation techniques: Empirical evaluation, theoretical validation and evaluation by other comparisons. Each of these is useful in its own way and may or may not be useful in different circumstances of the model.

7.2.1. Empirical validation

Empirical validation works by comparing the output data from the model and either historical, field-test or simulator/laboratory data Davis (1998). The KPI's of the bicycle supply chain model are difficult to validate in this manner, as the most of the important output factors revolve around the measuring of effort, which is not accurately measured in real-life. The specific hourly workload per supply chain within Defence has been investigated prior to this research, but with no meaningful results. Other KPI's such as *budget exceedance* and *average waiting time* are more easily monitored. The next paragraphs will validate some of the important model aspects.

Time Correspondence with the head of Operations Support (bedrijfs ondersteuning) gave insight in the length of processes at the facility companies, see appendix A.2. He explained that when end-users file an order, it should take 1 day to get it checked by the service station at a military base. The service station forwards the order to Inventory control and Logistics. They then upload the order into the digi-inkoop system, which the supplier is also connected to. The supplier can then read the order and deliver the bicycles accordingly. This whole process should not take more than 5 working days. The actual delivery of the bicycles is outside of the scope of the model, although a shortage in stock can be simulated in order to see how the system reacts to a low supply.

In the model, the average waiting time is measured in ticks. Every tick equals 2 days in real life. In the exploration scenarios and policies, we see a high density of runs varying around 0 to 10 days, see figure 7.1. The delays in the simulation model occur not in the described processes by head of operations, but rather when the assortment manager or finance and control intervene based on their decision rules. The interview with Finance and Control (see appendix A.3) learns that delays in the chain occur when large orders are filed that exceed the budgetary limit of the facility company region. It can therefore be concluded that the simulated delays originating from the assortment manager or finance and control cannot be validated from the point of view from the head of operations. Concluding, the average waiting time can partly be validated from the perspective of Finance and Control.

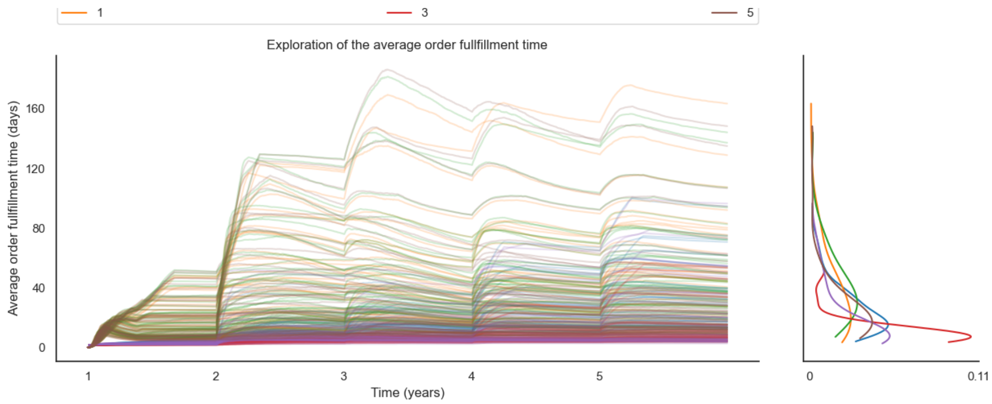

Figure 7.1: Average fulfillment time on orders. From initial order creation to bicycle delivery to the end-user.

7.2.2. Theoretical validation

Theoretical validation revolves around the logic behind the model. Are the assumptions reasonable? Are causes and effects in-line with what is expected? To this end, the results and behavior of the model is analyzed. For example, the policy of increasing willingness to share information causes the effort of Facility Companies to rise, instead of the expected decline. This caused some unexpected results in chapter 8. However, since it is very difficult for one actor specifically to have an birds-eye view on the subsystem of the bicycle supply chain as a whole, face validating the model with use of experts is difficult. It was said multiple times during the interviews with operating actors in the chain that all the different Military bases within Defense have their own manner of specific distribution of bicycles. This is why resolution is kept lower than that level of detail.

7.2.3. Difficulties in validation

The effort KPI's are a quantification of working hours put into the bicycle supply chain. Almost all agents within the supply chain, except the external supplier, have other task alongside that of the provision of bicycles. For example, the facility companies provide many other facilitating goods. From kitchen appliances to pencils. The employees working at a facility company will spend their effort on multiple supply lines per day, making measuring exact hours spent per line almost impossible. This indicates the trouble of gathering very detailed process measurements.

Also, decisions that actors take are always a difficult feat to accurately conceptualize, as some agents might not even realize on which information they base their decision, or they might not even know that they are making a significant decision. In other words, persons begin represented as agents make subjective choices, which are hard to quantify and put into a model as programmable rules (Bonabeau, 2002). This makes the validation of such decisions a difficult feat.

8 Results

In this chapter the result are discussed regarding the behavior of the model. The research sub question that is important in this final stage of the research is the following.

> *How do different policies influence the processes of the agents and thereby influence the average waiting time, budget and effort, under varying demand and supply scenarios?*

To answer this question, this chapter will show the results of the model behaving under different scenarios and policies. The scenario and policy designs are created in the first section, focusing on exploration of the model behavior using the Exploratory Modelling and Analysis (EMA) workbench python package. The EMA workbench allows for easy exploration of simulation models. The sensitivity analysis following from the execution of the experimental design are discussed and analyzed in the second section. Finally, interesting experiment designs are further reviewed using narrower parameter spaces.

8.1. Base case

The base case is the base scenario where all parameters have the values as defined in 6.2. These values are estimated to be closest to the current real-life situation, without accounting for variations in the input parameters due to future uncertainty. Figure 8.1 shows the outcomes over time for all the KPIs, with 50 repetitions of the base scenario. There is quite linear behavior for most of the KPIs, except for the *budget exceedance* in the second to last graph. The budget is redistributed at the end of every year, which sets the budget exceedance back to 0 and causes the lines to start at 0 again.

Most of the Key Performance Indicators show a large spread of outcomes across the 50 repetitions. This can be explained by the stochastic nature of an Agent-Based Model, but most of the spread can be explained by the randomness of the initial demand value. This randomness is build according to the distribution of order quantities. The initial amount of bicycles in the system is determined by the initial demand. The last graph in figure 8.1 shows that the initial demand can range from around 6000 to 7200. The randomness of the demand value is due to the uncertainty in the current amount of bicycles in the system. There is no accurate picture on how much bicycles the End-Users currently own within Defense. But, apart from the initial variance in the demand, there is even more variation when the model is running. After the first year, demand has dropped significantly for some of the repetitions.

The *orders waiting time* graph in figure 8.1 shows the average time between order creation and bicycle delivery. Every order takes at least one tick to process, which translates to two real life days. This is due to the sequential nature of the constructed ABM model. The End-User specifically is the cause for this, as he always either creates his order, or sends the order information to the Supplier/Facility Company. The End-User cannot do both in the same tick, creating a situation where always one tick is needed for the order creation and one tick for further processing.

The effort values for each agent differ significantly. Finance and Control and End-Users both exhibit a high constantly increasing effort value, while Facility Companies and the Manager share relatively low effort values. This can be explained by the constant processes of Finance and Control and the

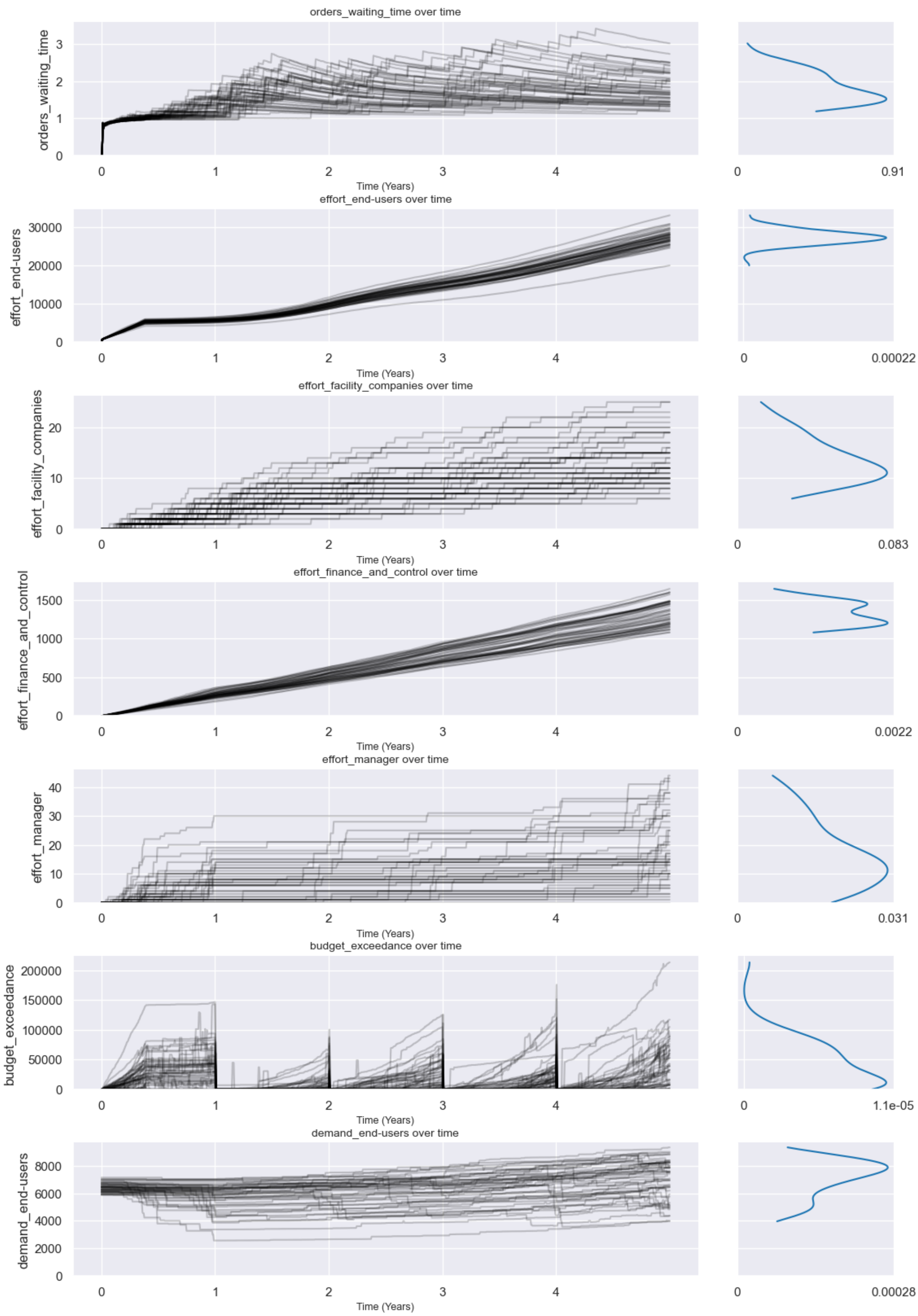

Figure 8.1: Outcomes of the base case run for each KPI, repeated 50 times.

