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MIOM05 Degree Project in Production Management

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# Exploring Rush Order Policies in a Multi-Echelon Inventory System

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# ABSTRACT

**Title:** Exploring Rush Order Policies in a Multi-Echelon Inventory System

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**Background:** The Case Company is currently transitioning their inventory control from a single-echelon to a multi-echelon optimization approach. As no formal rush order policy currently exists, it is of great interest to explore the impact on rush orders in this transition and investigate the potential value of introducing rush order policies.

**Purpose:** The purpose of this thesis is to analyze the rush order processes, particularly with regards to how decisions are made. Based on the current situation, the objective is to formulate possible rush order policies that could be implemented in Volvo Groups' distribution system. The cost and emission impact of implementing these policies at the dealers will be analyzed, and the effect on the number of rush orders will be evaluated through simulation, by comparing the current system to a proposed MEIO controlled system.

**Methodology:** The methodology in this thesis consists of two parts. The first part was an exploratory research study, adopting methods proposed by Höst et al. (2006). This included an extensive literature study and conducting interviews with selected employees at the Case Company. A simulation study framework by Hillier and Lieberman (2021) was employed for the second part of this thesis, to guideline the numerical study utilizing simulation.

**Conclusion:** The current order processes lack traceability on the arrival of incoming stock orders. Access to accurate pipeline information have potential to reduce the number of unnecessary rush orders. Through simulation, a pipeline policy was found to reduce the expected number of rush orders by 23.5% in a single-echelon system and by 19.4% in a multi-echelon system.

**Key Words:** inventory control, multi-echelon, rush order, pipeline information, spare parts

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First, we would like to express our sincere gratitude to our supervisor at Lund University, Professor Johan Marklund. His extraordinary guidance and feedback have been invaluable in moving this project forward.

We would also like to thank our supervisors at Volvo SO&T, Philip Mårtensson and Johan Lidvall, for their continuous support, as well as guiding us within the organization and helping us connect with the right people.

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*Stina Nilsson & Lina Solbu, May 2026*

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# ABBREVIATIONS

| **Abbreviation** | **Definition** |
|---|---|
| CDC | Central Distribution Center |
| DIM | Dealer Inventory Management |
| DRP | Distribution Requirements Planning |
| EM | Extended Model |
| EOQ | Economic Order Quantity |
| ETA | Estimated Time of Arrival |
| GHG | Greenhouse Gas |
| IL | Inventory Level |
| IP | Inventory Position |
| KPI | Key Performance Indicator |
| MCDM | Multiple Criteria Decision-Making |
| MEIO | Multi-Echelon Inventory Optimization |
| MRP | Material Requirements Planning |
| NRP | New Reorder Points |
| OWMR | One-Warehouse-Multiple-Retailer |
| RDC | Regional Distribution Center |
| SCM | Supply Chain Management |
| SDC | Support Distribution Centers |
| SE | Single-Echelon |
| SLA | Service Level Agreement |
| SO&T | Service Operations & Technology |
| TSL | Target Service Level |
| VAS | Volvo Action Service |
| VCE | Volvo Construction Equipment |
| VMI | Vendor Managed Inventory |
| VOR | Vehicle Off Road |

# 1 INTRODUCTION

This chapter provides a background for the master thesis, consisting of a general introduction to inventory control and the Case Company, Volvo Group. The problem is formulated and the thesis purpose is presented. Lastly, the delimitations of the thesis and the outline for the upcoming chapters are presented.

## 1.1 Background

Today, Supply Chain Management (SCM) is of crucial importance to any business or organization (Axsäter 2015). SCM has many different definitions in literature. For example, Mentzer et al. (2001) provides the following definition: "*[...] the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.*". Axsäter (2015) summarizes SCM as "*the control of the material flow from suppliers of raw material to final customers*".

Inventory control is a crucial part of *SCM* (Axsäter 2015, p. 1). As inventories stored in various stages of the supply chain accumulate high cost and investments, it is often an area for improvement where cost reductions are possible. The purpose of inventory control is to decide the time and quantities for placing orders (Axsäter 2015, p. 39), while considering factors such as cost, future demand, and current stock situation.

Controlling spare parts inventory is in general more challenging than it is for regular products, and is therefore often considered as a special part of inventory management. The effects of spare part stock-outs can have substantial financial consequences on an organization, demand is typically uneven and difficult to forecast, and the unit prices can be very high (Hua et al. 2007, p. 52). These challenges often result in organizations wanting to maintain high inventory levels in order to reduce the risk of shortages. However, this results in increased holding costs. It is therefore in many companies' interest to minimize spare part inventory costs, while still maintaining sufficient customer service levels.

The thesis will be conducted in collaboration with Volvo Service Operations & Technology (SO&T). SO&T's main responsibility is to deliver service market solutions and spare parts for the divisions within Volvo Group, focusing on an efficient and resilient service market supply chain.

## 1.2 Volvo Group

Volvo Group was founded in 1927 in Gothenburg, and is a major actor in the market for sustainable transport and infrastructure solutions (Volvo Group 2026a). The brand portfolio consists of different brands within trucks, buses, construction equipment, and engine- and power solutions. Volvo Group is present in over 180 markets across the globe. An organizational chart is presented in Figure 1, where Volvo SO&T belong to the Trucks Technology & Industrial Division.

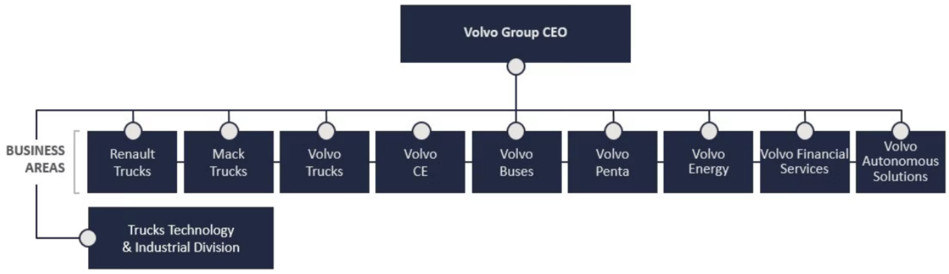

***Figure 1.*** *Volvo Corporate Structure (Volvo Group 2026a)*

### 1.2.1 Current Distribution Network

As Volvo SO&T supports a large organization, they are responsible for around managing 700 000 part numbers (Volvo Group 2026b). The logistics flows in their general distribution network are presented in Figure 2.

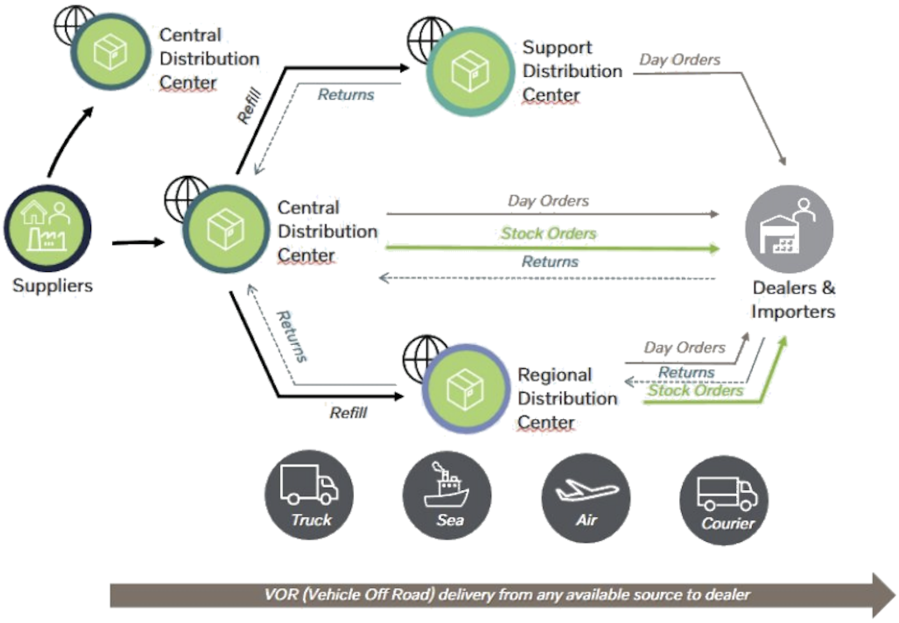

***Figure 2.*** *Distribution network for Volvo Group SO&T (Volvo Group 2026b)*

Figure 2 illustrates the distribution network consisting of Central Distribution Centers (CDCs), Regional Distribution Centers (RDCs) and Support Distribution Centers (SDCs). However, Support Distribution Centers are only used in Europe. Thus, for other markets the supply chain structure consists of CDCs, RDCs, and dealers. There are also external suppliers. The dealers are the customer serving interface and can be either owned by the Volvo Group (internal), or be independent privately owned companies (external). There are three different order types that flow within this system; regular stock orders, day orders and Vehicle Off Road (VOR) orders. Stock orders are delivered to the dealers from the CDCs or RDCs, triggered when a refill is requested at the dealership. Day orders are shipped from the CDCs, RDCs or the SDCs, and are categorized as rush orders, typically sent overnight in case of a stock out at the dealers. VOR orders are rush orders of severe urgency, and are delivered from any available source.

Regarding inventory control, Volvo SO&T has ownership of the CDCs, RDCs and SDCs, which gives them full control over the inventory and rush orders at these installations[1]. For most dealers (some owned by Volvo, others not),

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[1] Interviewee 1: Supply Chain and Analytics Expert, Volvo GTO, SO&T, Advanced Analytics. Conducted on February 17 2026

Volvo use vendor-managed-inventory (VMI) contracts called Dealer Inventory Management (DIM). This allows Volvo to control local inventories at the dealerships. For dealers not owned by Volvo, without DIM, Volvo has no control of the inventory decisions. These will be referred to as independent dealers.

Volvo SO&T currently operates their inventory control system using a single-echelon (or single-node) optimization approach. This means that inventory decisions at each node are optimized independently without considering the decisions made at the other nodes in the network (Hausman and Erkip 1994). However, Volvo are currently exploring the transition to multi-echelon inventory optimization (MEIO) for their inventory control of spare parts. MEIO considers the installations in the system together and jointly optimizes the inventory control decisions (Mårtensson 2025). MEIO has gained growing interest in many supply chains over the past decades (Axsäter et al. 2013, p. 187). The reason is that MEIO generally leads to large inventory reductions, while maintaining or even improving the service level towards the end customer (Mårtensson 2025). At the same time, it is a much more complex control problem, both conceptually and computationally.

## 1.3 Problem Formulation

Volvo SO&T is on a path of transforming their inventory control system from a single-echelon system to a multi-echelon system. Typically, when switching from single-node optimization to MEIO, inventory is re-distributed from the higher echelons to downstream echelons, i.e. the dealers. However, changes in stock levels and redistribution of inventory does not come without complications.

Today there is no general policy for when to place rush orders; it is more or less up to the dealer to decide. For the RDCs, there may be a policy, currently unknown by SO&T. Thus, in the transition, it is interesting to examine the impact of rush orders and specifically consider implementing policies for placing emergency orders. This will be the focus area for this thesis. The analysis will stem from analyzing the current behavior when it comes to placing rush orders. Because there is no formally defined policy regarding when rush orders should be placed, there is a need to gain a better understanding of how decisions are actually made both when RDCs and local dealers request rush orders, and what information they would need to make better decisions.

In Volvo Groups' spare parts distribution network, there are both internal players and external privately owned dealers. As of today, it is unclear if decision making regarding rush orders differs between external and internal dealers. The internal dealers and the RDCs are controlled by the Volvo SO&T, making it easier to observe and control rush order behavior compared to external dealers, where there is a lack of insight into their decision making processes. Understanding the current behavior in a single-echelon system provides a basis for formulating regulated rush order policies in a future multi-echelon system. Such policies should, for reasons of stability and trust, include decision rules not too far from how decisions are made today. However, they should also avoid panic rush ordering, while keeping costs and emissions low, compared to not having such a policy.

## 1.4 Purpose

The purpose of this thesis is to analyze the rush order processes, particularly with regards to how decisions are made. Based on the current situation, the objective is to formulate possible rush order policies that could be implemented in Volvo Groups' distribution system. The cost and emission impact of implementing these policies at the dealers will be analyzed, and the effect on the number of rush orders will be evaluated through simulation, by comparing the current system to a proposed MEIO controlled system.

## 1.5 Delimitations

Volvo Group is a large organization with many individual variations due to geographical region, brand, etc. Due to the limited time frame for this thesis, some delimitations has been made. The process mapping and interviews cover dealers concentrated in Europe and one RDC located in the Middle East. The test data represents the RDC in Johannesburg, South Africa, and the dealers who receive stock orders from Johannesburg. Johannesburg, as well as the interviewed European dealers receive most of their replenishment from the CDC in Ghent, Belgium. The qualitative results in this thesis will be representative of the general structures of the Volvo SO&T distribution network, but may not be applicable for all markets. The numerical results will apply to the specific set of items, the Johannesburg RDC, and the connected dealers, but indicate the effects of the simulated policy on other markets.