End-Users, as opposed to the rather dependent processes of the Facility Companies and Manager. The following paragraphs will explain this.

The End-users will spend effort for each order they decide to create and place, and they will spend more effort per action as well. For example when they provide justification, the effort scales to the height of the justification. In the base case, they therefore already spend 30/10=3 effort with each order. Adding the effort of placing the order on top of this, the increase of effort for the End-Users is significant each tick. There are also just a lot (144) of End-Users present in the model, adding to the total amount of effort. Given the estimated average of around 28,000 effort in total (see figure 8.1) for the End-Users, this comes down to 28,000/144=194 effort per End-User over the 5 years. This amount is high because a part of the End-User process will repeat and count effort every tick, even when an order is already placed. That part is checking which bicycles need replacements, in the case that the amount of bicycles in possession is getting below the 25% of demand threshold. This is an **unintended** dynamic, as it is not logical for End-Users to keep checking which bicycles to replace when they already placed an order.

Finance and Control is only one agent, but still has a high effort value. This is caused by its large role when Facility Company budgets are exceeded *and* when justification on orders is too low. The budget reallocation process takes always 1 effort, if there is an order that will exceed the budget limit of the facility company he is visiting. This 1 effort entails investigating which Facility Companies have budget left. Another 1 effort is expended by Finance and Control when they decide to redistribute the budgets. The justification gathering takes 1 effort for each tick and each order that he gathers justification for. These dynamics make that most of the ticks, Finance and Control will spend 1, 2 or even 3 effort. Given the amount of ticks being 5*183=915, it then makes sense that the effort of Finance and Control reaches about 1300. 1300/915=1.4 effort on average per tick, which is in the range of 1 to 3 effort per tick.

The Facility Companies and the Manager only spend effort when they need to. Facility Companies only process orders coming in that are send by the End-User. The End-User has already checked if the order is within the Facility Companies threshold, otherwise the Facility Company does not come into play. This makes that no excess effort is spend on orders and the process of the Facility Companies seem efficient, keeping effort low. The same goes for the Manager, where he only spends effort if there is need to. The Manager cancels orders when they, combined with the current expenditures, will exceed more than 105% of the budget and Finance and Control could not increase the budget by redistribution. So, only in extreme cases will the manager come into play which explain the relatively low effort values.

8.2. Experimental design

The experimental design follows the XLRM framework which the EMA workbench also uses (see figure 8.2). The XLRM framework stands for external factors (X), policy levers (L), relations within the system (R) and performance metrics (M). The external factors are in this case represented by the uncertainties as posed in table 8.1, along with the policy levers and performance metrics. The relations within the system are defined by the agent based model, that is coupled to the EMA workbench within python. The defined parameter ranges in the ”Range” column in 8.1 represent the parameter space that is investigated. The parameter space is kept broad by using wide ranges over the parameters that are uncertain in the future. The given ranges are assumptions as per the estimation of uncertainty of that specific variable. This is done arbitrarily. Especially if the corresponding variable was assumed in the base case in the first place, these changes give insight in the behavior given different model configurations. In total, 300 experiments are created using Latin Hypercube Sampling over the policy and uncertainty spaces. 50 uncertainty scenarios and 6 policies, of which each policy is combined with each of the scenarios. Due to the stochastic nature of the model, each experiment is run 10 times. The results of the model are measured using the Key performance Indicators as defined in section 6.4.

8.2.1. Uncertainties

The first 4 uncertainties in table 8.1 concern demand and the bottom 4 uncertainties concern supply uncertainties. Important choices in parameters and ranges are explained in this paragraph, starting with the demand uncertainties. The *yearly demand growth* parameter represents the growth in bicycle demand due to either the expansion of Defense itself, meaning more employees, or higher demand

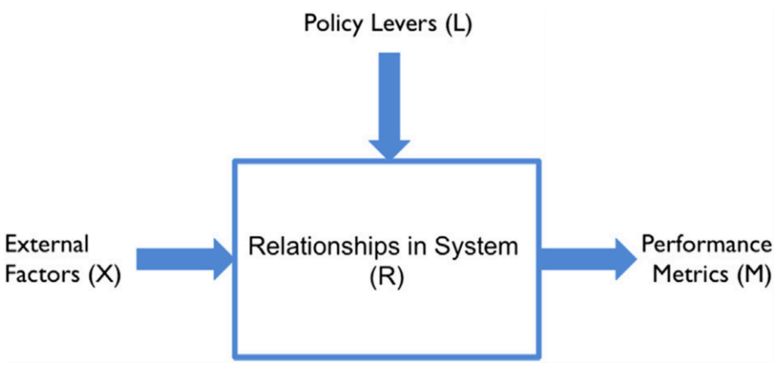

Figure 8.2: The XLRM framework (Kwakkel, 2017).

Table 8.1: Parameter space definitions.

Type	Parameter	Range	Source
Uncertainties	*yearly demand growth*	0-10% of total demand	
	bicycle average lifetime	4-6 years	
	share demand malfunctioning	10-40% of possession	
	initial amount of bicycles	2-6 factor*	
	manufacturing cycle	3-9 months per year	
	production rate	5-20 bicycles per day	
	max Supplier stock	100-2000 bicycles	
	price per bicycle	200-600 euros	
Policy levers	*initial justification*	0-50	
	order processing capacity	1-5 orders	
	critical budget left share	0-20% of budget	
	Facility Company budget yearly total	300k-1m euros	
	general willingness to share	low, medium, high	
	predictive replacements	true-false	
Performance metrics	*orders waiting time*		
	demand End-Users		
	effort of End-Users		
	effort of Facility Companies		
	effort of Finance and Control		
	effort of Manager		
	budget exceedance		

density among employees. This number cannot be negative, as the parties during the elections of 2021 all had the standpoint of increasing investments in Defense. It is assumed that this will also mean a larger demand in bicycles. The maximum range of 10% increase might only be realistic with a small chance, however it is interesting to see how the system reacts in such an extreme scenario. The threshold *share of demand malfunctioning* is the percentage of bicycle demand per End-User that needs to be either broken down (removed from the model) or in very bad state, before the End-User will create an order. The unit of *initial amount of bicycles* is a factor, which is multiplied with the initial generated demand of End-Users. The generated demand is based on real-world data distributions among End-Users, but it does not resemble the quantities of bicycles in possession of the End-Users.

The supply uncertainties originate from the Supplier. It could happen that the Supplier is not able to sustain adequate production, does not have enough stock or other complications due to which the Supplier cannot comply to Defense's demand. For example in the COVID-19 pandemic, when the demand for bicycles rose explosively because it was one of the few activities that was still allowed by the government. As the Dutch are avid bikers, a lot of people invested in a new bicycle resulting in a surge for demand and a shortage of supply (Van Marrewijk, 2021). The *manufacturing cycle* is the time period per year in which the Supplier produces the specific model of bicycles needed by Defense. The Supplier cannot produce the same model of bicycle the whole year round and is also not able to produce all models at the same time, because the capacity of the manufacturing line is limited.

8.2.2. Policy levers

The policy levers are also shown in table 8.1, consisting of structural and parameter based policies. *Initial justification* is the justification that every End-User initially has and that they pass onto the orders they create. The higher the justification, the better the argumentation behind the order created. Ambiguity of this lever value exists, as elaborated in the conceptualisation chapter 5. However, it is an important driver of the processes behind the supply chain of bicycles because it guides other agents such as the Facility Company and Finance and Control in their decisions. The maximum value of this variable in the model is 100. In the experimental design, the maximum initial value is set to 50. This will ensure that large order are always investigated further by Finance and Control, because the justification threshold for medium orders is also set to 50.

The *order processing capacity* is the amount of orders the Facility Company agent can process in parallel. In real-life this can be translated to the size of the workforce and efficiency available to the Facility Company. This can of course vary by the available operational budget and variations in the total workload for the Facility Company.

The *critical budget left share* is the threshold at which Finance and Control are more strict on the justification behind the order.

Facility company budget yearly total is the budget that the Facility Companies receive each year for the provision of bicycles. The cost of every bicycle that is ordered is subtracted from the budget of the according Facility Company. Right now, the budget in total for all the Facility Companies combined is 500,000 euros per year. Variations on this budget will show how it influences the effort of the different processes.

The *general willingness to share* is the willingness of End-Users to share more information on the justification behind their order. One scenario in which this willingness becomes low is when for example the trust among agents is low. Agents are not eager to share when they do not fully trust other agents. Distrust could arise from mistakes made in for example a declination of an order by the Manager.

The final policy lever *predictive replacements* is a structural policy in which extra action is taken by the Facility Company as described in chapter 6.

8.3. Sensitivity analysis

The sensitivity analysis aims to explore how the variance in input parameters explain the variance in the output variables, or behavior of the model. Thus, what input variables are of the most influence on the outcomes of the model. The EMA workbench provides a feature scoring test (as explained in chapter 3) that shows how sensitive outputs are to inputs. This test is executed on the results of the 300 experiments run in the previous section. See figure 8.3 for the feature score test. The value in the cells can range from 0 to 1, 0 meaning no influence and 1 meaning full influence of the input parameter on a performance indicator. The rest of this section will discuss the findings from the feature scores in