Dealers not owned by Volvo and not under DIM will not be considered further in this thesis project, as Volvo cannot dictate any of their inventory decisions.

## 1.6 Thesis Outline

The rest of the thesis consists of the following chapters:

**Chapter 2: Extended Background on Volvo SO&T**
This chapter provides an in-depth description of the Volvo distribution network and its order classes, and describes the current inventory control system at Volvo SO&T.

**Chapter 3: Methodology**
This chapter describes the methodology employed in this thesis study, which consisted of two parts. The first part was an exploratory literature and interview study following the recommendations by Höst et al. (2006). The second part was a simulation study, which was conducted by adapting a framework by Hillier and Lieberman (2021).

**Chapter 4: Theory**
In this chapter, theoretical concepts related to the thesis are introduced and explained. The theory section begins with inventory control concepts and policies, and introduces single-echelon and multi-echelon systems. Then, a literature review is conducted examining potential rush order policies and models, as well as a review for including emissions in inventory control systems.

**Chapter 5: Current Rush Order Process**
This chapter presents the results of the first part of the study, which was understanding the current rush order processes at Volvo SO&T. The chapter includes both process maps and in-depth descriptions of the process, and motivations for the selected simulated policy.

**Chapter 6: Simulation Study**
In this chapter, the analytical model, on which the simulation model is based, is presented and briefly described. The simulation study, data, and scenarios are introduced.

**Chapter 7: Results and Analysis**
This chapter presents the numerical results from the simulation study, as well

as an analysis of both the qualitative and numerical results.

**Chapter 8: Conclusion**
The last chapter presents the conclusions of the thesis study, as well as recommendations for further research.

# 2 EXTENDED BACKGROUND ON VOLVO SO&T

This chapter provides an extended background on the Volvo SO&T distribution network and its order classes, as well as an introduction to their inventory control system.

## 2.1 Network Structure and Material Flow

The Volvo SO&T distribution network presented in Figure 2 follows a divergent network structure, where the number of parallel installations increase downstream in the distribution system (Axsäter 2015, p. 147). There are five CDCs spread across the Volvo Group brands, around 30 RDCs, and 10 SDCs[2]. The SDC structure is as mentioned only used in Europe. There are around 5000 dealers in the network. In general, the installations are connected based on geographical region.

Of the dealers, around 3000 are under DIM agreements[2]. What differs the DIM agreements from traditional VMI contracts is that the dealer owns the inventory at their installation under the DIM, while the supplier may own the inventory in a traditional VMI contract. Volvo SO&T have authority of the inventory control, but have some limitations due to the inventory ownership structure. For example, dealers may place manual orders beyond regular stock replenishment. Another aspect of the DIM agreement is that there is a return policy, where Volvo is obligated to buy back inventory not sold after an agreed period of time.

There are three types of orders handled in the system: stock orders, day orders and VOR orders. The material flow for stock orders is as follows: the CDC replenishes the RDCs and SDCs, and the RDCs supply the dealers[2]. In European markets, where there are SDCs instead of RDCs, the dealers are replenished with stock orders from the CDC.

Volvo SO&T uses external distribution providers for the transport of all shipments. The mode of transportation varies between road, air, sea, and, on rare occasions, train[2]. Generally, stock orders are shipped by road in Europe. However, small and capital intensive articles are sometimes shipped by air.

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[2] Interviewee 1: Supply Chain and Analytics Expert, Volvo GTO, SO&T, Advanced Analytics. Conducted on February 17 2026

### 2.1.1 Day Orders and VOR

Both day orders and VOR are categories of rush orders within the Volvo SO&T distribution network. Day orders are typically sent over night upon request from the dealer, and there are currently no rules restricting when a day order can be issued[2]. In a market with an SDC, the day order is sent from the SDC, given that the part is in stock. If not, it will be sent from the CDC instead. In a market without the SDC structure, the day order is supplied by the same RDC that the dealer receives stock orders from. A rush order requested by the RDC is supplied from the CDC. The day orders are usually sent via truck or airplane, depending on the situation.

VOR orders are rush orders of high urgency. There is no specified material flow for VORs. Instead, a VOR may be sent from any available source, such as another dealer or any of the upstream installations[2]. To place a VOR, a case must be created in Argus, a tool to facilitate communication between Volvo Group and the dealers. There is a rule that a truck or machine must be broken down for a VOR to be accepted.

## 2.2 Inventory Control at Volvo SO&T

Volvo SO&T's inventory control system aims to minimize total costs while maintaining high service levels across the organization. Currently, two different IT systems for inventory control (MMI and DSP) are used for planning refills to the dealers, which are based on $(R, Q)$ principles. The CDCs, RDCs, and SDCs are in the phase of implementing a Distribution Requirements Planning (DRP) system in a planning system called PlanIT [2]. In the future, the plan is to incorporate the dealers in this system and phase out the current $(R, Q)$ system. The DRP system Volvo use is based on the Material Requirements Planning (MRP) logic[2], in which the reorder points are continuously updated based on known discrete requirements (Axsäter 2015, p. 160). However, as demand in reality is uncertain and stochastic, the assumption of known discrete requirements is a limitation with MRP/DRP.

### 2.2.1 Total Cost Model

Volvo SO&T uses a total cost model for evaluation and optimization of the inventory costs. The model considers different cost drivers that are categorized by country, segment, life-cycle, frequency, weight and warehouse type. For example, *interest rate* is dependent on the country which a part is sold in, while *chance of rush multiplier* is a probability estimated based on which segment a part belongs to. Based on parameters such as reorder point, economic order quantity (EOQ), and safety stock, the total cost for a part number is calculated and broken down in different cost types: inventory, scrap, returns, order-handling, rush freight cost, bad-will and lost sales. The total cost model also has an optimizer, which through iterative stepwise testing optimizes the inventory control parameters to minimize the total cost. The output is a service level, which represents the fill rate for the optimal solution.

### 2.2.2 Target Service Level and Inventory Control Parameters

For each part, a Target Service Level (TSL) is decided, based on segmentation. The segmentation considers factors such as life-cycle stage, criticality, capital, frequency, and cost. The segmentation is necessary to meet the agreed Service Level Agreement (SLA) with as low tied-up capital and costs as possible. For example, parts about to be phased out can have a lower service level than parts in the peak of their life cycle. Based on different rules, the parts are assigned to a segment and receive a segmentation code. In PlanIT, which is currently used at the CDCs, RDCs and SDCs, the TSL for the segment is decided by running the total cost model and choosing the TSL that leads to the lowest total cost[2]. Note that this TSL is not always chosen, as negotiations with market subsidiaries may result in other agreements. For dealers, parts are assigned to a price-frequency matrix that determines the TSL.

There are slightly different methods for choosing $R$ and $Q$ in the different systems. For dealers, both $R$ and $Q$ are treated as parameters in the total cost model. The parameters are varied with some step-length, until the lowest total cost is achieved[2]. In PlanIT, the EOQ formula is used to decide the order quantity $Q$. The reorder point $R$ is calculated following $(R, Q)$ logic, given the TSL and demand distribution. Subtracting the lead time demand from the reorder point gives the safety stock level.

The order review system for dealers can be characterized as a continuous review system[2]. For smaller dealers, although reviews can be conducted daily, shipments may be dispatched less frequently in order to avoid small deliveries.

Replenishments are normally handled automatically for stock orders, but can also be placed manually by a decision maker at the inventory installation. Day orders are always placed manually by the dealers. VOR orders follow other procedures, as described previously. If a replenishment can not be delivered in time, it results in shortage costs. For standardized products that can be sourced from competitors, non-satisfied orders are usually considered as lost sales[2]. Other products are more unique to Volvo Group, leading to customers being willing (or forced) to wait until the item is available and therefore treated as back-orders.

# 3 METHODOLOGY

This section describes the methodology employed in this thesis. The thesis project was divided into two studies. The first one was an exploratory study aimed at understanding the current rush order process. The exploratory research utilized tools recommended by Höst et al. (2006), such as interviews. The second was an operations analytics study, aimed at quantifying the impact of using a rush order policy in the system using discrete event simulation. This study utilized a simulation study outline presented by Hillier and Lieberman (2021), which is a simulation specific version of their general framework for operations research. Both studies were supported by a thorough literature review conducted according to Höst et al. (2006).

## 3.1 Literature Review

For the literature review, the process recommended by Höst et al. (2006) was followed to gather relevant information. The process consists of three steps: Search wide, select, and search deep.

### 3.1.1 Search Wide

In the first step of the literature review, the goal was to search wide in order to gain an overview of potential relevant sources. This was primarily done through the Lund University search engine Finn, but also through other databases such as Scopus and Google Scholar. The keywords used in this stage were "Inventory Control" AND "Rush Order". Since the concept of rush orders can be described using different terms, the advanced search engine was used to include variations such as "emergency orders" OR "emergency replenishment".

### 3.1.2 Select

In the second step, the aim was to select the sources deemed most relevant for the study and to investigate them more thoroughly based on the initial screening. In Höst et al. (2006) several methods for assessing the credibility of a source are presented. For example, a source is considered more credible if it has been published in an academic journal, and if it has been peer-reviewed. It is also considered more credible that the source has been cited multiple times in other articles.

### 3.1.3 Search Deep

In the third and last step, the search was narrowed to focus on specific relevant terminology for the subject (Höst et al. 2006). One common approach is to utilize the reference list in relevant articles. The deep search was narrowed down into "Inventory Control" AND "Rush Order" AND "Multi-Echelon". This resulted in the selection of a limited number of relevant articles that aligned with the purpose of this thesis. However, the initial wide search resulted in a quite limited number of articles that matched the search criteria, leading to other methods being employed. The main method used then was searching already selected articles for key references.

## 3.2 Interviews

Interviews have been used to gather information on the current state regarding rush order policies in Volvo SO&T. Interviews can be conducted in multiple ways, ranging from fully structured interviews to open ended interviews (Höst et al. 2006). In fully structured interviews, all the questions are prepared in advance, and the interview works as an orally administered questionnaire. Open ended interviews allow for more flexibility for the interviewee to determine the direction of the interview, while remaining within the relevant topic. In addition, semi-structured interviews combine predefined questions while leaving some room for flexibility, allowing the interviewer to adjust the order and structure of the interview as it goes.

To explore current rush order processes across different supply chain actors, a semi-structured interview approach was adopted. An interview guide was prepared in advance to ensure that all relevant areas were covered, while still allowing for follow-up questions and providing interviewees with the opportunity to raise additional aspects they considered relevant for the study. The interview questions are presented in Appendix A and B.

The first interviewees were selected in consultation with Volvo supervisors. Additional participants were identified through recommendations from previous interviews. All interviews were conducted via Microsoft Teams, with the exception of one, which was carried out via email.

## 3.3 Simulation Study Framework

The simulation study part of this thesis followed an adapted version of a simulation study outline presented in Hillier and Lieberman (2021). They outline the typical process when conducting an operations research study focused on simulation. The simulation performed in this thesis was based on an existing simulation model that was modified. Thus, some of the steps presented by Hillier and Lieberman (2021) was adapted to fit the nature of our study. Simulation guidelines presented by Laguna and Marklund (2025) was also used in certain steps, providing additional methods to perform a successful simulation project.

### 3.3.1 Step 1: Formulate the Problem and Plan the Study

Hillier and Lieberman (2021) states that the first step is having a meeting with management to address certain questions, such as "What is the problem that management wants studied?" or "What are the overall objectives for the study?". Laguna and Marklund (2025) more thoroughly describes the phase of problem definition. To do this, they propose the method to construct a list of questions that the model is supposed to answer. These questions can be classified as either "key" or "desirable", depending on the criticality of answering a certain aspect. The questions should be both open-ended and specific.

The initial problem was identified through collaborative efforts between the authors of this thesis and supervisors from both Volvo and LTH. Then, the problem was clearly defined in a Goal Document that was revised and accepted by all parties to serve as a basis for the thesis purpose.

### 3.3.2 Step 2: Collect the Data and Formulate the Simulation Model

The next step is to collect the data, which will depend on the simulated system (Hillier and Lieberman 2021, p. 900). Examples of data types is the distribution of interarrival times and service times. It is also highlighted that it is important to simulate random observations under some probability distribution, rather than using averages. The probability distributions are often only possible to estimate, which in most cases is sufficient.

The second step presented by Laguna and Marklund (2025), *Step 2: Understanding the Process* emphasizes understanding the process to be simulated before constructing the model. They propose two useful tools for this step: Flow Diagrams and interviews. A simulation model should be constructed to answer the problem formulated in Step 1 rather than imitating the process exactly as it is. Thus, it is necessary to determine which process components that are vital and make sure they are included in the model.

The data was provided by Volvo, collected for a previous master thesis and research project. In line with suggestion from Laguna and Marklund (2025), interviews were conducted to understand the current rush ordering process. The purpose of the interviews were mainly as a basis for creating process maps, which was one of the desired outcomes of this thesis. Both activities deepened the understanding and facilitated the simulation phase.