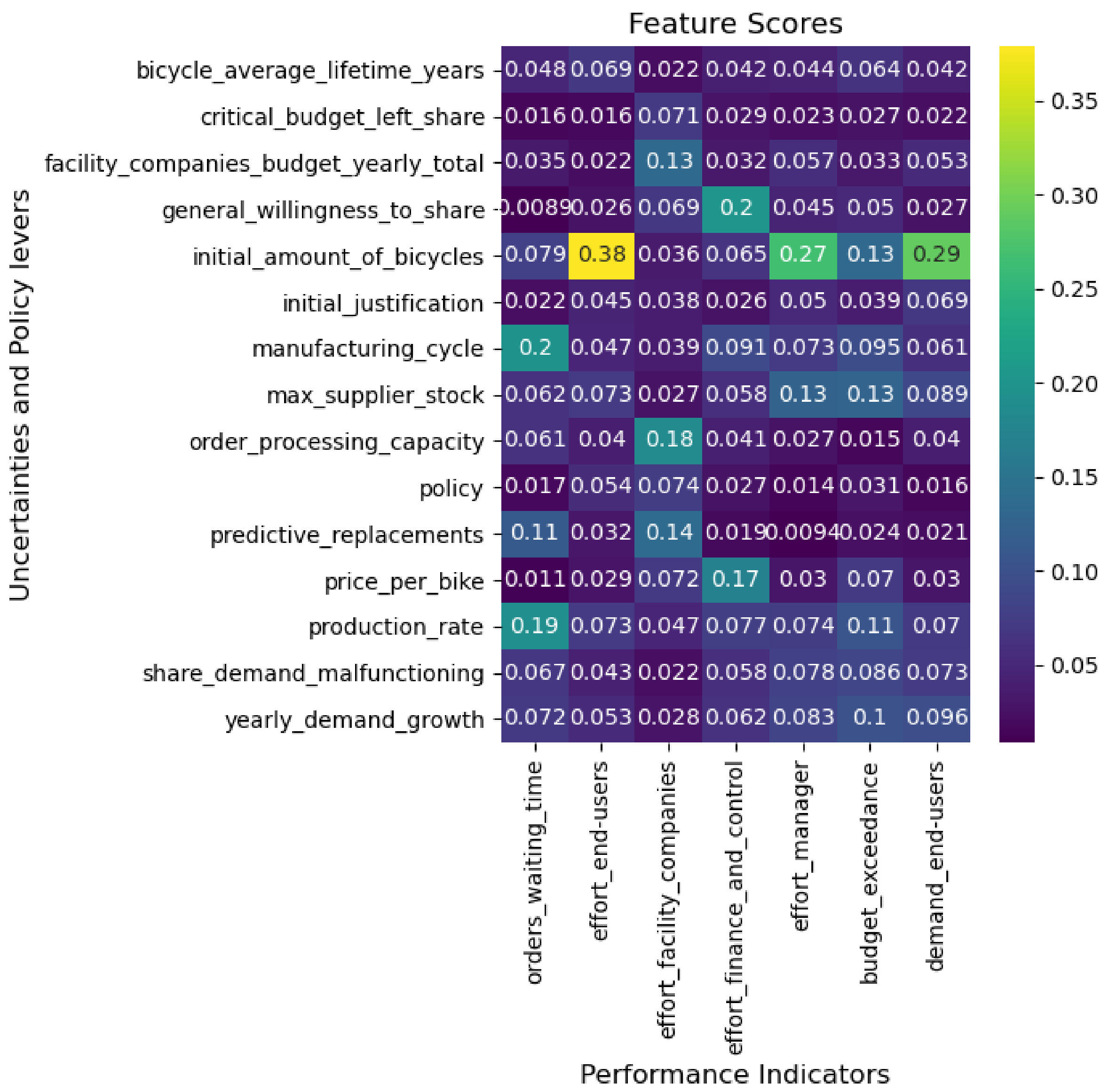

Figure 8.3: Feature Score test on the bicycle supply chain model outcomes.

figure 8.3.

In general, the feature scores are low with no extremely high values (see figure 8.3). The maximum score that can be achieved in that test is 1. In that case, a parameter would fully determine the value of the corresponding KPI. In the executed feature scoring test, the maximum score achieved was 0.36 with most of the values not coming close to that number. This means the uncertainty and policy parameters all influence the KPI's, albeit in varying strength. There are some parameters that do influence the model behavior more significantly than others. These parameters and specific feature scores will be explored in the next paragraphs.

Budget and Effort of Facility Companies The *Facility Companies budget yearly total* (from now on just "Facility Company budget") influences the *effort of Facility Companies*. The Facility Company budget is a policy decision made by the dutch government ultimately, but more directly by Finance and Control. Finance and Control is responsible for the specific budget distribution per type of product and per Facility Company and therefor have a big say in budgetary distributions. Facility Companies experience a change in effort in their processes as budget changes, as seen by the feature score. Most of the effort within Facility Companies comes from checking medium and large sized order and fitting these into their budget limits. If the order is to high of value or budget is limited, the Manager or Finance and Control become active. Also, if the budget is limited, more effort has to go towards containing expenditures within the budgetary limits.

The range of budget only had a minimum of 400k in the experimental design. That is why the influence of the budget is relatively low on most of the performance indicators. For example, one would expect that a low budget causes a low demand. The demand-driven approach of the supply chain system probably prevents this dynamic: The demand is set either way, budgetary limit or not. Only the Manager can scale down the demand by saying no to the End-Users. However, there is no such influence shown due to the low feature score of budget on the effort of the Manager.

Willingness to share The *general willingness to share* is a policy lever within End-Users that can be shortly defined as the willingness to provide arguments on the necessity for orders that require more justification from the Facility Company or Finance and Control. Either due to the cost of the order triggering more inspection by Finance and Control or the Manager. This willingness to share influences the effort of Finance and Control significantly. The effort of Finance and Control lies in the gathering of information on the justification, thus this relation makes sense from a model viewpoint.

Demand dynamics An indirect effect via total demand can be seen in the feature scores of the 1) *initial amount of bicycles*, but also in the 2) *price per bike*. These two uncertainties influence the *demand End-Users*, but also simultaneously influence the *effort Manager*. This strongly indicates an indirect effect of demand of End-Users on the effort of the Manager, which makes sense combined with the knowledge on the Managers' processes; The Manager is responsible for ”selling the no” i.e. decreasing demand if necessary due to budgetary constraints. So, would demand rise given a constant budgetary limit, then Managers have to put more effort in containing expenditures.

Another point on demand is that, in the model, the total demand of End-Users is made up of two factors: 1) *yearly demand growth* (new demand due to growth of Defense as a whole) or 2) maintenance demand (due to bicycles breaking down). The first factor, yearly demand growth, does **not** greatly influence the total demand variable of End-Users. The demand KPI is therefore relatively insensitive to the demand growth. This means that most of the total demand variance comes from replacing maintenance bicycles.

Initial amount of bicycles The initial amount of bicycles means a factor with which the initial distribution of demand is multiplied, see appendix C for more information. How the different agents cope with a high demand and low budgetary constraints is explained in the next section. The *initial amount of bicycles* is an uncertainty with the most influence across the whole of the KPI's as seen in the feature scores in figure 8.3. It is therefore one of the most important uncertainties in the model. On top of the interactions described in the paragraph above on the demand dynamics, it also influences the *effort of End-Users* greatly. A smaller influence can be seen on the *budget exceedance*, possibly through the same indirect effect as described in the previous section.

supply uncertainty Two of the supply uncertainty parameters, the *manufacturing cycle* and the *production rate*, declare for the most part the variance in the average waiting time performance indicator. When supply is insufficient to satisfy the demand, waiting time increases until there is enough supply available.

Predictive replacements policy Looking past the supply uncertainty, the *predictive replacement* policy lever parameter has a small but significant influence on the waiting time as well. However, there is an influence on the effort of the Facility Companies, as the predictive replacements take pro-active effort when determining where to replace the bicycles.

8.4. Exploration of future scenarios and policies

Figure 8.2 shows the 6 sampled policies, but only those policy levers that had a significant influence on the Key Performance Indicators in the feature scoring test in figure 8.3. Those being the *General*

general_willingness_to_share	facility_companies_budget_yearly_total	order_processing_capacity	predictive_replacements	policy
medium	723054	3	False	0
high	631804	2	True	1
medium	955070	2	True	2
low	409024	5	False	3
high	449295	4	False	4
low	781279	1	True	5

Table 8.2: Sampled policies with the policy levers that the bicycle supply chain model is sensitive to.

willingness to share, *Facility Companies yearly budget*, *Order processing capacity* and *Predictive replacements*. First we investigate the trade-off between the predictive replacements policy. Then, the general willingness to share impact is investigated.

8.4.1. Predictive replacements

Figure 8.4 shows the impact of the *prediction replacement* policy on the value of the *orders waiting time* and the *effort* of the different agents per experiment. The density plots on the right hand side display the distribution of the experiment lines. The third graph shows a clear difference in the effort of the Facility Companies, with (orange lines) and without (blue lines) the predictive replacements policy implemented. There is an increase in effort for the Facility Company in most of the experiments with the policy implemented. Also, the form of the lines change to a sort of step function; The effort jumps in value at the end of the year. This can be explained by the bicycles that are evaluated and replaced by the Facility Company at the end of the year, which requires administrating and ordering bicycles and thus increased effort. The rest of the year, between the steps, most experiment lines stay relatively steady and flat with a low coefficient. Except for some of the upper lines. Although an increase in effort for the Facility Companies means more labor force going towards that process, other agents experience a slight decrease in their effort values. This can be seen in the bottom two graphs, which display the effort of Finance and Control and the assortment Manager. The density plots on the right show a slight shift downward, indicating a decrease in their general effort input. However, the first graph on orders waiting time and the second graph on End-User effort seems to have a slight shift upward, indicating a general rise of the performance indicators values. The extreme cases in the first graph on order waiting time have also increased.

8.4.2. Increased willingness to share

Figure 8.5 shows the results of the experiments categorized by the *General willingness to share*, for the KPI's *effort of Facility Companies* and *effort of Finance and Control*. The willingness to share policy could not declare significant variance in other key performance indicators. The first graph in figure 8.5 shows a clear bifurcation in the experiments with a *low* willingness to share. Part of the effort values at the end of the run bundle around 50 and another part bundle around 5. This variance can be further declared by the predictive replacements policy as shown in figure 8.6. With predictive replacements policy on True, effort values come out much higher than without this policy. However, a non-intuitive finding is that the effort of Facility Companies increases as the willingness to share also increases. Low willingness to share combined with no predictive maintenance policy implemented comfortably gives the lowest effort values for the facility company.

In the second graph of figure 8.5, the higher the willingness the share, the less effort Finance and Control has to put into their processes. This dynamic is expected as one important aspect of the process within Finance and Control is the gathering of justification. This task of Finance and Control is triggered when End-Users did not provide sufficient arguments as to why they need their demand. The rate of the willingness to share information of the corresponding End-User determines how much effort it takes for Finance and Control to gather justification. The more willingness to share, the more information Finance and Control can gather.

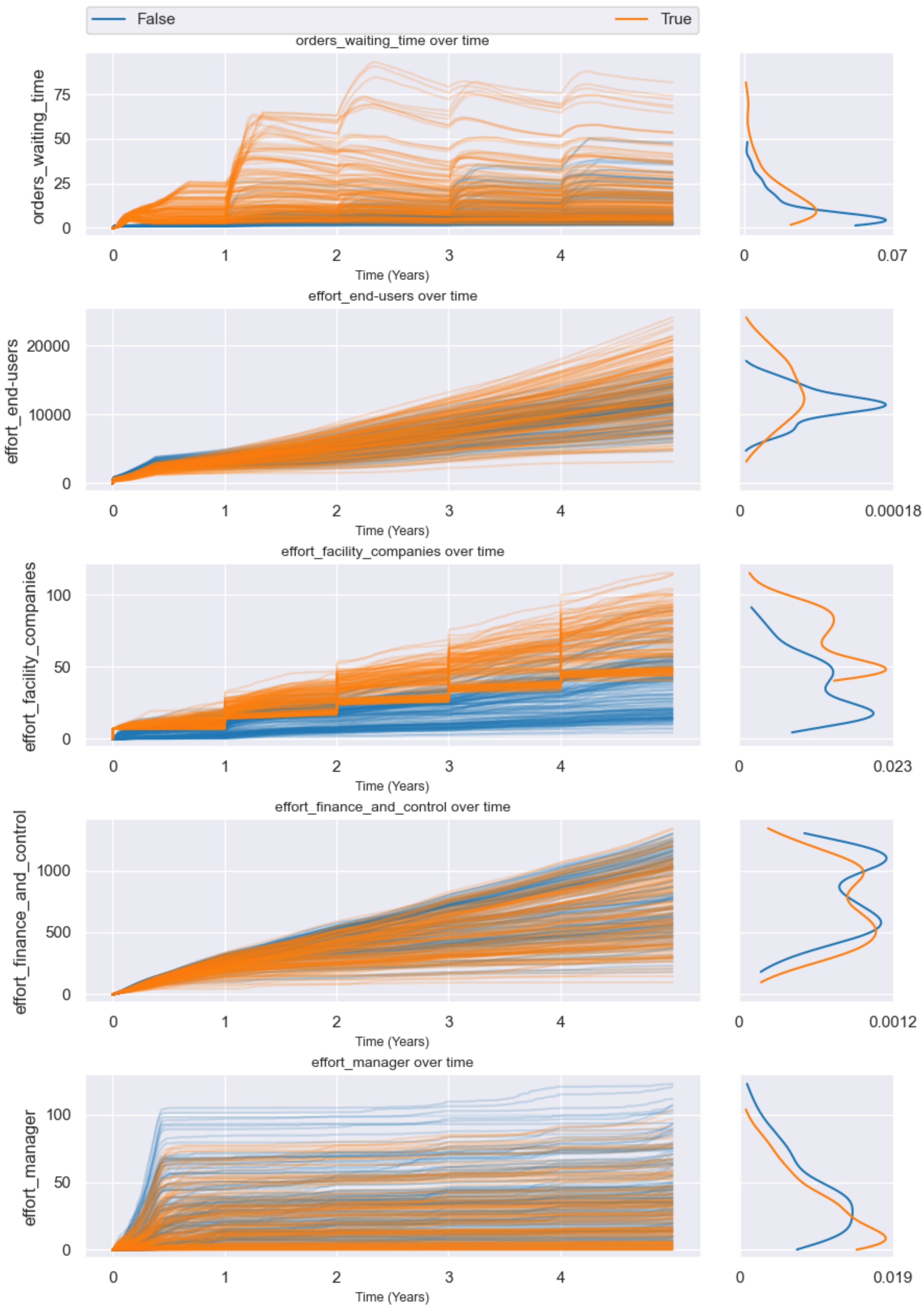

Figure 8.4: Outcomes of the experiments, categorized by the Boolean value of the prediction replacements policy.

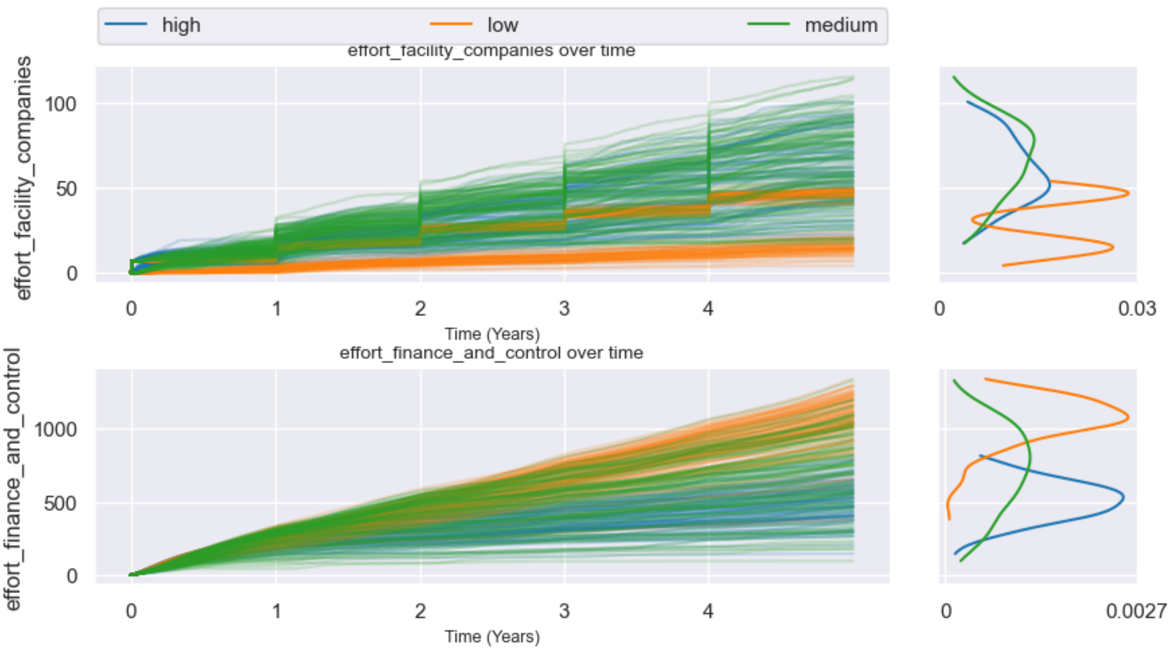

Figure 8.5: Outcomes of the experiments for ”effort Facility Company” and ”effort Finance and Control”, categorized by the ”willingness to share” policy.

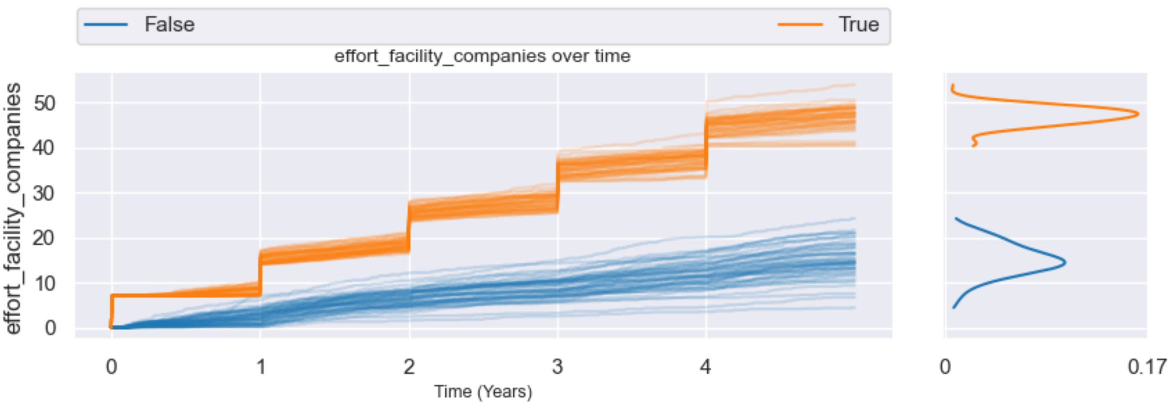

Figure 8.6: Outcomes of the experiments where the ”willingness to share” policy is low, corresponding to the the line that shows the bifurcation in figure 8.5. The lines are now categorized by the predictive replacements policy and one can see that the variance in the low willingness to share policies is now fully declared by the predictive replacements

9 Discussion

9.1. Findings and alternative explanations

The complexity of the supply chain system within Defense originates from the multitude of processes concerned with the functioning of the supply chain. These processes occur in multiple structures: The financial, information and physical goods distribution structure. This complexity made the evaluation of policy measures complicated, if not impossible to do holistically. Therefore, gaining an insight into the processes behind the bicycle supply chain of Defense was central in this research. The different processes were conceptualized and implemented in a simulation model, which allowed better understanding of the entire system.

The simulation data gathering approach and most important findings from this data are first restated and summarized in this section. The first step was running a base case scenario to which other result could be compared. Then, extracting the behavioral data from the model with an exploratory approach using the EMA workbench. 300 Experiments were run including 50 scenarios and 6 policy combinations, giving outcomes on 7 different KPI's. The goal of these runs was to see how the model behaved under diverse conditions of demand and supply uncertainty. A feature scoring test gave insight in the sensitivity of the KPI's to the uncertainties and polices. Plots of the relevant outcome values categorized by effective policies gave insight in specific relations. The following findings were most significant.

- The **base run** showed large variability in outcomes, even though the same input parameters were used over the repetitions. The uncertainty on the current amount of bicycles is one cause for the initial variance in demand. However, the results showed an increasing variance over the model run. One alternative explanation for this dynamic could lie in the sequential and random nature of the Finance and Control agent process. The Finance and Control agent randomly visits one of the Facility Companies that still have open standing order, indicating a hick-up in that Facility Companies' process. This hick-up is a trigger for Finance and Control and why it is coming to help. However, if there are some very large orders in process, the manager might see this while monitoring expenditures and budgets. Before Finance and Control has a chance to either increase budget or increase justification, the manager might intervene and cancel the order, and accompanying, decrease the demand of the End-User that filed the order. This can explain the drop in demand, even though each repetition is subjected to the same budgetary limit.

- The sensitivity analysis showed how most of the uncertainties and policies influence **multiple** metrics. The interactions between agents and processes therefore seem to have effects throughout the whole model, on multiple structures within the system. This can be explained by the interconnection of the structures, through for example the budgetary and information interactions.

- The varying **budgets** posed on the Facility Companies only resulted in small behavioral changes of the model. This result is somewhat unexpected, as a limited budget could create an increase in effort from the Facility Companies and Finance and Control towards the tracking of expenditures in case of high demand scenarios. However, no such dynamic was found.

- There seems to be an **indirect effect** of the price and initial amount of bicycles on the effort that the Manager has to put into his process. This process is the containment of expenditures when they are reaching budgetary limits. Such an indirect effect shows the complexity of the system and the difficulty in seeing the effects of an uncertainty on the behavior of the model.
- **Demand** and **supply uncertainties** greatly influence the effort that has to be put into different processes in order to keep the whole system running. When demand is increasing, more strain is put on the order processing as budgetary limits are reached sooner and there are more large demand orders to be processed by multiple agents.
- **Predictive replacements** is a promising policy implementation. However, a trade-off occurs between a) decreasing effort for Finance and Control and the Manager and b) increasing the effort for the Facility Companies and the average order waiting time. Moreover, the increased waiting time is opposite of what was aimed at when implementing this policy. The increased waiting time probably occurs due to the limited stock of the supplier. Orders for predictive replacements are placed at once at the end of the year, resulting in a surge of demand which the supplier is not ready for. On the other hand, such yearly events can easily anticipated by consulting with the supplier because it greatly increases the predictability of demand timing and quantities. This finding does show the complexity of the system and the dynamics between the agent processes. The trade-off effect of the policy implementation is not a clear cut improvement of the system, but rather gives insight in difficult choices to be made for decision-makers. This finding is in-line with Bisogno et al. (2016) who found their simulation method for business process analysis also gave insight in trade-offs between KPI's, which is helping managers in achieving operational performance in a complex environment.
- End-Users' **willingness to share** information on the justification behind their demand greatly influences the effort of Finance and Control. The higher the willingness of sharing information, the more efficient Finance and Control can gather information, thus expending lower effort in total. However, higher willingness to share is causing the effort of Facility Companies to *increase*, which contradicts expectations. This could be explained by the slower throughput of the Facility Company. Slower throughput could be caused by a slower rate of justification gathering by Finance and Control as a result of the lower willingness to share information of End-Users. This causes the specific order to spend more time in the order list of the Facility Company, and thus not advancing in the process. The Facility Company only spends effort when they send an order to the supplier, but if the orders never reach this step due to insufficient justification, less effort will be spent on this step in total.