### 3.3.3 Step 3: Check the Accuracy of the Simulation Model

Before the model is built in a simulation software, the accuracy of the conceptual model should be checked (Hillier and Lieberman 2021). Typically, this is done by a structured walk-through of the conceptual model with relevant company people. Assumptions may be added and errors corrected.

As the base model has been employed in previous research collaborations between Volvo and LTH, the conceptual accuracy of the model was already validated.

### 3.3.4 Step 4: Select the Software and Construct a Computer Program

The fourth step is to make a decision on what simulation software to use (Hillier and Lieberman 2021). They mention examples of different simulation software classes, such as spreadsheet software, general-purpose programming language, and application-oriented simulators. There are also two different approaches to discrete-event simulation; the event-scheduling approach and the process approach, where the process approach focuses the modeling of the processes that generate the events rather than the event itself.

For this thesis, the model was already built in ExtendSim10, a discrete-event simulation software that follows the process approach, that both our LTH Supervisor and Volvo SO&T are well familiar with. ExtendSim is owned by Andritz, a global technology company with headquarters in Austria (Andritz 2026).

### 3.3.5 Step 5: Test the Validity of the Simulation Model

A key step in simulation modeling is to test if the model is providing results that are representative of the system it is supposed to simulate (Hillier and Lieberman 2021). It is important that the performance measures for the real system can be closely approximated by those in the simulation model. Methods to check the validity include using a simpler mathematical model to provide results for the system and compare it to the simulated results and observe animations to see if the models behaves correctly.

The base-simulation model have been validated, as it has been used in other previous research. However, as extensions were made to the model for this thesis, this maintained an important step in the simulation process. To ensure the accuracy of the simulation model, test runs were conducted after extending the base model, and compared to previous results.

### 3.3.6 Step 6: Plan the Simulations to be Performed

The next step in the simulation process is to plan the simulations and which system configurations to simulate (Hillier and Lieberman 2021). One needs to address statistical issues, such as the simulation length, to reach steady state before the data collection. It is important to consider the simulation results as statistical rather than exact, and have strong statistical experience.

These decisions were made in consultation with the supervisor at LTH. The number of simulation runs per scenario was chosen as 30, and the simulation length to 10 000 time units.

### 3.3.7 Step 7: Conduct the Simulation Runs and Analyze the Results

The seventh step presented by Hillier and Lieberman (2021) is to run the simulation and analyze the results. As mentioned, the simulation output consist of some statistical estimates of desired performance measures, normally with a confidence interval to indicate a range of likely values. In this step, it is noticeable that some system configuration is performing better than another, and it is possible to fine-tune to reach the best results.

The simulation was conducted on a set of 23 items and four scenarios per item. The simulation output data included the mean and variance of selected performance indicators and were copied into Microsoft Excel for further data analysis.

### 3.3.8 Step 8: Present Recommendations to Management

Lastly, recommendations from the operational research study needs to be presented to management (Hillier and Lieberman 2021), usually through a written document and oral presentation.

This thesis report serves as a written presentation of our analysis. Moreover, a presentation for relevant management at Volvo Group was held at the end of this thesis project. An academic presentation was conducted at LTH as part of the thesis requirements.

# 4 THEORY

This chapter consists of theory relevant to this thesis. Section 4.1, 4.2 and 4.3 introduces common concepts and policies employed in inventory control. Common demand distributions for stochastic demand are introduced, and inventory control using a continuous review $(R, Q)$ policy is explored under a single-echelon setting. The concept of multi-echelon inventory optimization (MEIO) is introduced. Section 4.4 presents a literature review on how rush orders can be modeled, both in single- and multi-echelon systems. Lastly, Section 4.5 describes how emissions can be considered within inventory control operations.

## 4.1 Inventory Control

### 4.1.1 Inventory Control Terms

The goal of inventory control is to decide when, where and how much to order. This order decision should not be based solely on stock on hand, i.e. the number of units currently held in the warehouse, as it is also important to account for the outstanding orders, i.e. the units in transit to the warehouse, and the backorders, i.e. the units that have been requested by customers but not yet delivered (Axsäter 2015, p. 40). The *inventory level (IL)* is the number of units in stock minus the backorders, and is relevant when calculating holding and shortage costs. The *inventory position (IP)* also considers the outstanding orders and is what usually characterizes the stock situation at an inventory installation. The inventory level and inventory position are defined in (1) and (2).

$$\text{IL} = \text{stock on hand} - \text{backorders} \tag{1}$$

$$\text{IP} = \text{outstanding orders} + \text{IL} \tag{2}$$

Although the inventory position is sufficient for inventory control in some cases, more information may be required. For example, when considering emergency deliveries, the number of outstanding orders is not sufficient information, but rather where in the pipeline the outstanding orders are. In some cases, customers are allowed to reserve units for later delivery, which also needs to be captured in the inventory position (Axsäter 2015, p. 40).

### 4.1.2 Ordering Systems

#### 4.1.2.1 Review Policies

In the ordering system, it is possible to continuously monitor the inventory system over time (Axsäter 2015, pp. 40–41). Such a system is called *continuous review*. For example, in an $(R, Q)$ system this means that as soon as the inventory position reaches or falls below the reorder point $R$, an order of $Q$ units will be triggered. The order will then arrive after a certain time $L$, that is defined as the lead time. The lead time includes all activities from the order is placed until it arrives.

Alternatively, one may review the inventory system only at certain given points in time (Axsäter 2015, pp. 40–41). This is known as *periodic review*. Instead of continuous monitoring, the inventory system state is only noted in between (often constant) time-intervals. The review-period is denoted as $T$, and is the time in-between review intervals. For example, in an $(R, Q)$ system this means that the inventory position might fall below $R$ before the system is reviewed and an order of $Q$ units can be placed. Thus, the uncertain time becomes $T + L$. This means that it is a larger window of time in which one must hedge against variations in demand compared to a continuous review policy. However, periodic review is advantageous when it comes to coordinating orders for different items. For high demand items, periodic review usually reduces the total cost of the inventory system. However, for items with low demand, the cost of continuous review is only marginally higher. In practice, it is therefore common to use continuous review for items of low demand.

#### 4.1.2.2 Ordering Policies

The ordering policy refers to a decision rule of when to order and how much. One of the most common ordering policies in practice is the aforementioned $(R, Q)$ policy (Axsäter 2015, p. 41), where an order of $Q$ units is placed when the inventory position reaches or becomes less than $R$. For continuous or one-by-one demand, $IP$ will always hit $R$ exactly and then reach $R + Q$ directly after an order is placed. However, in a periodic review system or if demand is more than one unit at a time, the inventory position may fall below $R$ before an order is triggered.

Another policy similar to the $(R, Q)$ policy is the $(s, S)$ policy (Axsäter 2015, pp. 42–43). In this policy the reorder point is $s$, i.e. an order is triggered when $IP$ becomes $s$ or below. However, unlike the $(R, Q)$ policy, the batch-quantity is not constant. Instead, an order is placed, such that the inventory position reaches the maximum level $S$. In the case of continuous review, and or continuous one-for-one (unit) demand, the reorder point will be exactly $s$ every time an order is triggered. If $R = s$ and $S = R + Q$, it will be equivalent to the $(R, Q)$ policy with $Q = S - s$. One common variation of the $(s, S)$ policy is the *base stock policy* (also called order-up-to-S policy). Under this policy, $S$ is the base stock level, and an order to reach $S$ is always placed regardless of the inventory position. In other words, unless the period demand is zero, an order is always placed. The base stock policy is equal to the $(R, Q)$ policy with $R = S - 1$ and $Q = 1$. For continuous review systems, this policy is often denoted as $(S - 1, S)$. It has been shown that the $(s, S)$ policy is optimal for a single-echelon system under very general assumptions. Although in practice, the cost difference of having an $(R, Q)$ policy is generally small and it is easier to implement.

### 4.1.3 Service Levels

To measure the performance of the inventory system, the service level can be used as a Key Performance Indicator (KPI). It is also possible to determine levels of safety stock or reorder points by basing them on a predefined target service level (Axsäter 2015, p. 79). The three different types of service levels considered in this report are:

$S_1$ = probability of no stockout per order cycle.

$S_2$ = "fill rate", the fraction of demand that can be satisfied immediately from stock on hand.

$S_3$ = "ready rate", the fraction of time with positive stock on hand.

The service level, $S_1$, can be viewed as the probability that an order arrives in time, before the stock on hand is depleted (Axsäter 2015, p. 79). One significant drawback of using $S_1$ to measure the service level is that it does not account for the batch size $Q$ in its calculations. This can lead to misleading interpretations, as a low value on $S_1$ does not necessarily reflect poor service performance, as long as the batch size $Q$ is large enough to cover most of the demand.

The fill rate, $S_2$, and the ready rate, $S_3$, both account for the batch size $Q$ and are often considered better measures of the service performance than $S_1$. In cases where the demand is continuous or Poisson-distributed, $S_2$ and $S_3$ are identical. However, when orders can be placed in batches, they may be quite different. For example, if the stock on hand most of the time is low, and some customers order batches much larger than the available stock on hand, the fraction of time with positive stock ($S_3$) is high, while the fill rate ($S_2$) becomes very low.

### 4.1.4 Common Inventory Costs

Three common costs related to inventory control are holding costs, ordering costs, and backorder costs.

#### 4.1.4.1 Holding Cost

When holding stock, costs are accumulated as tied-up capital in inventory (Axsäter 2015, p. 38). In principal, the holding cost should be related to the return of an alternative investment with similar risk profile. However, it is important to include all variable costs from holding stock, for example tax, storage space, and material handling. The holding cost per unit and time unit is denoted $h$, and is usually determined as an interest rate, multiplied by the value of an unit. The holding cost $h$ is relevant when considering the stock on hand, i.e. the positive realizations of the inventory level.

#### 4.1.4.2 Ordering Cost

The ordering cost are the fixed (or semi-fixed) cost elements incurred from replenishment (Axsäter 2015, p. 38). This cost is usually due to administrative costs of order handling or in connection with transportation and material handling. The ordering cost is assumed to be independent of the batch quantity $Q$ (at least over certain ranges of $Q$). In production, this cost is usually referred to as *set-up cost* and relates to machine setup and learning costs.

#### 4.1.4.3 Shortage Cost

Shortage costs, or backorder costs, are related to the failed delivery of a demanded item (Axsäter 2015, pp. 38–39). If a customer arrives and there is a shortage of the requested item, the customer can agree to wait for the item. Then, the order will be backlogged, and costs are incurred due to eventual price penalties, extra administration, etc. If the customer is not willing to wait, a cost is incurred in terms of loss of sales. There is typically two types of shortage costs considered; a shortage cost per unit and time unit denoted $b_1$, and a shortage cost per unit denoted $b_2$ (Axsäter 2015, p. 80). For example, a shortage cost per unit and time unit $b_1$ is appropriate when there is a shortage of a spare part that leads to stop time in a machine, proportional to the customer waiting time. A shortage cost per unit $b_2$ may be suitable for shortages covered by an overtime shift at a higher cost or an emergency delivery. The shortage costs are often difficult to estimate. Instead, it is common to implement a service constraint as a replacement for quantifying the shortage costs. Determining an adequate service level tends to be less complex in practice.

The costs discussed above are commonly included in inventory models. However, there are many other cost aspects possible to consider, depending on the complexity of a model.

## 4.2 Single-Echelon Systems

### 4.2.1 Stochastic Demand

In inventory control, it is common to assume some stochastic demand model to capture the variability and uncertainty of future demand. There are different ways to model this stochastic demand. Since demand is often a non-negative integer, it is reasonable to use a discrete demand model, such as a compound Poisson distribution (Axsäter 2015, pp. 65, 72). However, there are situations when it can be beneficial to use a continuous demand model, such as the normal distribution, instead of a discrete distribution. The central limit theorem states that the sum of many independent random variables is approximately normally distributed. Additionally, the demand generated by a Poisson process is approximately normally distributed when the time period is sufficiently long. This, in combination with the analytical convenience and efficiency of the normal distribution, makes it a widely used demand model. One weakness with the normal distribution is that there will always be a small probability of negative demand, which is not realistic. This means that some solutions that are exact for a discrete demand model only will be approximately true for the normal distribution.

In the following paragraphs, the compound Poisson distribution and the Normal distribution are described more thoroughly.