9.2. Generalizing to other goods

Given the outcomes of the case study on bicycles, what can be said about intra-organizational supply chains on other goods? To answer this question we categorize bicycles using a portfolio purchasing model and logically assume that the conclusions of this case study can apply to the goods falling in the same category. Bicycles officially fall into the assortment of "non-system bound goods and non-military equipment". But, how does this compare to the categorization that has to be made when choosing supply chain designs? A recent paper by Ekström et al. (2021) developed a new Portfolio Purchasing Model for military organizations, taking into account the wishes of practitioners when it comes to the usefulness of such a model. This model is shown in figure 9.1.

Using the model in figure 9.1, the category which bicycles fall into can be identified and used to extrapolate. The first stage of the model concerns the operational requirements and selecting the appropriate values as laid out in the model. For bicycles, this is assumed to be an *availability* of at most 3 months, here we are limited to the dimension values set by the authors because 3 months is pushing it, but it does provide a better comparison to other goods by sticking to these values. The *preparedness* of bicycles is in hours, a bicycle can be reasonably expected to be functional (after delivery) within at most a couple of hours. Sustainability should be conform contract agreement, which is currently defined as "the chance of bicycles breaking down should be as low as possible", giving no concrete value on sustainability.

The *market's ability to deliver supplies on time* dimension for bicycles can be set to "High", as "guaranteed" has not proven possible during the covid-19 crisis. The demand for bicycles in the Netherlands

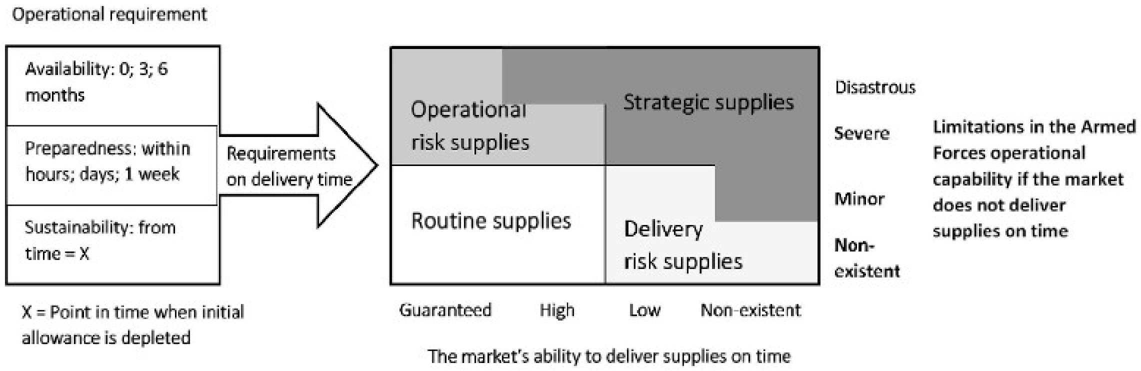

Figure 9.1: A Portfolio Purchasing Model by Ekström et al. (2021) for the categorization of goods and the design of supply chains.

skyrocketed due to most sports being canceled, which meant that many Dutch citizens took up their favorite past-time and bought bicycles en masse. This caused the supply for Defense to be halted a short while, but other models could be offered shortly after to compensate the lack of supply capacity. The *limitations in the Armed Forces operational capability if the market does not deliver supplies on time* final dimension means the effect of not having bicycles on the functioning of Defense as a whole. For bicycles, the effect will be ”Minor” as bicycles are used most often in a non-combat scenario.

To conclude, bicycles in this research can be classified as having **low operational requirements** and placed in the **”Routine supplies”** quadrant. Thus, the conclusions made in this paper can potentially be extrapolated to goods that have the same classification, according to the model by Ekström et al. (2021) that is. Other portfolio purchasing models exist, but Ekström's model is very recent and is specifically aimed at Defense organizations. It also involved the evaluation of previous purchasing portfolio models by practitioners from within the (Swedish) Defense organization.

9.3. Suitability of Agent Based Modelling

This section will reflect on the use of agent-based modelling for the analysis of the bicycle supply chain and similar systems. Supply chain systems can be viewed from a multi-agent perspective, where agents operate autonomously and are heterogeneous. However, the order-centric nature of supply chain systems is less suitable for agent based modelling approaches (Chatfield et al., 2006). A holistic perspective on the effectiveness of the used method is formulated by first stating the characteristics of the bicycle supply chain system. Then, comparing these characteristics to the agent-based world view and noting the usefullness and hurdles encountered in this research. Finally, reflections on the three simulation options of *system dynamics*, *discrete event simulation* and *agent-based modelling* are elaborated on.

9.3.1. The bicycle supply chain as a system

The bicycle supply chain as found within Defense is clearly characterized by agents: The End-Users, Facility Companies, Finance and Control, Managers and supplier. These agents have their own goals and responsibilities within the chain. These goals and responsibilities are shortly reiterated here, *within* the scope of the research and the boundaries of the supply chain system. End-Users create the demand and provide justification on their orders. Finance and Control is concerned with the budget distribution. Facility Companies with the provision of the bicycles by processing the orders. Managers with cancellation of orders and suppliers with the production and delivery of bicycles. These goals are often conflicting. For example, the Manager needs to contain the expenditures within the budgetary limit and the End-Users want all their demands met. The difference between these goals, and the decision rules that are a result of these goals, means heterogeneity between the agents.

We also identify bounded rationality within the bicycle supply chain, where not all agents have the access or capacity to all information. This is modelled in the ”justification” on orders. The End-User created an order with a certain degree of justification as to why he needs the amount of bicycles he is ordering. The other agents are aware only of the given justification, but initially do not fully grasp the full argumentation behind the order. Only with gathering of information by the Finance and Control agent more justification is achieved. The agents other than the End-Users are bounded by their own rationale in this aspect. Bounded rationality is a key aspect of the agent-based world view (Crooks and Heppenstal, 2012).

Another characteristic lies in the order-centric nature of the supply chain, and supply chains in general. The whole model revolves around the orders being passed from agent to agent, starting at the End-Users that ultimately determine the demand. Along the way, the order is analyzed by different agents when appropriate, for example when the expenditures approach the budgetary limit. Order-centric systems are best modelled using an process-interaction formalism, in which the sequence of actions and events are laid out for each entity (Chatfield et al., 2006). Here the system differs from what the agent-based approach is intended for.

9.3.2. Difficulties in programming

The behavior and heterogeneity between the agents was natural to implement using the agent-based method. However, the process oriented and order-centric nature required extensive modelling. Using lists as attributes within the agents, the order could be sent trough the model and to each of the agents. Timing and coordination of the order lists between the agent required interception code at each agent, reading and acting on the information within the orders. Each agent needed to contain the same order reading code and capacity of order storing. Extracting data on the orders was also difficult, as the orders themselves were not defined as objects and thus did not leave readily extractable information on processing times and expenditures.

9.3.3. Other simulation formalisms

Given the order-centric, agent and behavioral characteristics of the system, multiple simulation formalisms are suited. The mentioned strengths of agent representation, bounded rationality and heterogeneity of ABM were more suited for the modelling of information dynamics in the system of study in this research. Which is similar to the findings from Pathak and Dilts (2002) that identify ABM as a suited method for information dynamics within supply chains. Discrete-event simulation makes the modelling of an order-processing system easier with regards to flow of goods and orders. System dynamics is also suited for modelling the flow of goods and inventory levels, but requires a static approach to the system structure that can be captured in differential equations. This static approach makes the integration of individual behavior of entities in the supply chain more difficult (Chatfield et al., 2006).

9.4. Limitations

The most important KPI's are based on the abstract notion of effort. Effort can mean a multitude of things, ranging from administrative tasks to communication and information gathering. The ambiguity of this term is one of its pitfalls, but also one of its strengths. On the one hand, the different processing steps that the agents have to execute to maintain the service level of the supply chain are often heterogeneous and encompass very different tasks. For example, effort for Finance and Control could mean the gathering of information on the justification behind an order and the Manager might put effort towards cancelling an order if that order means exceedance of the total budget. Capturing such very different tasks in one value reduces the clearness of what the value entails. 50 effort by an agent does not tell us anything quantifiable relating to monetary value, time or otherwise due to this difference in meaning per case. On the other hand, capturing heterogeneous tasks in one value makes them comparable. Comparability makes the understanding of the behavior of a system easier. When one would subject a system (in a model) to different scenarios, but the processes are measured in different metrics, one cannot weigh them against each other. E.g. Time vs monetary value. Using a comparable metric, this system load distribution is more easily measured and weighed.

The notion of time as a measurement of workload also arose during the process of modelling the system and has been used for the measurement of delivery time. Yes, time is an easy measurable concept. Both in real life and in a model. Take a watch and stand by an employee sending an email about trailing orders and you just measured part of the process. Correspond the duration of the communication process in the model to the measured time and you have created a perfect model for analysis. This is a simplified example but it illustrates the impossibility with its simplicity. It is impossible to measure every process step duration in real life. It is already very difficult to get a grasp of how long each order spends at each agent.

Apart from the difficulty of measurement of time, or other measurable metrics such as monetary value, effort has an added benefit. It facilitates the correct external view on the results of the model. With time as a metric, it gives the indication that the system is measured and *understood* at such a detailed level. The results are perceived to be directly applicable to the real world and decisions could be made on this detailed information, for example to cut the budget of a specific agent. Using more abstract notions prevents these conclusions from being made. It must be said that time *is* used in the model, as a part of the bicycle supply chain system is measured in this way in real life as well: delivery time by the supplier.

One of the hurdles in the running of experiments was the run time. The 300 experiments with 10 repetitions each took about 20 hours in total. While this is enough for the purposes of this paper (this research did not focus on an elaborate uncertainty analysis using the full robust decision making cycle, thus not needing exhaustive experiments across the parameter space), more repetitions would have made the results more reliable, as the base case showed that there was a fairly large spread of values. The means of the current runs might be open to change under more repetitions, which could potentially cause other interpretations of the results. The long run time also made quick iterative changes to the model policies or uncertainties more difficult after the results were run and analyzed.

A point that was mentioned in all the interviews held with key actors within Defense was that every military base has a different specific distribution of bicycles in place. There is no general overview of how these different military operate on a detailed level with regards to bicycle distribution. However, the system granularity scope for this research did not include that level of detail. Especially the different physical distribution forms were not modelled with great detail, as this was outside of the scope of the research. agent-based modelling is also unsuited for detailed flow of physical delivery of goods, which is another reason why this process is simplified. This can be viewed as a strength, but also as a limitation of this study. One strength is that physical distribution factors do not form a barrier in using the created model for other supply chains. A limitation is that the lack of detail in the physical distribution aspect does not account for transportation times. Not only does the waiting time of orders now only measure intra-organizational waiting time, but the effects of extra transportation time on other processes are now left out. Would another product entail an elaborate internal physical distribution, then the model has to rebuilt with in this respect.

Budgetary constraints within the bicycle supply chain are comparable to other facility goods, but not to more essential goods such as weapon systems. The dynamic of a Manager saying no to an End-User on the basis of the budget exceeding will probably not occur that easily with essential weapon systems. As one interviewee worded it:

> *"Priority is not with DOSCO* (the Defense department providing bicycles) *in general. The choice between gear for a soldier and facility goods is quickly made."*

Therefore, one should limit the findings of this research and the model used to only facilitating goods that have the same priority level and effects on the functioning of Defense as a whole in regards of the goals of Defense.

10
Conclusion

This research focused on the problem of shortages within Defense regarding personnel and budgets. This called for a more efficient and thought trough design of the supply chain for different goods. The design needed to be improved and appropriate methodology providing insight in the current organizational complexities was required to anticipate the effectiveness of policy implementations. Answers to the research questions are stipulated first in which the findings from previous chapters are synchronized. Then, practical and theoretical implications are articulated in this chapter. Finally, directions on further research are given.

10.1. Answering the research questions

In the methodology chapter 3, the main research question is given along with 3 sub questions. These are all restated and answered here in this concluding chapter. Finally, the main research question is answered at the end of this chapter.

> *"Which actors, processes and relations between the processes are most important in the functioning of the bicycle supply chain of Defense?"*

This question aimed at the information gathering in general sense on the workings of the bicycle supply chain system. Interviews and policy documents gave insight into the aspects that make up the entire system. Through this information we can answer this first question. But first, what does the "functioning" of the bicycle supply chain mean? The functioning can be described as providing goods (in this case bicycles) to the different Military bases and the employees working at those bases. This delivery is driven by an order-centric system of interacting processes. The *level* of functioning is defined in the other sub questions on conceptualization and implementation, but especially in the results where levels of functioning are discussed. The most important actors, within the scope of this research, are the Manager, Finance and Control, Facility Company, End-Users and the Supplier. The most important processes are aimed at the monitoring and management of budgets, where expenditures on bicycle purchases are tried to be contained within the budgetary limit. This involves the sharing of information between the End-Users, Finance and Control and the Facility Companies. Also, demand dynamics and justification is an important aspect of the system, as the whole system is demand-driven. This means that the end-user "pulls" the bicycles trough the system on his initiative. Other actors are reactionary to this process.

> *"How can the complex supply chain of bicycle distribution and the underlying processes be conceptualized and implemented in an agent-based simulation model?"*

The conceptualization of the supply chain system is visualized in the system diagram that is showed first in chapter 5 on the conceptualization. This figure is shown here again for easy reference, see figure 10.1. The actors and processes as described in sub question 1 are visualized and their relations with regards to the physical distribution, management, finance and information are displayed. The BPMN diagram in appendix B describes the process flow in greater detail, demarcating important decision moments as well. These decision moments form the bridge between the conceptualization and implementation, as agent-based modelling is build towards such decision moments. The state and conditions of the model will determine how decisions are made. These states are influenced by the different structures in the model, such as information provision, achieving the implementation of the conceptualized relations between the agents.

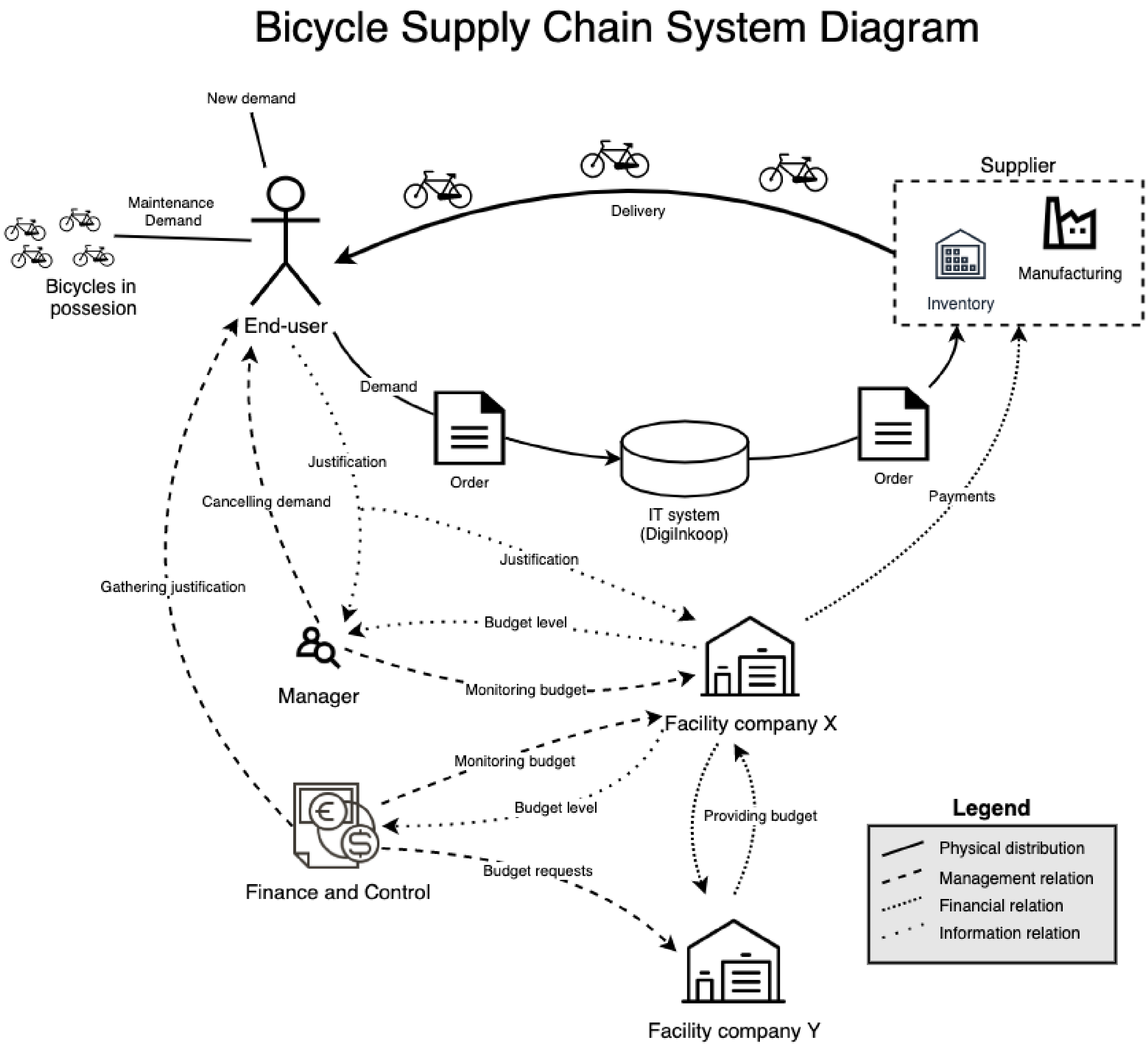

Figure 10.1: Conceptual model of the intra-organization, multi-structural Supply Chain system within Defense

How do different policies influence the processes of the agents and thereby influence the average waiting time, budget and effort, under varying demand and supply scenarios?

The most important results will be discussed here, involving the base case, sensitivity analysis and exploratory results from chapter 8 and 9. The base case without any policy or uncertainty variation already showed a large variance in outcomes. Multiple dynamics are the expected cause of this variance, but primarily the sequential nature of the agent processes. If the processes are not aligned at every decision made by agents, such extra variance and unpredictability in the behavior is seen. On top of this, due to the long run time of the model, only 10 repetitions per experiment could be run in the exploratory part. A combination of high variance in base case and low amount of repetitions makes the results less robust.

Either way, the exploratory results show that the structural **predictive replacements** policy is promising. However, implementation does require a **trade-off** between a) decreasing effort for Finance and Control and the Manager and b) increasing the effort for the Facility Companies and the average order waiting time. There are opportunities of decreasing the negative effects in this trade-off, specifically average order waiting time, due to the increased predictability of demand for the Supplier. Another interesting finding is the **willingness to share** information, which is a policy that influences the willingness of End-Users in sharing the argumentation, or ”justification”, on their orders. It **significantly reduces** the effort of Finance and Control, which the policy is aimed at. However, a contradictory finding here is that the higher willingness to share for end-users is causing the effort of Facility Companies to **increase**. Slower throughput of orders and orders not even reaching the supplier might explain this dynamic.

Lastly, the main research question.

> ***What are the effects of novel policies on the functioning of intra-organizational supply chain business processes, while taking into account the behavior and heterogeneity between key actors?***

This research aimed to fill the research gap of how one can analyze intra-organizational supply chain business processes, embedded in a complex multi-structural system. The case study of Defense’s bicycle supply chain provided such business processes within a complex organization, spanning a large range of capabilities and disciplines.

Using the agent-based modelling worldview and accompanying simulation tools, the processes on the supply chain were conceptualized and implemented in a simulation model, taking into account the behavior and heterogeneity between agents. The sequential nature of the model gave unexpected results, but did provide valuable lessons on the implementation of a supply chain model in agent-based modelling: The process-oriented and order-centric nature of supply chains require extensive modelling. Probably more than using the discrete event simulation formalism. It did allow for more dynamic information sharing between agents, which could account for the behavior and heterogeneity between agents.

The results of the model run via EMA workbench gave insight into promising policies and determining uncertainties. Both predictive replacements and willingness to share information were promising policies, but do require a trade-off. The uncertainty in demand and supply greatly influenced the effort required of the different agents. Further answering of this question regarding its theoretical and practical implications are stated in the next sections.

10.2. Implications for practice

Multiple policy implementations on the functioning and design of Defense’s supply chain are evaluated in this research by building a simulation model and investigating the resulting behavior. This section will discuss how practitioners within Defense, but also those involved in non-military supply chains, can use the outcomes of this research in order to improve supply chain dynamics.

Due to the changing geopolitical threat landscape, Defense is looking to improve adaptability and flexibility. However, structural shortages in the budget of Defense from the last years has resulted in a decrease in functioning of a lot of areas within Defense. Also, as Defense is originally a large and inherently complex organization, adaptability and flexibility require redesign of important, but complex, processes. This research aimed at understanding the business processes behind the bicycle supply chain using a computer simulation model. The model is an attempt at capturing the complexity of such business processes and examining the trade-off that often occurs when implementing policies aimed at improving Defense’s supply chain as a whole.