#### 4.2.1.1 Compound Poisson Demand

When demand is compound Poisson distributed, customers arrive according to a Poisson process with a given intensity $\lambda$ (Axsäter 2015, p. 65). This means that $\lambda$ represents the mean arrival rate during a time interval $t$. The probability of $k$ customers arriving during this time period $t$ is Poisson distributed according to (3). The mean and variance are both equal to $\lambda t$.

$$P(k) = \frac{(\lambda t)^k}{k!} e^{-\lambda t}, \quad k = 0, 1, 2, \ldots \tag{3}$$

For compound Poisson demand, the demand size per customer is also a stochastic variable, independent of the customer arrival distribution and other customer demands (Axsäter 2015, p. 66). The probability of one customer demanding $j$ units can be denoted as $f_j$ $(j = 1, 2, 3 \ldots)$. $f_j^k$ is defined as the probability that $k$ customers demand a total of $j$ units. With this the stochastic demand during $t$, denoted as $D(t)$ can be decided. Using that $f_0^0 = 1$ and $f_j^1 = f_j$, $f_j^k$ is calculated recursively as seen in (4).

$$f_j^k = \sum_{i=k-1}^{j-1} f_i^{k-1} f_{j-i}, \quad k = 2, 3, 4, \ldots \tag{4}$$

Utilizing (3) and (4), the stochastic demand during $t$ is calculated according to (5).

$$P(D(t) = j) = \sum_{k=0}^{j} \frac{(\lambda t)^k}{k!} e^{-\lambda t} f_j^k \tag{5}$$

To decide the average demand per unit of time, $\mu$, and the standard deviation of the demand per unit of time, $\sigma$, new notations needs to be introduced (Axsäter 2015, p. 67). $K$ is defined as the stochastic number of customers during the time unit, $J$ is defined as the stochastic demand size of one customer, and $Z$ is defined as the stochastic demand during time unit considered. Using these definitions and the previous assumptions that the customer arrivals follow a Poisson process, this enables the calculations of $\mu$ and $\sigma$. This is shown in (6) and (7).

$$\mu = E(Z) = E_K\{E(Z \mid K)\} = E_K\{KE(J)\} = E(K)E(J) = \lambda \sum_{j=1}^{\infty} j f_j. \tag{6}$$

$$\sigma^2 = \lambda E(J)^2 = \lambda \sum_{j=1}^{\infty} j^2 f_j \tag{7}$$

It is important to note that it is not possible to model demand as compound Poisson when $\sigma^2/\mu < 1$ (Axsäter 2015, p. 67). This follows from (6) and

(7), where $\sigma^2/\mu = E(J^2)/E(J) \geq 1$ is with equality only for pure Poisson demand.

To decide the mean and standard deviation of the demand during a time $t$, $\mu$ and $\sigma$ from (6) and (7) are multiplied with the time period $t$, so that $\mu' = \mu t$, and $(\sigma')^2 = \sigma^2 t$.

#### 4.2.1.2 Normally Distributed Demand

For normally distributed demand, the parameters $\mu'$ and $\sigma'$ are needed to calculate the density function and the distribution function (Axsäter 2015, p. 72). $\mu'$ represents the demand during the lead time, and $\sigma'$ is the standard deviation during the lead time. A constant lead time $L$ is used to calculate these parameters, as seen in (8) and (9).

$$\mu' = \mu L \tag{8}$$

$$\sigma' = \sigma\sqrt{L} \tag{9}$$

If the stochastic variable $X \in N(\mu', \sigma')$, a transformation to a standardized normal distribution is easily done, letting $Z = \frac{X-\mu'}{\sigma'}$, where $Z \in N(0, 1)$. For the standardized normal distribution, where $\mu = 0$ and $\sigma = 1$, the density function $\varphi(x)$ and the distribution function $\Phi(x)$ are calculated according to (10) and (11).

$$\varphi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}, \quad -\infty < x < \infty. \tag{10}$$

$$\Phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-u^2/2}\, du, \tag{11}$$

For general values of $\mu'$ and $\sigma'$, the calculations for the density function $\varphi(d)$ and the distribution function $\Phi(d)$ are shown in (12) and (13).

$$\phi(d) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{d-\mu}{\sigma}\right)^2}, \quad -\infty < x < \infty \tag{12}$$

$$\Phi(d) = \int_{-\infty}^{d} \varphi(x)\, dx \tag{13}$$

### 4.2.2 Continuous Review (R,Q) Policy

For an $(R, Q)$ policy, there are two parameters that need to be determined, the reorder point $R$ and the batch quantity $Q$. For stochastic demand, $R$ and $Q$ are jointly optimized to minimize the total cost $C(R, Q)$, i.e. $\min_R\{C(R, Q)\}$ (Axsäter 2015, p. 107).

However, in practice, it is common to assume that demand is deterministic when determining the batch quantity $Q$, even if demand is almost always stochastic (Axsäter 2015, p. 45). Then, the stochastic demand is replaced by its mean for determining $Q$. A stochastic demand model is then used to determine the reorder point $R$, given $Q$. This approach is computationally simpler and, in general, only leads to a small cost increase compared to the optimum.

The following section describes this approximate procedure. Lead times are assumed to be constant, and demand is assumed to be compound Poisson, as it is most appropriate for items of low demand such as spare parts.

#### 4.2.2.1 Choosing Q

First, the order quantity $Q$ is determined under the assumption of deterministic demand. The $(EOQ)$ formula is one of the most well-known results in inventory control (Axsäter 2015, pp. 45–46). The $EOQ$ formula was first derived by Harris (1913) but is also attributed to Wilson (1934). The simplest version of the $EOQ$ formula assumes that; demand is continuous and constant, ordering and holding costs are constant over time, non-integer batch quantities are possible, no shortages are allowed and that the whole batch quantity is delivered at the same time. The costs that vary with the batch quantity, $Q$ are the holding costs and ordering costs, which can be expressed according to (14). The holding cost per unit and time unit is denoted $h$, the ordering cost $A$, the demand per time unit $d$, and the costs per time unit $C$.

$$C = \frac{Q}{2}h + \frac{d}{Q}A \tag{14}$$

The cost function $C$ is convex in $Q$ (Axsäter 2015, p. 46). Using the first order condition the optimal order quantity $Q^*$ is found, see (15).

$$Q^* = \sqrt{\frac{2Ad}{h}} \tag{15}$$

Performing a sensitivity analysis on the optimal order quantity, it turns out that quite large deviations from $Q^*$ lead to limited increases in cost (Axsäter 2015, p. 47). In practice, the batch quantity may be dependent on factors such as truck-loads, pallet-sizes and other aspects restricting the possible choices of $Q$. Even if simple, the $EOQ$ often leads to quite good choices of $Q$ in terms of cost, even if the assumptions do not hold in their entirety in practice.

#### 4.2.2.2 Choosing R for a Given Q

Given $Q$, a stochastic demand model can be used to choose an appropriate reorder point $R$. To do this, the most common approach is to determine the distribution of the inventory level $IL$. In a system controlled by a continuous review $(R, Q)$ policy with discrete demand, an important result is that the inventory position, $IP$, is uniformly distributed between $R + 1 \leq IP \leq R + Q$ (Axsäter 2015, p. 74). Another important relationship to determine the distribution of $IL$,, which is presented in (16):

$$IL(t + L) = IP(t) - D(t, t + L) \tag{16}$$

In (16), $L$ is the constant lead time and $D(t, t + L)$ is the stochastic lead time demand in steady state. The probability that the inventory level is some integer $j$ for a given $R = r$ under discrete compound Poisson demand can then be expressed according to (17) (Axsäter 2015, p. 76).

$$P(IL = j \mid R = r) = \frac{1}{Q} \sum_{k=\max\{r+1,j\}}^{r+Q} P(D(L) = k - j)) \qquad j \leq r + Q, \tag{17}$$

The next step is to choose a suitable $R$, which can be based on either satisfying a certain service constraint, or minimizing the sum of holding and backorder (or shortage) costs.

**Service Level Constraints**

As discussed in Section 4.1.3, both the fill rate $S_2$ and the ready rate $S_3$ consider the batch quantity $Q$. Assuming that $Q$ is given, either one of these measures can be used to determine the reorder point $R$ that satisfies the service level constraint.

The ready rate $S_3$ is defined as the fraction of time with positive stock on hand, see (18) (Axsäter 2015, p. 81).

$$S_3 = P(IL > 0) \tag{18}$$

Using (17), $S_3$ is quite easy to calculate for compound Poisson demand. The fill rate $S_2$ can be considered as the ratio between the expected satisfied quantity and the expected total demand quantity according to (19) (Axsäter 2015, p. 82).

$$S_2 = \frac{\sum_{k=1}^{\infty} \sum_{j=1}^{\infty} \min(j,k) \cdot f_k \cdot P(IL = j)}{\sum_{k=1}^{\infty} k f_k}. \tag{19}$$

Both $S_2$ and $S_3$ increase with the reorder point $R$. Another aspect is that both measures are zero for any $R \leq -Q$. The procedure for determining $R$ is therefore quite simple: start with $R = -Q$ and increase by one unit until the desired $S_2$ or $S_3$ is obtained (Axsäter 2015, p. 82).

**Minimizing the Expected Holding and Backorder Cost**

Another way to determine $R$ is to consider the holding cost $h$ and a backorder cost $b_1$ per unit and time unit, and choose $R$ to minimize the sum of expected holding and backorder cost (Axsäter 2015, p. 84). To do this, the following relationships in (20) and (21) are useful.

$$(x)^+ = \max(x, 0), \tag{20}$$

$$(x)^- = \max(-x, 0), \tag{21}$$

The expected inventory level $E(IL)$ can thus be expressed as (22), where $E(IL)^+$ is the expected stock on hand and $E(IL)^-$ the expected number of backorders (Axsäter 2015, pp. 84–85).

$$E(IL) = E(IL)^+ - E(IL)^-, \tag{22}$$

For compound Poisson demand, the expected costs per unit of time $C$ can be expressed according to (23) and (24), using the relationship in (22), where $\mu'$ is the mean lead time demand (Axsäter 2015, p. 85).

$$C = hE(IL)^+ + b_1 E(IL)^- = -b_1 E(IL) + (h + b_1) E(IL)^+ \tag{23}$$

$$C = -b_1\left(R + \frac{Q+1}{2} - \mu'\right) + (h + b_1)\sum_{j=1}^{R+Q} j\,P(IL = j) \tag{24}$$

Considering the cost difference $C(R+1) - C(R)$, (25) can be derived, see Axsäter (2015) p.85 for more details.

$$\begin{aligned} C(R+1) - C(R) &= -b_1 + (h + b_1)\sum_{j=1}^{R+1+Q} P(IL = j \mid R+1) \\ &= -b_1 + (h + b_1)S_3(R+1) \end{aligned} \tag{25}$$

As the ready rate increases when the reorder point $R$ increase, it follows that the cost difference $C(R+1) - C(R)$ is increasing in $R$, i.e. the cost is convex in the reorder point. This means that, as before, the optimal $R$ can be found by starting with $R = -Q$ and increasing $R$ one unit at a time until the cost increases.

From (25), it is apparent that there is a relationship between the ready rate and the cost parameters in the optimal solution. For the optimal reorder point $R^*$, (26) is true.

$$S_3(R^*) \leq \frac{b_1}{h + b_1} < S_3(R^* + 1) \tag{26}$$

## 4.3 Multi-Echelon Systems

When studying single-echelon (SE) systems, only a single installation is considered at a time. However, in practice, it is more common to have inventory systems with multiple installations connected to each other, so called multi-echelon systems (Axsäter 2015, p. 147). For example, many companies have a central distribution warehouse, often located close to a production facility or at a logistics hub enabling efficient deliveries from suppliers, and multiple local warehouses close to customers in different markets. Figure 3 shows such a distribution system with two echelons.

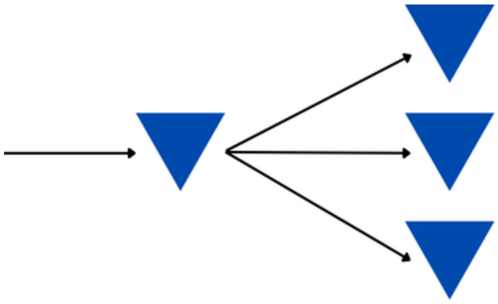

***Figure 3.*** *A two-echelon distribution system with one central warehouse and three local retailers.*

Distribution inventory systems are generally divergent, which means that the number of parallel installations increase along the material flow (Axsäter 2015, p. 148). Larger distribution systems may have even more echelons. An example is shown in Figure 4, where there is a central warehouse, three regional warehouses, and multiple local retailers.

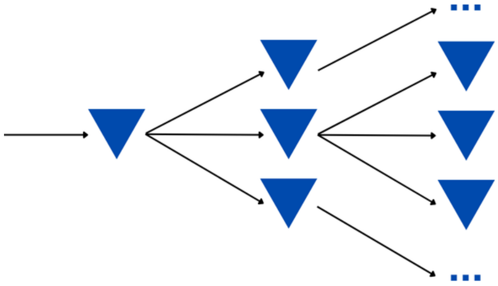

***Figure 4.*** *A three-echelon distribution network.*

The best distribution of stock in the system will depend on factors such as the structure of the system, demand variation, transportation lead times, and costs (Axsäter 2015, pp. 148–149). The stock at the retailers is necessary to maintain a high service level towards the customers, and the stock upstream is necessary to support the retailers. Having higher stock at the central warehouse ensures shorter and less variable lead-times towards the retailers, but leads to increased holding costs at the central warehouse. Although it may depend, it is common that the optimal solution distributes stock from the central warehouse towards the local retailers.

As mentioned in Section 4.1.2.2, the $(s, S)$ policy is optimal for single-echelon systems under very general assumptions. For multi-echelon inventory systems, there is generally no known optimal policy. The complexity increase with multi-echelon systems, making MEIO more difficult in practice compared to single-echelon optimization. Optimal decisions in a MEIO system require a high degree of centralized decision making, as a lot of information is required. If all relevant information is available centrally and all managerial concerns are reflected in the objective function, the optimal MEIO policy will always outperform a single-echelon policy (Hausman and Erkip 1994). Today, better information and data sharing are possible because of new and improved technologies. However, data movement and coordination come with additional costs, especially when the installations are located far from each other (Axsäter 2015, p. 153). There are also organizational challenges to achieve a high degree of centralization, for example sub-optimization and individual performance measurement (Hausman and Erkip 1994). Nonetheless, the interest in MEIO is large and growing. Avoiding the "bull-whip effect" has gained a lot of attention in literature, and the possibility of achieving lower total costs is appealing to businesses.

## 4.4 Rush Orders

Rush orders are orders requested beyond regular replenishment orders, usually in case of a stock-out or to avoid an anticipated stock-out. In literature it is most commonly referred to as emergency orders, emergency shipments, or emergency replenishments. There are different structures for emergency replenishment discussed in literature.

### 4.4.1 Structures for Rush Orders

One possibility is to have an inventory system that utilizes *lateral transshipments*. A lateral transhipment is when a local stock point is supplied with stock from a parallel local stock point in case of an emergency situation (Axsäter 2015, p. 151). Lateral transshipments are faster than regular replenishment from an upstream supplier, but incur higher costs. These models are common in practice, but are difficult managing from a modeling perspective.

Another common structure is a *dual-sourcing* network. In such a system, inventory can either be replenished from a normal source or an emergency source (Song et al. 2017) , where the emergency source has a shorter lead time but a higher per unit cost. There is also a version of this structure where dual transportation modes are employed, for example sea or air.

Lastly considered in this thesis, is an inventory system with a *support warehouse* structure. This is common in practice to deal with distribution of spare parts (Axsäter et al. 2013), and consists of one central warehouse that serves several markets, with one local warehouse in each market referred to as the support warehouse, and a large number of local retailers that serve the end customer. The local retailers are normally replenished by the central warehouse, however in case of a shortage an emergency order is placed with the support warehouse, at an additional cost.

### 4.4.2 Rush Orders from a Modeling Perspective

From a modeling perspective, there are different methods for how rush orders are considered regarding inventory system structure, decision-rules and flow of information. The following section provides a literature review of both single- and multi-echelon models relevant for this thesis.

#### 4.4.2.1 Single-Echelon Models

A dual supply inventory control system is analyzed by Moinzadeh and Schmidt (1991), in a single-echelon context. Demand is assumed to be Poisson distributed, with one supply channel for normal replenishments according to a $(S-1, S)$ policy, and one emergency supply channel. In the $(S-1, S)$ policy an unlimited number of outstanding orders are allowed in the backlogging case, while up to $S$ outstanding orders are allowed in the lost sales case. Moinzadeh and Schmidt (1991) considers having a policy that avoids unnecessary emergency orders by utilizing information about the timing of incoming orders. As soon as a demand occurs, an order is placed due to the $(S-1, S)$ policy. Whether the order should be a normal or emergency order is determined based on the age of the outstanding orders and the stock on hand at the time of the demand. They consider a normal supply cost per unit and an emergency supply cost per unit, with constant lead times for each supply option, with the emergency option having the highest cost and shortest lead time. Along with the variable $S$, some stock level that triggers the consideration of emergency ordering $\hat{S}$ is chosen. The policy is formulated such that if the inventory level is larger than $\hat{S}$, a normal order is placed. If the inventory level is less than $\hat{S}$, and the remaining lead time of the closest outstanding order is less than the emergency lead time, a normal order is placed. Else, an emergency order is placed. They do not claim that this policy is optimal, however they show that under this policy the system has a quite simple steady-state distribution. The results from Moinzadeh and Schmidt (1991) are extended by Song and Zipkin (2009). They summarize the system information, i.e. lead times and outstanding orders, into two separate inventory positions for each supply source. With this reinterpretation, the system can be viewed as a two-node network of queues and a state-dependent routing mechanism. These results are extended to consider stochastic lead times and non-Poisson distributed demand.

Axsäter (2007) also considers a single-echelon inventory system with dual supply modes; one for normal replenishment, and one mode for emergency replenishments. The system modeled faces compound Poisson demand and uses a continuous review $(R, Q)$ policy for normal replenishments. The lead times are constant with the emergency source being faster. Demand that is not directly met is backordered, and costs considered include standard ordering, holding and backorder costs. Additionally, other costs associated with emergency ordering are included. Axsäter (2007) provide a heuristic decision rule for when emergency orders should be triggered. The logic is that for some $R$ and $Q$, when demand occurs and there is no stock on hand, an emergency order is considered. If an emergency order is triggered, it is assumed that its quantity $Q$ is large enough to bring the inventory position above R, which means that a normal order cannot be triggered at the same time. If an emergency order is not triggered, a normal order is instead triggered according to the $(R, Q)$ policy. The decision rule presented is to assume that there is no future possibility for emergency orders. The best alternative, i.e. emergency order or normal replenishment, is then chosen under this assumption, and then the rule is repeated as an heuristic. Under certain approximation, Axsäter (2007) gives a performance guarantee that the decision rule will lead to reduced expected costs.

Olsson (2015) also presents a single-echelon model with emergency ordering, but with lateral transshipments that takes pipeline information into account. The model considers an inventory system with continuous review and two parallel locations, where lateral transshipment can be utilized between the locations. Both locations face independent Poisson demand, and the transshipment lead times are deterministic and positive $(\iota > 0)$. A policy for when to perform lateral transshipment is introduced, with two conditions that must be satisfied. First, the supplying location must have positive stock on hand. Secondly, the lead time of the transhipment must be shorter than the lead time of the next outstanding replenishment order. The author emphasizes that this policy is not optimal, and mentions possible extensions to their model. The suggestions include allowing transshipments only when the transshipment lead time is sufficiently shorter than the residual lead time, and only when the supplying location has sufficient stock on hand to cover the demand from their customers. The result from the modeling is not exact, since the demand stream at the retailers is approximated as a doubly stochastic Poisson process, which generally leads to reduced variability. Consequently, the expected stock on hand and the expected number of backorders at the locations are underestimated in the model, resulting in a slight underestimation of the total costs compared to reality. The findings indicate that even small reductions in transshipment lead times can result in substantial cost reductions.

#### 4.4.2.2 Multi-Echelon Models

Axsäter et al. (2013) propose a multi-echelon inventory model with transshipments from a support warehouse associated with an extra cost, following the introduced support warehouse structure. In the model, the lead time from the support warehouse to the retailers is assumed to be zero. There are two costs considered: holding cost per unit and time unit and a fixed transshipment cost per unit shipped from the support warehouse to the retailer. The latter quantifies extra costs incurred from receiving an emergency shipment compared to a regular, such as extra picking, loading, and transporting.

In Howard et al. (2015), the research in Axsäter et al. (2013) is extended by considering customer waiting costs and pipeline information. Moreover, if an emergency shipment request to the support warehouse cannot be fulfilled, the demand is satisfied from the central warehouse instead, which is assumed to always be able to deliver (Howard et al. 2015). Both models are motivated by a research collaboration with Volvo Parts, which is a previous title for Volvo SO&T. Howard et al. (2015) introduces an $(S, T)$ policy at the individual stock points, where $S$ represents the base-stock level and $T$ the threshold time for backordering instead of placing an emergency order. The decision rule of the system is to request an emergency replenishment if no regular order is sufficiently close in the pipeline, i.e. will not arrive within $T$ time units. The model allows for partial backordering, i.e. demand can be either backordered or lost to the local warehouse depending on the system state. They consider the customer waiting cost per unit and time unit at the local warehouse, as well as a fixed per-unit cost associated with a rush order being placed to the support warehouse. As an emergency shipment can be sent from the central warehouse instead of the support distribution center if the SDC is out of stock, the authors consider an additional fixed per-unit cost, which is assumed to be larger than ordering with the support warehouse. The work from Howard et al. (2015) provides a basis to consider both cost structures and pipeline information as decision rules for placing rush orders.

Another multi-echelon model that considers utilizing pipeline information is presented by Wang and Minner (2026). In this model, there can either be lateral transhipment between local stockpoints to fulfill demand, or emergency deliveries from upper echelons. Pipeline information is incorporated to decide if an emergency order should be triggered, or if one should wait for the next incoming replenishment. Their model assumes a $(S-1, S)$ policy at all local warehouses, meaning that each demanded unit from a customer triggers a replenishment order from the central warehouse. They consider stochastic lead times, which can lead to additional delays if the central warehouse is out of stock, while many other models (for example Howard et al. (2015)) assume ample capacity at the central warehouse. The costs considered are a penalty cost for customer waiting time, holding cost, and a unit cost per emergency shipment. This unit cost varies depending on whether the order is a lateral transshipment, from the central warehouse, or from an external emergency supplier.

Johansson and Olsson (2018) propose a model for a multi-echelon spare part distribution system with a central warehouse and multiple local retailers. They suggest using pipeline information to request an emergency shipment from an external supplier if the waiting time for an incoming order in the regular channel is too long, i.e. there is a maximum time a customer is willing to wait. They consider a non-linear backorder cost structure, with a fixed backorder cost whenever the customer waiting time exceeds the maximum acceptable waiting time, instead of a linear backorder cost per unit and time unit, like the aforementioned models. They also consider an associated cost per item for requesting an emergency shipment, assumed to be lower than the backorder cost. Another aspect in their model is that it captures that orchestration of an emergency order may not be possible within a given time window, i.e. ample capacity is not assumed. Johansson and Olsson 2018 also quantify the expected $CO_2$ emissions in the inventory system, considering both transportation emissions and production waste due to perishable products being scrapped. The findings from Johansson and Olsson (2018) are extended by Kouki et al. (2024) to consider generally distributed lead times at the central warehouse, which are constant in the model by Johansson and Olsson (2018). In their analysis, they use observations by Howard et al. (2015) to model the lost sales queueing network described above.

## 4.5 Emissions

Traditionally, the objective in inventory management has been to satisfy customer demand while minimizing total costs. As sustainability has become increasingly important in society, this development has also influenced inventory control. The concept of Green Inventory Management aims to minimize both costs and emissions while maintaining a high level of customer service.

One challenge is to understand how different decisions in the inventory system affect costs and emissions. Since these two objectives are often in conflict, another challenge is to identify solutions balancing the two objectives as effectively as possible.

For reporting purposes, there is a global framework for standardized emissions accounting known as the Greenhouse Gas (GHG) Protocol (GHG Protocol Initiative n.d.). In this protocol, three different scopes for direct and indirect emissions for corporate and GHG accounting purposes are defined.

**Scope 1: Direct GHG emissions**
Direct carbon emissions occur from sources owned or controlled by the company, such as combustion in owned or controlled boilers, furnaces, and vehicles (GHG Protocol Initiative n.d.).

**Scope 2: Electricity indirect GHG emissions**
Scope 2 emissions include GHG emissions generated from the production of electricity purchased and consumed by the company (GHG Protocol Initiative n.d.). Any electricity brought in to the boundary of the organization belong to Scope 2.

**Scope 3: Other indirect GHG emissions**
The third scope allows for inclusion of all other indirect emissions. These emissions are a consequence of the activities performed by the company but from sources not owned or controlled by the company itself, both upstream and downstream in the supply chain (GHG Protocol Initiative n.d.). Some examples of Scope 3 emissions are emissions from transportation of purchased products and the use of sold products.

### 4.5.1 Types of Emissions

The emissions associated with inventory management can be categorized into three different types, according to Marklund and Berling (2024). The first type are the emissions related to ordering, for example producing and transporting the goods. The second type are the emissions caused by holding products in stock. The third and last type are the emissions resulting from not satisfying customer demand in time.

#### 4.5.1.1 Emissions Related to Ordering

Emissions related to the ordering of products can be divided into a fixed component and a variable component (Marklund and Berling 2024, pp. 145–146). The fixed emissions are independent of the order size, for example emissions associated with operating a truck or airplane regardless of its load. The variable component depends on the order size, meaning that the emissions increase as the transportation load becomes heavier. The transportation emissions are usually the largest emission factor to consider.

#### 4.5.1.2 Emissions Related to Holding Items

The emissions caused by holding products in stock largely consist of emissions from the energy required to handle inventory and operate storage facilities (Marklund and Berling 2024, pp. 146–147). Also included are emissions resulting from waste and disposal of items. In calculations of emissions, it is often assumed that the relationship between inventory levels and emissions is proportional, i.e., when the inventory increases, emissions increase as well. However, this assumption does not always hold in practice, although it may be justifiable to assume this relation in order to simplify calculations. There is also a trade-off between transport emissions and holding emissions, as a decrease in one of them often leads to an increase in the other.

#### 4.5.1.3 Emissions Related to Not Satisfying Customer Demand

Emissions resulting from not satisfying customer demand in time can often be difficult to determine, and are largely dependent on the type of goods and how the calculations are made (Marklund and Berling 2024, pp. 147–148). For example, failure to deliver a spare part to a machine can result in substantially different emissions depending on the product that the machine handles, for example if the waste is of perishable nature or not.