One important finding is that the implemented policies of predictive replacements and increased willingness to share had positive and negative impacts on the effort put into the business processes of different actors, as well as order waiting time. Predictive replacements decreased effort for the Manager and the Finance and Control actors, but increased effort for the Facility Company along with the average waiting time of orders. Initially it might seem that this policy does not increase overall functioning of the bicycle supply chain, but it shows that choices have to be made in what found important within the supply chain. Choices on effort distributions versus waiting time for end-users for example. One must also take into account the long-term visions of Defense with regards to the goals of the organization as a whole. If adaptability is most important, more investments must be made in opening up the processes of Defense with regards to outsourcing. For example within Finance and Control, how can their processes be simplified and decrease their effort?

The used simulation methodology in this research is a novel approach to investigate complex but practical problems occurring within Defense's processes. However, hurdles in using this methodology were encountered. The conceptualization and implementation process learned that a clear pragmatic goal is important to establish beforehand, as during this research the goal was changing often. A recommendation to practitioners is also to qualitatively and holistically investigate which business processes determine the system in which a problem is found. Thus, exploring all the processes involved before implementing a simulation model or looking to explain quantified performance indicators. This will help in a better and more valid representation of the model compared to reality and make conclusions more valid as well.

10.3. Theoretical implications

The literature review in chapter 2 concluded with a research gap identified in the present literature. This research gap consisted of on the one hand a lack of research on intra-organizational supply chains (Guertler and Spinler, 2015; Clausen et al., 2019) and the use of a multi-structural framework Ivanov et al. (2010). But also a research gap on the methodology of using simulation for the analysis of business processes. This gap specifically regards the aspects practical applications, limitations and generalizability of using simulation model on business processes (Rosenthal et al., 2018). The question central in this section is therefore: How does this research map into the identified knowledge gaps? to answer this question, each of the aspects is elaborated on in the next paragraphs.

Most research encountered in the literature review on supply chain simulation involved the design of inter-organizational supply chains (Clausen et al., 2019), often represented as networks with manufacturers , distribution centers and suppliers. Analyzing the intra-organizational supply chain within Defense showed that, using the multi-structural framework by Ivanov et al. (2010) for a holistic perspective, most of the intra-organizational system structures are on the financial and management levels. Only a limited amount of physical distribution was present within the use-case. This moved the supply chain problem space from a classic distribution network perspective to a more process oriented perspective. We can go as far as to say that, in general, intra-organizational supply chain research would benefit from a more process oriented perspective. However, this of course does depend on the type of product and the amount of outsourcing present.

On the research gap of practical applications, limitations and generalizability we can say the following. This research provided a practical application of business process simulation through the use of Business Process Model Notation and agent-based modelling. However, true implementations of policy directions are required before the effectiveness of the method in a practical sense can be confirmed. Limitations of simulation approaches to business process analysis are found within the specific application of the Business Process Model Notation method conceptualization method combined with agent-based modelling. The main limitation originates from the use of agent-based modelling for business processes. The behavior and heterogeneity between the agents was natural to implement using the agent-based method. However, the process oriented and order-centric nature required extensive modelling. Generalized of the results goes as far as goods that have the same classification. For this, one can use sector specific or generic portfolio purchasing models that meet the requirements of the problem owner. In this research the portfolio purchasing model by Ekström et al. (2021) was used, which allowed for the classification and extrapolation of findings to goods that fall into the same classification.

10.4. Limitations

Limitations of this research consist of three points: *Effort as KPI*, *run time* and *extrapolation*. Effort is ambiguous which reduces clarity on what it represents, but it also facilitates comparisons between effort of different agents. Also, it can arguably facilitate the correct external view on the results. The relatively long run time of the model prevented extensive experiment testing and sufficient repetitions, reducing accurateness of the results. Extrapolating the findings to supply chain of other goods must be proceeded with caution, as the model is conceptualized towards that of bicycles.

10.5. Further research

Further research might investigate the possibility of extrapolation to other supply chains, as it is currently unclear how other supply chains within defense compare. Also, the structure considerations could be expanded, especially the geographical structure. Involving distances might make comparison to other goods easier as well. Finally, uncertainty considerations can be expanded past demand and supply. Geographical aspect implementation would for example facilitate the understanding of international uncertainty impacts.

Expanding structure considerations This research has focused on modelling the structures of information, physical distribution and finance, based on the multi-structural framework as posed by Ivanov et al. (2010). However, Ivanov et al. (2010) identify other structures than the ones identified for the use case in this research. One such structure is the topological (geographical) structure. The geographical structure was explicitly outside of the scope of this research because the physical distribution of bicycles is entirely outsourced for Defense; The Supplier directly delivers to the End-User. However, including the geographical structure could add to the understanding of the system. For example, distance between the End-Users and Finance and Control or Manager makes monitoring and information sharing more difficult. In this research it is assumed that distances do not influence any of the model states. Also, not all goods within Defense have their physical distribution outsourced. Especially non-facilitating goods that have higher priority and create larger problems if supply is insufficient. Thus, adding geographical structure dynamics can facilitate model use for other goods.

Other goods Further research might expand past the bicycle supply chain to understand if the agent-based model approach, as used in this paper, can be useful and applicable to other types of goods as well. The approach can provide insight into the processes behind goods that have a different categorization in the model of Ekström et al. (2021) in figure 9.1.

Such research can on the one hand validate this research in its approach and understanding of Defense's processes. Comparing two different supply chains will show similarities and differences, which can both be investigated in order to gain an insight into strengths and weaknesses of different supply chains. Also, these models could be combined to create a more meta model of supply chains within Defense in general. Policies can be tested on this meta model to more holistically, with regards to Defence as an organizational whole, understand and evaluate policy effects on the behavior of the system.

Uncertainty Future scenario uncertainty as conceptualized in this research mainly originates from demand and supply, but integrating for example a geographical structure might open up other uncertainty dimensions as well. A geographical scope could allow the testing of greater distances between supply chain processes. Think of international mission scenarios for prolonged periods of time. How would this for example influence the monitoring capabilities of the Manager or Finance and Control? And how would this influence the that expenditures only happen with adequate justification?

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A
Interviews

This appendix contains summaries of the different interviews and e-mail correspondence held with key figures within the supply chain of the Netherlands Armed Forces. The summaries of the interviews are structured according to the different subjects that occurred within the conversation.

A.1. Assortment manager, for bicycles specifically

distribution specifics:

- The specific distribution of bicycles functions differently at the locations at which this bicycle distribution occurs.
- Specifics on the variations in the processes of administration and such behind the distributions at different locations are not known.
- Loan bikes occur at most military bases.
- The Army has two other assortment of bicycles.

Financials:

- There is a central budget for procuring bicycles.
- Military bases that have a shortage in budget look to shift budget from departments within the specific base or other military bases that have a surplus in their budget. If these options do not work, budget is requested higher up.
- The financial department centrally determines the budget for each military base regarding their facility company.
- There is constant shifting within facility management within a military base when budgets are insufficient.
- There is a tendency of departments finishing budget in order to receive their full budgets again next budget-round.

Responsibilities of assortment management:

- Predict the demand that will form the basis of a new contract
- Predict the demand based on historical data.
- Start and manage the (aanbestedingsprocedure) for a good within their assortment
- Check the quality of the delivered goods when a procurement (aanbesteding) is made.

- Difficulty lies within creating the technical demands that goods need to conform to. The assortment manager manages a variety of goods of which he/she has no technical knowledge or clear unanimous demands from the end-users.
- Questions from the interviewee (assortment manager):
  - On which basis are the distribution chains designed in the form they are in now?
  - There is a wish to connect the different systems used in the logistical departments, as now DigiInkoop and SAP are used for different goods in the different Defence Organisations. These do not communicate with each other and persons making demand in SAP cannot interact with and order from the assortments in DigiInkoop unless the person uses that interface.

Supplier:

- The supplier has a manufacturing lock-in, where they cannot easily switch production between different types of bicycles. When the supply is too low, there is not an easy way to satisfy this extra demand.
- Because the demand of Defence is not that high compared to other commercial clients of the bicycle distributer, Defence does not have the highest priority when it comes to satisfying demand in situations of extra demand.
- Solution of a situation with extra demand: The manufacturer offered different, similar, bikes in order to still fulfill the demand of Defence.

General:

- DOSCO uses the DigiInkoop ICT system for administrating and creation of orders. Other DO's often use SAP, but other DO's can use DigiInkoop for requesting the bicycles in this assortment.
- Use and necessity of orders are reviewed by the facility company. Contract management checks if the demand can be placed under the current contract. The requested product must be part of the same category as determined in the contract with the supplier, as also described in the laws of procurement (aanbestedingsrecht). Even if the supplier can deliver that good, they cannot because the exchange is bound to the contact.

A.2. Head of (bedrijfsondersteuning) DOSCO

Goals of Facility Company Defence:

- Role of FBD is providing bicycles to the different military bases in two ways:
  - Providing bicycles in bulk to a commandant or Defence department and maintaining those bikes regularly, or letting them be maintained.
  - Providing bicycles to military basis which end-users can make a reservation for and use whenever they need to. This is especially present in area's where biking distances between Defence locations and the homes of employees are easily reachable by bike.
- The location manager and (Defensie Onderdelen) on location make demand orders towards the facility company.

Problems:

- Every DO on different locations are responsible for the design of their own logistical chain of bike provision.
- maintenance of bikes need to be done by lots instead of sending a mechanic for a single bike.
- End-users do not have an incentive to provide accurate information, because:

  - Budget lies with the facility company (facilitair bedrijf) to buy bicycles. With this budget they need to satisfy demand of the end-users. End-users do not manage the budget which makes requesting bikes without much consequences.
  - End-users do not share the responsibility in providing accurate predicted demand for a new contract.
  - Practical examples of these misaligned incentives:
    - ◇ End-users order new bikes whenever a new contract is closed with a new supplier, even though the current bikes they have are of sufficient quality.
    - ◇ Sometimes, 100 bikes are provides and when the bikes are counted only 80 are left. Nobody then knows what happened to those bikes.
- There is no central information registered on:
  - How many bikes each military base or DO or commandant or soldier has
  - What the state of these bikes is.

Improvement directions:

- To know which bikes need maintenance or replacement will prevent that a whole bulk of bikes need to be replaced suddenly without notice. Accurate bike state will provide the information needed to intervene before the demand will spike.
- A better information processing system where bikes can be handled like the ”OV-fiets” at the NS stations that can be scanned and processed in the information systems automatically without intervention of a person that needs to provide the key and take the bike at the end of the rent. This will save time and therefore money, which could potentially offset the higher procurement costs.
- An electronic key-safe that can be unlocked by scanning the personal ”Defensiepas”. By scanning the pas, accurate information can be kept on who loans what bike at what time and place. Responsibility will shift more towards the end-user as he can be tracked in his actions.