Emergency shipments are often used as a tool to handle inventory shortages, and the emissions resulting from these shipments can be seen as a consequence of failing to satisfy customer demand in time (Marklund and Berling 2024, p. 148). These emissions are often high due to the use of faster, and more emission intensive transport modes (e.g., air freight or trucks), as well as lower vehicle utilization, which leads to higher variable transport emissions.

### 4.5.2 Calculating Emissions

The transportation sector is responsible for 17% of the global GHG emissions (Climate Watch 2025). When focusing on freight transport and logistics activities, it is estimated that 90% of the $CO_2$ emissions stem from freight transport, other logistics activities, such as buildings, represent only 10% (Blanco and Sheffi 2024, p. 102). Considering this, when estimating emissions in a logistics network, transportation emissions carry the largest weight, and it is reasonable to focus on mitigating these emissions.

#### 4.5.2.1 Methods for Emission Calculation

There are different methods to estimate the GHG emissions from transportation. A *fuel-based/energy-based* approach is recommended by the IPCC and is deemed the most accurate for $CO_2$ emissions (Blanco and Sheffi 2024). This approach uses estimates on the amount of greenhouse gases that is produced during combustion of different fuel types. Another method proposed is the *activity-based* approach. Accurate fuel consumption data is not always accessible for third-party logistics providers or other decision-makers. The fuel consumed is estimated based on vehicle characteristics or a combination of fuel consumption data and activity data. Alike the fuel-based method, the choice of fuel emission factors will be crucial for accurate results.

### 4.5.3 Including Emissions in Cost Calculations

Logistics and inventory control leads to emissions, which can be identified and approximately quantified. However, a challenge persists in how to include emission impact in inventory control models to support the "best" decision making, both from a cost and emission perspective. Often, minimizing both costs and emissions are conflicting objectives. Marklund and Berling (2024) presents four approaches to mutually consider costs and emissions in inventory control to support the "best" decision making.

#### 4.5.3.1 Translating Emissions to Costs

One option for balancing costs and emissions objectives is to translate emissions into costs and then minimize the total costs using existing models (Marklund and Berling 2024, p. 149). This can be done by introducing a tax $t$ ($t > 0$) per unit of $CO_2$ equivalents emitted, and then including $t$ as a parameter in the cost minimization (Chen et al. 2013, p. 176).

#### 4.5.3.2 Introducing an Emission Cap

Sometimes governments or other regulatory agencies introduce emission caps, where penalties must be paid if the limit is exceeded (Chen et al. 2013, p. 177). In this case, only emissions exceeding the cap result in penalties, unlike taxing all emissions.

#### 4.5.3.3 Cap-and-Trade Systems

A cap-and-trade system is an extension of the regular emission cap, in which emission rights can be bought and sold on a market (Marklund and Berling 2024, p. 155). If a firm emits less than the emission cap, its excess can be sold on the market, to firms exceeding their limit. In this case, firms with low emissions levels may generate additional revenue by selling their unused emission allowances, potentially strengthening their economic performance compared to a system without regulations (Marklund and Berling 2024, p. 156).

#### 4.5.3.4 Multiple Criteria Decision-Making Techniques

Instead of trying to translate emissions into costs in different ways, different multiple criteria decision-making (MCDM) techniques can be used to jointly consider the cost and emission perspectives (Marklund and Berling 2024, p. 149). This can, for example, be achieved through the use of utility functions, efficient frontiers, and identifying Pareto optimal solutions.

# 5 CURRENT RUSH ORDER PROCESS

This chapter provides an in-depth description of the current rush order processes within the Volvo SO&T distribution network. The findings, in the form of several process maps, are based on an interview study. The purpose of this part of the thesis project is to gain insight into the current state, both how rush order decisions are made at the dealers, and how such an order is processed until it arrives at a dealer. This provides a foundation for proposing new rush order policies and highlight improvement opportunities. There are two general types of market structures within the network: European markets that follow an SDC structure, and other markets that have an RDC structure. The rush order process differs between the two market types, each represented by two process maps.

## 5.1 Interviews

Interviewees were selected to include both dealers within the network, either Volvo-owned or privately owned with DIM, and employees within the Volvo Group organization who are not dealers but have relevant knowledge of these processes, referred to as internal respondents. The selection process of the interviewees is described in Section 3.2 in the Methodology chapter. The internal respondents are presented in Table 2 and the dealer respondents are presented in Table 1.

***Table 1.*** *Overview of dealer interviewees.*

| Dealer | Brand | Market | Role | Date |
|---|---|---|---|---|
| D1 | Volvo Trucks | Sweden | Business Developer Spare Parts | 06-03-26 |
| D2 | Volvo Trucks (Privately owned) | United Kingdom | Part Supervisor | 19-03-26 |
| D3 | Volvo Trucks | United Kingdom | Part Supervisor | 23-03-26 |
| D4 | Volvo Construction Equipment | Sweden | Chief of Logistics | 13-04-26 |

The interview questions were adapted depending on the interviewee's role and area of expertise. The dealer interview questions are found in Appendix A and the internal interview questions are found in Appendix B.

The interviewees were chosen based on expertise within the area, but also based on accessibility within the time frame of this thesis. Thus, the dealers are concentrated to European markets, with an over-representation of Volvo Trucks; the largest brand within the Volvo Group. Most of the internal respondents are located in Europe, with differing global reach and responsibilities.

***Table 2.*** *Overview of internal Volvo SO&T interviewees.*

| Interviewee | Role | Date |
|---|---|---|
| I1 | Supply Chain & Analytics Expert | 17-02-26 |
| I2 | Senior Excellence Manager of Dealer Inventory Management | 05-03-26 |
| I3 | Business Logistics Manager | 06-03-26 |
| I4 | Service Center Coordinator | 12-03-26 |
| I5 | Head of Order & Reverse Management | 18-03-26 |
| I6 | Service Developer | 25-03-26 |
| I7 | Head of OP/Refill | 27-03-26 |
| I8 | General Manager at SDC | 13-04-26 |
| I9 (Email) | Dealer Inventory Manager RDC | 13-04-26 |

## 5.2 Process Maps

The process maps representing an SDC structure are presented in Figure 5 and Figure 6 below. Figure 5 captures the dealer perspective, i.e., the decisions made at the dealerships, as well as the interactions with Service Center and the SDC and CDC. Figure 6 captures how the order is managed more thoroughly at the SDC and possibly CDC, with details that may not be visible to the dealer. There is some overlap of the process maps due to communication between the interfaces and access to similar information.

Similarly, the RDC process is represented through the dealer perspective in Figure 7, while the RDC perspective is represented in Figure 8.