Extended e-mailing correspondence When the client creates the demand he needs at the Service station there is a check if all information is correctly filled in (1 day). Then the order is throughput to inventory control and logistics. They process the order into the digi inkoop system so that the order is placed with the supplier. For this process there is a norm of 3 days. The delivery time is contractually limited to 10 working days (for accessory this is 5 days). Preparing the bike for use takes 1 day. In total the whole process should maximally take 15 working days. There is no difference between small or large orders, but sometimes bicycles or not in stock at the supplier, in that case the delivery date is agreed upon between the end-user and the supplier.

A.3. Finance and Control

Goals of finance and control:

- Checking the efficiency and legality of procurements and investments within the Facility Company of Defence (FBD - Facilitair Bedrijf Defensie). Done by controlling the full cycle of the financials, from planning to the execution year.
- Checking the demands: At the servicepoint at which demand for a product can be made, there is a first check on the reasons behind why a specific purchase is needed. → The logistics administrator puts the purchase into the system that is used (digiinkoop/sap/on paper!) → Location manager will evaluate orders up to 30.000 euro. → Larger orders than 30.000 euros will be checked by finance and control → in this case, the controller checks the arguments for the demand of the end user and/or the location manager.
- Checking how much of the contract for a specific good or service (DVA - Dienstverleningsactiviteit) is already incurred. If the incurred goods purchased seem to reach the contractual agreed limit of purchased goods, action might be taken depending on the sum of exceeding expenditures. This can range from extending the contract to closing a new contract.

Budget distribution

- The budget for the whole of defence is determined in the formation of the government. The central question in determining this budget is what capacities does defence need for the long term goals of defence.
- From the central budget of Defence, part is distributed to the Facility Company and its 7 geographical regions: Havelte, Schaarsbergen, Breda, Den Helder, Den Haag, Soesterberg and Oirschot. From there the budget is again distributed among 6 different Facility Categories:
  - Food en Drinks
  - Interior design and Moving locations
  - Cleaning of facilities
  - Facility management (among wich the subcategory of bikes)
  - Office supplies
  - Trash processing
- The Region manager and Location manager predict the demand for the coming execution year by analysing the needs of the customer. When demand for a good is filed, a check is done on the current expenditures compared to expenditures in previous years. This way, large differences might show and current expenditures may be decreased. The demand is checked on justness by multiple departments (Vraag en Aanbod Portfoliomanagement, STAF Facilitair Bedrijf Defensie) and if they also recognize and find these expenditures just.
- If in the execution year a demand is created that does not fit within the budget of that location, the justness of the expenditure is checked and fit into the budget. If that is not possible, budget that is available and unused in the same region may be shifted towards the budget with a deficit. Or else across the whole of the Facility company. If that is not possible, the commander Facility Company should put this up with its division commander. If during the prediction phase there is future demand identified which is exceeding the available budget or if it falls outside of defined budget categories, it is escalated in a bottleneck note. In the execution year it will become clear if the demand can be satisfied or not.

General:

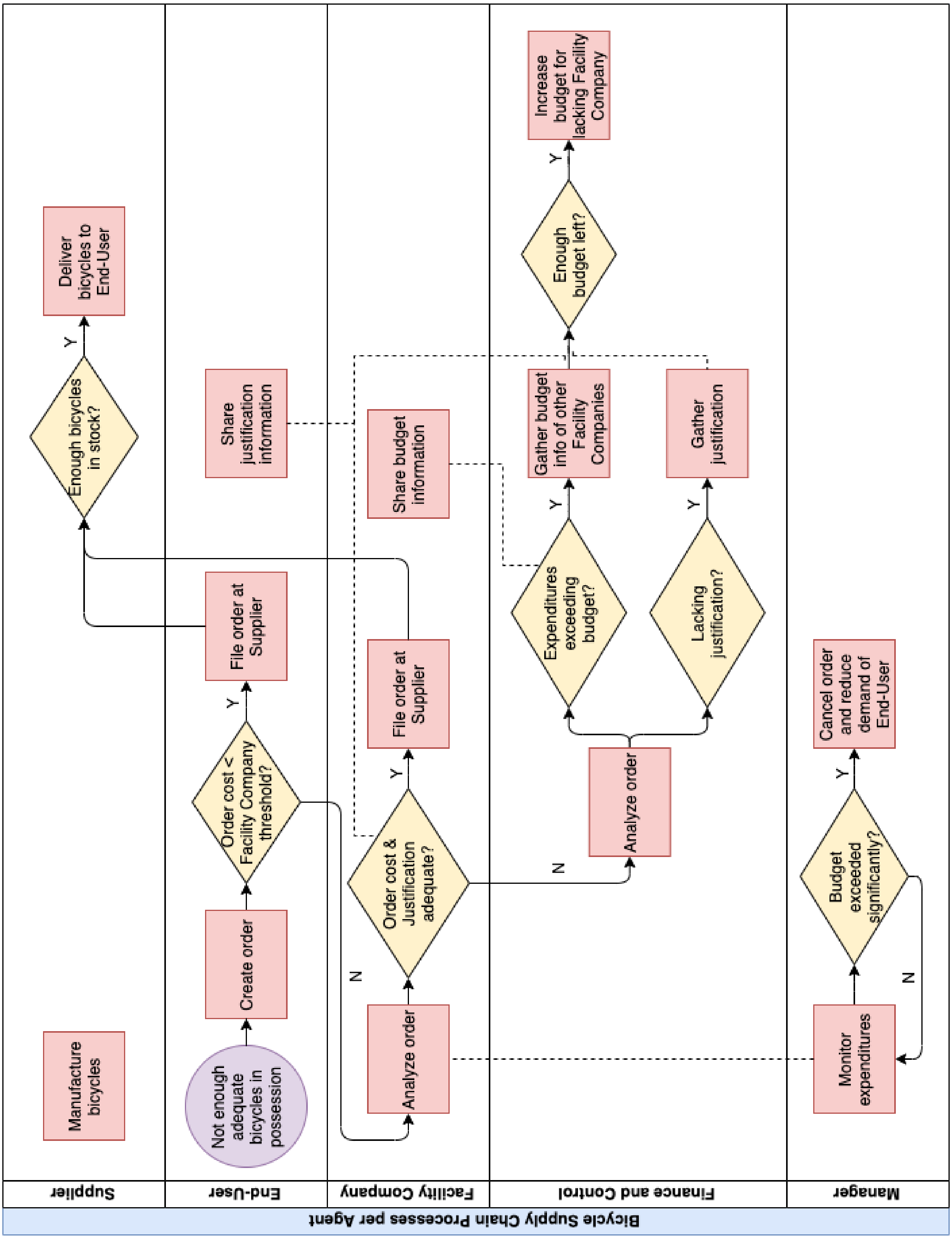
- Difficulty is in keeping oversight on different processes and reacting adequatly.
- Priority is not with DOSCO in general. The choice between gear for a soldier or facility goods is quickly made.
- growing with the current technological trend is always aimed at but not always possible in the current budgetary constraints.
- Environmental factors by for example a reorganisation can quickly escalate budgetary spendings
- Bicycles are relatively simple (compared to other assortments within the Facility Company) because there is oversight on what where when.
- Different colors (cultures within military branches) all have their own perspective which you have to take into account when they set their demand.

B

Business Processes Model - BPMN

The Business Process Model from the conceptualization is shown in full on the next page. This model describes the different interacting process that the agents (or employees in the Defense as organization) execute. Onggo (2012) state that the Business Process Model Notation is suited for conceptualizing multi-agent systems and implementing agent-based simulation models on those systems.

The red boxes contain actions which each of the agents make. Notice how not all those actions are connected to other decisions or actions. This is a conscious choice as some of the actions are independent, such as the creation of bicycles. Nothing from within the model will influence the rate of production, thus the action of production is on itself standing. The yellow diamonds demarcate decisions to be made. The Y and N along the lines indicate a yes or no answer given to the decision. If there is no N line, then the agent just waits and executes this again next tick to see if conditions are changed. The dotted lines indicate important specific information exchange. The circle at the start is the beginning of all the dependent processes, thus excluding for example the independent action of creating bicycles.



Bicycle Supply Chain Processes per Agent
Supplier
End-User
Facility Company
Finance and Control
Manager
Manufacture bicycles
Enough bicycles in stock?
Y
Deliver bicycles to End-User
Not enough adequate bicycles in possession
Create order
Order cost < Facility Company threshold?
Y
File order at Supplier
Share justification information
Analyze order
N
Order cost & Justification adequate?
Y
File order at Supplier
Share budget information
N
Analyze order
Expenditures exceeding budget?
Y
Gather budget info of other Facility Companies
Lacking justification?
Y
Gather justification
Enough budget left?
Y
Increase budget for lacking Facility Company
Monitor expenditures
Budget exceeded significantly?
N
Y
Cancel order and reduce demand of End-User

C

Assumptions

This appendix shows the most important assumptions made. Two distinctions are made between assumptions as described by Galán et al. (2009); **Core** and **Accessory** assumptions. Core assumptions are important for the functioning of the model *in light of the purpose of the model*. Accessory assumptions are included ”*to make the model work*”.

Core assumptions:

- Effort is an arbitrary concept and does not resemble effort as in real-life.
- The justification value resembles the strength of the argumentation on a specific order. This is hard to quantify, but trough the justification value we assume the strength of argumentation.
- End-users are created randomly on the map, without any resemblance of the geographical locations of actual military bases. The facility companies do resemble their real-life locations, but this does not have any effect in the model as transportation time is left out.
- The distribution of bicycles in possession at the initialization phase of the model is in form equal to the order data quantities. E.g. if 30% of the orders have a demand quantity of 2 bicycles, then 30% of the end-users will have a factor x times 2 bicycles. That factor is equal among all the end-users and is saved in the global variable *initial_amount_of_bicycles*.
- Orders are never revoked by the end-user creating the order. Finance and control plus the facility companies will try and fill all possible orders, how high and exorbitant they might be. Only the manager can stop an order if budgetary limits are exceeded.
- Finance and control will reallocate budgets at a very precise manner and always reallocates when possible. There is no real ”negotiation”.

Accessory assumptions:

- A quarter of the demand of an end-user has to be either missing or in poor state to trigger the end-user. Demand is the amount of bikes the end-user perceives to need in order to do its job. Whatever that may be.
- Contractual limitation is an external variable. The process of procurement is outside the scope.
- Budgetary constraint is an external variable. The process of budget allocation is outside the scope.
- Finance and control does not stop with adding justification at the rate given by the end-users willingness to share information attribute. There is no limit, except when sufficient values of justification on an order are reached.
- Finance and Control will only visit one facility company per tick. Thereby increasing the justification of the pending order at that facility company for just one tick as well.
- There are 144 End-Users and these will not change in any of the scenarios.