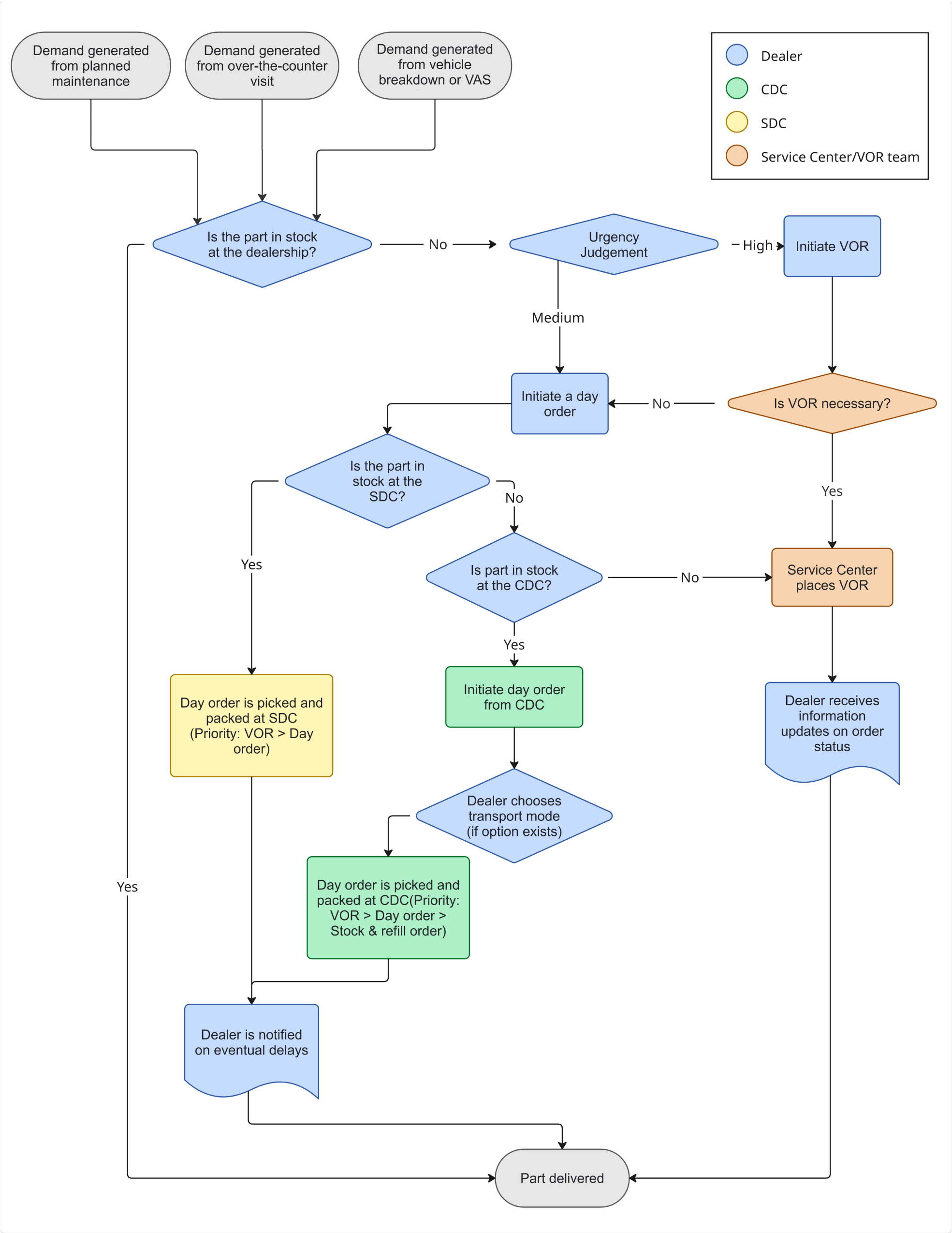

***Figure 5.*** *Map of the rush order process on an European market, from the perspective of a dealership.*

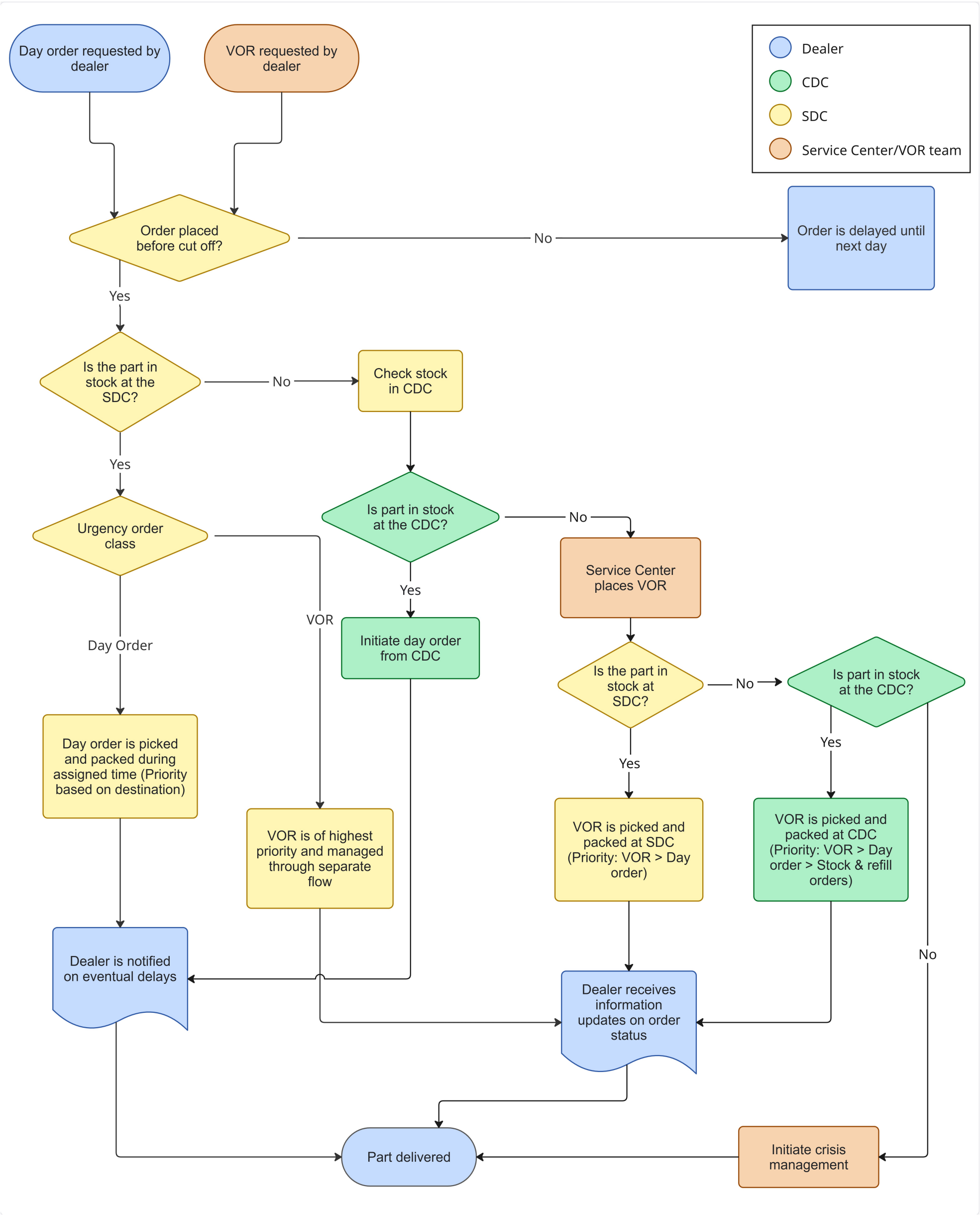

***Figure 6.*** *Map of the rush order process on an European market, from the perspective of the SDC.*

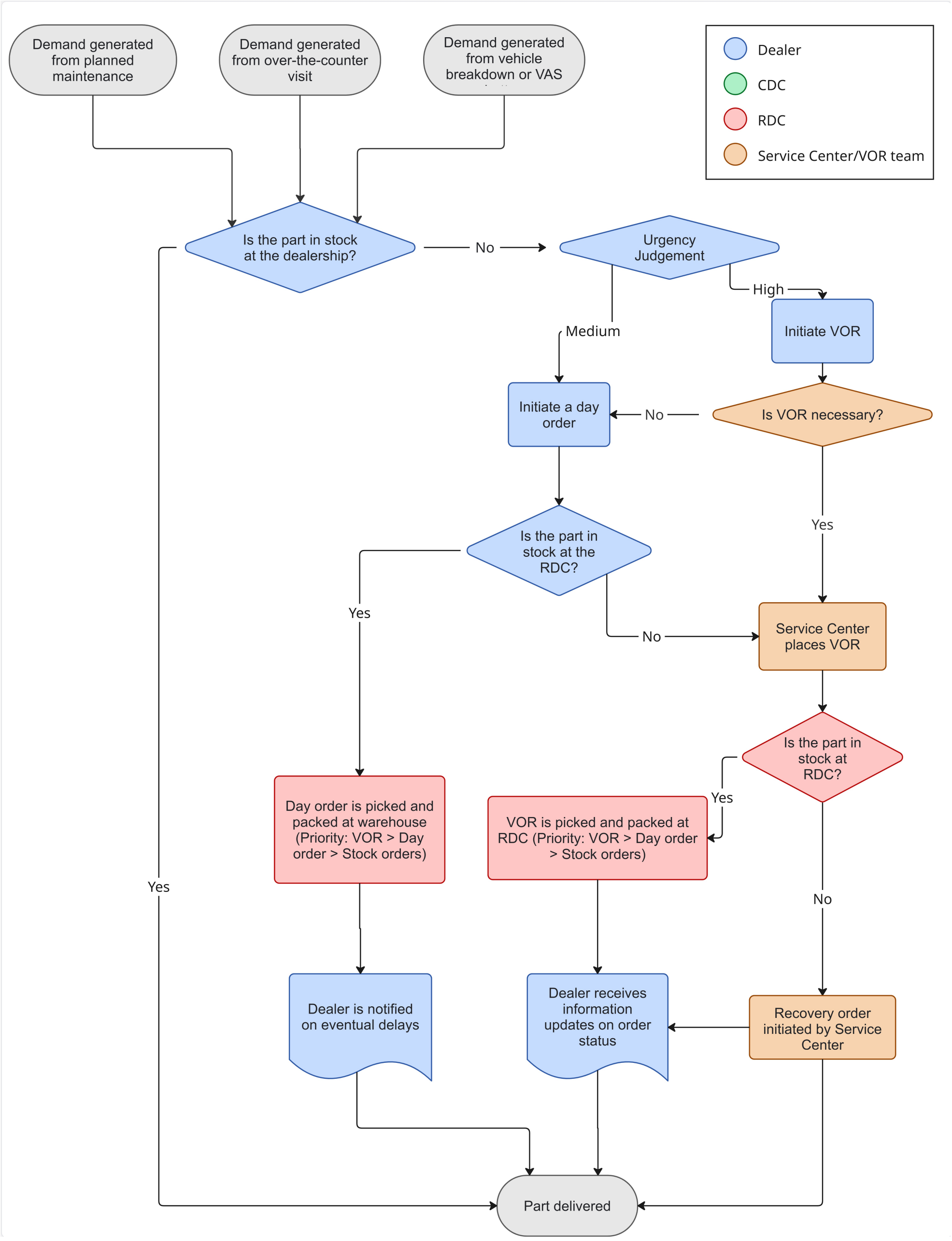

***Figure 7.*** *Map of the rush order process on an RDC market, from the perspective of a dealership.*

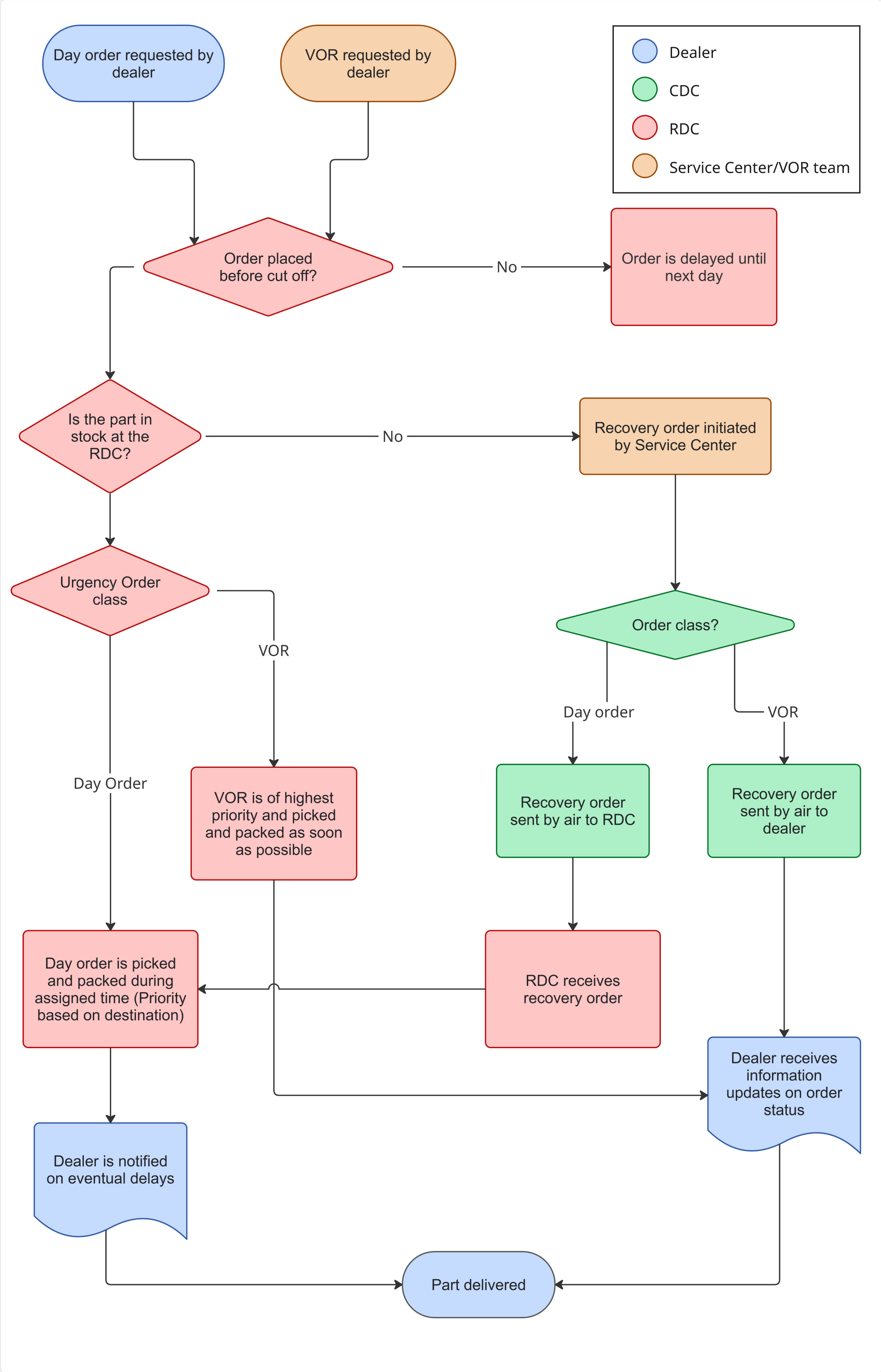

***Figure 8.*** *Map of the rush order process on an RDC market, from the perspective of the RDC.*

Within the Volvo Group there is a lot of individuality based on both brand and market, leading to the processes being quite different. This also means that segmenting only into two market categories, i.e., SDC and RDC, are not enough to capture all deviations and nuances in the processes. The process maps are representative of the markets and brands the interviewees represent, but not necessarily for all Volvo brands and markets.

The following subsection describes and discuss the processes more thoroughly and is divided into the perspective of the dealers, RDC, SDC and CDC.

### 5.2.1 Rush Order Process at the Dealership

The process of placing a rush order at a dealership begins with customer demand for a specific part, as illustrated in Figures 5 and 7. Demand may arise through several channels, such as planned maintenance, spontaneous over-the-counter visit, or a sudden vehicle breakdown on the road. Unexpected breakdowns can be signaled to dealers through a driver using the Volvo Action Service (VAS) button, which is an on-call service that customers pay a premium for.

If the requested part is available in stock, it can be delivered directly and no rush order is required. However, if the demanded part is not available in stock, a rush order may become necessary. Depending on the urgency of the demand and part availability at RDCs/SDCs/CDCs, several ordering options exist. Dealer 3 describes this part of the process as following: First, the stock availability at the SDC (Rugby for UK) and the CDC (Ghent for Volvo Trucks) is checked. If the part is available at either location, a day order is issued from there.

A day order can typically be initiated by any employee at the dealership, as confirmed by Dealer 2, Dealer 3 and Dealer 4. These orders are placed directly in the dealers' own systems (Parts-On-Line for Volvo Trucks), which subsequently trigger an order at the relevant warehouse. All interviewed dealers confirmed that day orders are issued daily, often multiple times per day. Depending on the type of market, the process differs. In Europe, day orders are primarily issued from the SDC if the part is available in stock, see Figure 5. The delivery time depends on the geographical location of the dealership and its proximity to a distribution center. Dealer 2 and 3, located in the United Kingdom, reported that day orders most often arrive the following day, unless there are customs issues. Dealer 1, located in Sweden and near an SDC, reports that orders may occasionally arrive on the same day they are placed, but otherwise typically arrive the next day. The transportation mode for day orders from an SDC cannot be selected by the dealer, but is instead chosen by the pre-determined freight code.

If the required part is not available at the SDC, the dealer proceeds to check the availability at the CDC, see Figure 5. If the part is in stock, a day order is issued from the CDC. When placing day orders from the CDC, some dealers have the option to select the mode of transportation. Dealer 1 has the option to choose between road (2 day delivery) and air (1 day delivery) for most day orders issued from the CDC, while Dealer 2 and 3 have no such option. This is confirmed by Interviewee 5, who states that the transport mode is generally based on the pre-determined freight code. For dealers who can select the transport mode for day orders, there is no cost difference between road and air. In general, the dealer does not have to pay a premium for a part issued through a day order. Any additional handling and transport costs are absorbed by the associated Volvo brand. These costs are then aggregated on a annual basis, and incorporated in the pricing of the parts for the upcoming year. Thus, the additional costs arising from rush orders and air transportation are allocated across all dealers. However, Interviewee 5 highlights some exceptions. Both Volvo Penta and Volvo Construction Equipment (VCE) dealers have to pay an additional fee when issuing day orders with air transport over road. Dealer 4 oversees multiple VCE sites in different parts of Sweden, and confirms the different structure for VCE dealers. For stock orders, dealers receive a discount on the order price, thereby incentivizing pre-planning. The cost of a day order is the same as the standard price, while an additional cost is issued for a VOR order. The discount or additional cost does not affect the end customer price, instead it is absorbed by the dealership. The only situation in which the end customer incurs an additional delivery cost is upon insisting on air transport, to ensure the fastest delivery possible. According to Dealer 4, the number of parts shipped by air has decreased since this cost was transferred to the end customer, implying that it is not always crucial to receive a part as fast as possible, but rather a question of convenience.

In situations where a dealer has checked the stock at both the SDC and the CDC, and the required part is not available at either location, a VOR is placed by contacting the Service Center, provided that the dealer wants the part as quickly as possible, as illustrated in Figure 5. Alternatively, the dealer maintains the day order and waits until the part is available. Interviewee 4 explains that quantities in stock may be blocked (or reserved) by material planners or members of the VOR team when inventory levels are low. This is done to ensure availability in case VOR orders are triggered for a specific part. Thus, upgrading a day order to a VOR, stock that was previously unavailable at the SDC or CDC may become available and allocated, which can be seen in Figure 6. However, this can lead to dealers issuing VOR orders even when the level of urgency is relatively low, as they are aware that certain inventory is reserved exclusively for VOR orders. It should be noted that a day order is not automatically removed when a VOR is placed for the same part, meaning that either the dealer or SDC needs to manually remove the day order. If not removed, two active orders will be allocated towards satisfying the same demand. In situations where VOR orders are issued for a part that is not available in any warehouse, crisis management is initiated. The details of this process are not within the scope of this thesis.

In markets with the RDC structure, the process for issuing rush orders at a dealership is illustrated in Figure 7. The initial steps are the same as for the European dealerships, i.e., demand is generated and a judgment of the urgency is made. Interviewee 5 explains that the main difference between this structure and the SDC structure is that dealers do not have the option to place a day order from the CDC if the part is unavailable at the RDC. In such cases, a VOR may be placed directly, according to Figure 7, again assuming that the dealer wants the part as quickly as possible. If the part is in stock reserved for VORs, the VOR is handled at the RDC. However, if the part is stocked out, a recovery order is issued by the Service Center, which is described more thoroughly in Figure 8.

If a dealer wants to place a VOR, a case is created in Argus. All VORs are managed by the Service Center operating in the market, which has the authority to question and reject VOR orders if they deem them unnecessary or unclear. However, there are no clear policies for which orders to approve or reject. Interviewee 4 confirms that such decisions are based on individual assessment. Interviewee 3 states that the purpose behind the VOR order class from Volvo's perspective is to provide a fast recovery for vehicle or machine downtime when the vehicle or machine is not usable due to technical or legal reasons. However, as highlighted in most interviews, VORs are frequently used in cases where no acute breakdown has occurred. Interviewee 2 mentions that the number of VOR orders has increased in the latest year, and that dealers can issue VOR orders instead of day orders to receive a higher priority at the warehouse and thus receive the part faster. Additionally, the dealer receives the most information on the status of a VOR. In Argus, the Service Center updates the VOR case whenever any new information about the part becomes available, such as its expected arrival at the dealership, or other relevant details. As highlighted in all maps, dealers are (generally) only notified about day orders when there is a delay to a day order, not the estimated time of arrival (ETA). However, while day orders typically arrive the following day as intended, Dealers 1, 2, and 3 highlight a lack of real-time ETA information on day orders.

Dealers have even less visibility into incoming stock orders. The lack of ETA information on stock orders is a problem addressed in several interviews. This lack of transparency may contribute to unnecessary day orders. For instance, a part may be in transit and scheduled to arrive within a few days, but due to the lack of information, a day order may still be placed for the same part. Interviewee 5 explains that European Volvo Truck dealers are only informed if a stock order has been picked, packed and invoiced at the CDC/RDC, but no information after the invoice stage is shared with the dealer. Although dealers can often estimate the delivery time based on historical delivery patterns, they are not automatically notified of delays. However, there are differences in information sharing between brands and geographical placements. In the Asia-Pacific market, an app has been developed to facilitate communication between warehouses and dealers. In this app, dealers receive updates on in-transit day orders and shipment quantities. The dealer is also connected to the carrier, enabling further communication between these parties. Interviewee 5 acknowledges this as a promising solution, but emphasizes the challenge of scaling this globally due to system differences and challenges.

### 5.2.2 Rush Order Process at the SDCs

The purpose of SDCs in the European market is to support dealers with day orders, reducing the costs of rush orders by positioning inventory closer to the markets compared to sourcing all rush orders from the CDC (Ghent for Volvo Trucks and Lyon for Renault Trucks). SDCs do not handle stock orders, only day orders and VORs. The SDC is refilled by the CDCs.

When a dealer places a day order in their system, it is automatically transferred to the related SDCs systems as a picking order. The SDCs operate their picking and packing schedule based on predefined cut-off times, as seen in Figure 6. At the SDC managed by Interviewee 8, a medium-sized SDC in southern Europe responsible for serving a single country, the cut-off time for orders to arrive the next day is 6:00 PM. This particular SDC also offers a milk run service, which is not offered by all SDCs. The milk run cut-off time is 11:30 AM. The milk run orders are delivered within the same day, for which the dealers pay a premium.

The afternoon is allocated towards picking and packing day orders up until 7:00 PM, which is an hour past the cut-off time. Day orders placed before the cut-off time are internally prioritized depending on their destination. Interviewee 8 notes that dealers in the southern region are always supplied by air freight due to the geographical distance, and therefore receive the highest picking priority to ensure on-time delivery. All other zones receive their day orders by truck. Day orders going by truck are consolidated into trailers which are collected by the distributor responsible for transportation.

Once a day order has been picked and packed, it is invoiced to the dealership. Interviewee 8 notes that no proactive notification is provided if the order is shipped on time. However, as previously discussed, dealers are informed if an order is delayed. During transportation, visibility depends on the traceability of the responsible distributor, which is often limited to arrivals and departure at key logistics hubs. For example, Dealer 4 mentions that an order sent from Ghent is not visible until it arrives at the distributor's hub in Gothenburg. Dealers may contact the Service Center for additional inquires about day orders and ETAs (Interviewee 4), for example when parts in shortage are expected to arrive at the CDC or SDC, which can indicate the recovery time on late orders. However, Interviewee 4 and 8 agree that it would be beneficial to have improved transport traceability in Volvo's system available directly to dealers.

Day orders placed for parts not in stock at the SDC are automatically back-ordered and transferred to the CDC, as previously discussed. This means that no type of recovery order is arranged from the CDC to the SDC, a key difference between the SDC and RDC markets. The SDC managed by Interviewee 8 receives daily deliveries from both Ghent and Lyon with stock refill. Dealers do not have full visibility of stock levels at the SDCs (and CDC). They can see whether a part is available when initiating an order, but not the exact stock level. Interviewee 8 states that this is a strategy to avoid panic induced rush orders when there are shortages. However, interviews indicate that some dealers systematically use the ordering system to figure out the stock on hand by testing different order quantities. VOR orders are placed through Service Center, which have full visibility as they can access the system information and reserve parts, making stock visibility less of an issue for VOR orders.

The particular SDC that Interviewee 8 manages has a special VOR team at the SDC that is separate from the day order operations. This ensures that VOR orders are given the highest priority and are processed as quickly as possible.

### 5.2.3 Rush Order Process at the RDCs

For dealers in markets with an RDC structure, orders are primarily sent from the RDC, regardless of order type. Inventory at an RDC is supplied from the CDC, and the refill process to RDCs is handled automatically by a refill team, using the internal Volvo system PlanIT. Figure 8 describes the process of managing day orders and VOR orders at the RDC. Interviewee 9, a Dealer Inventory Manager at an RDC in a country in the Middle East, explains that dealers place orders in their system (Parts-On-Line for Volvo Trucks) which are then released in their Warehouse Management System for employees to pick and pack. Order classes have different cut-off times for order release within the same day. The cut-off time for day orders is 12:00 PM, and 3:00 PM for stock orders and VORs. The warehouse team leader releases day orders for picking and packing first, to ensure that these are prioritized. Stock orders are released for picking and packing after 3:00 PM and processed until the warehouse shift ends at 4:30 PM. VORs are only processed until 3:00 PM, with the exception of special dealer requests. VORs are of the highest priority. In addition to order class, picking and packing release priority is based on dealer destination.

In the case of a stock out at an RDC, a recovery order is placed. Interviewee 9 describes that the procedure for a recovery order depends on which dealer order class that is affected by the stock out. If there is a stock order outstanding (not shown in the figure), a refiller/operational planner is responsible for arranging a recovery order from the CDC to the RDC, typically by boat. For day orders and VOR orders, the Service Center team places the recovery order, as seen in Figure 8. The responsibility is on the Service Center team to ensure that the rush orders are delivered to the dealer as quickly as possible. Recovery orders induced by outstanding stock- and day orders are typically sent by air to the RDC and then re-distributed to the dealer, while VOR orders go by air directly to the dealer without passing the RDC. As previously described, dealers are notified of potential delays for day orders, but receive more frequent status updates on VOR orders.

The RDC has full visibility over incoming orders from the CDC. Decisions regarding stock levels, safety stock, and order schedule are updated daily and automatically in a planning system used by the refill team (PlanIT) (Interviewee 7). The frozen period is equal to the lead time from the CDC to the RDC, and is thus not changeable. There are cases where the suggestions in the automatic planning system are blocked by the program and need manual override by a planner. For example, PlanIT may proactively suggest a refill order to the RDC by air to prevent potential shortages before they occur.

### 5.2.4 General prioritization in the CDC

The refills from the CDCs to the RDCs and SDCs differ in structure. The SDCs are geographically closer to the CDC (Ghent and Lyon for Europe), which leads to shorter refill lead times. Moreover, as SDCs do not handle stock orders, the product mix consists primarily of low frequency and high value items. The SDC managed by Interviewee 8 receives three deliveries per day by truck from the CDCs. In contrast, the RDCs are generally located further away from the CDCs, resulting in the refill pattern depending on proximity. For example, an RDC in Australia receives only one shipment (by boat) per week due to the long lead time (Interviewee 7). As RDCs provide dealerships with stock orders, they maintain a different product mix to ensure a high level of service towards the associated market.

When there is limited supply at a CDC, the rules for allocating available parts vary. Interviewee 7 states that although prioritization depends on the situation and the criticality of the part, VOR orders generally hold the highest priority, followed by day orders, with stock orders having the lowest priority. Within stock and refill orders, customer orders are usually prioritized over refill orders to RDCs and SDCs. In addition, older orders are prioritized over new orders. However, Interviewee 8 notes that the recovery time is also taken into consideration, which may alter the order prioritization. For example, an RDC in Australia has a longer recovery time than a dealer in Sweden, relative to the CDC in Ghent, due to the lead time. Thus, a refill order to the RDC in Australia may be prioritized over a stock order to a European dealership in order to maintain required service levels, as the RDC is responsible for supplying multiple dealerships with long recovery lead times. This prioritization logic is implemented in the planning system and is not determined manually.

## 5.3 Potential Improvements and Policies

Having established a clear understanding of the current rush order processes, potential policies to ensure that rush orders are triggered only in appropriate situations can be explored. Several interesting suggestions for improvements was brought up in the interviews that provides the basis of this discussion.

A major topic raised in the interviews is the lack of traceability on incoming orders, both for stock orders and day orders. As previously mentioned, there are local solutions, such as the app in the Asia-Pacific area, but most markets still lack traceability of orders. The lack of visibility regarding which orders are in transit materializes in many ways. First, there is a risk that a dealer places a rush order for a part that is incoming in a stock order, i.e., two parts are ordered to fulfill one demand. This leads to unnecessary rush order handling costs for Volvo. Moreover, for parts of low or infrequent demand, there is a risk that Volvo might need to buy back the part according to the DIM agreement. Secondly, lack of visibility leads to uncertainty for the dealers. All interviewed dealers, as well as all internal respondents, emphasize that the main priority is the customer, and that the customer should be served as quickly as possible. Thus, to be sure to serve their customers, dealers may place a rush order to assure that the part will arrive on time, even though that certain part is already in the pipeline.

The order class prioritization itself is another source of mistrust of stock orders. As certain quantities are reserved for day orders and VORs, stock orders are not prioritized when there is low availability at the warehouses. Consequently, there is always a risk that a stock order may be delayed, while upgrading to a day order/VOR secures the part. Moreover, dealers receive status updates on VOR orders, but are not actively informed on day and stock orders. Interviewee 5 highlights this as a misalignment within the organization. If some of the focus on monitoring VOR orders were shifted towards day- and stock orders, the dealer's trust in day- and stock orders would increase, and thereby reduce unnecessary VOR orders.

Another topic mentioned by many interviewees was pre-planning. Pre-planning refers to the process of allocating parts to planned services in advance. For example, for a service scheduled in two weeks, the dealership can reserve all necessary parts beforehand, and any shortages can be covered by stock orders. However, pre-planning is only effective if stock orders arrive on time. One initiative to increase pre-planning and ensure that stock arrives in time is the introduction of a new order type, called Order Class 4. Interviewee 6, a Service Developer responsible for the project, explain that this initiative has been ongoing at Volvo Trucks in Sweden since 2023, involving 16 dealers with DIM agreements. This currently covers around 33% of Volvo Trucks volume in Sweden, with plans to expand to Norway in the near future. The process is as following: Three days before a planned service or repair, the dealer stock is matched with the pre-planned requirements. If a part is missing, an Order Class 4 is generated, which is translated in their system to a day order and consequently prioritized accordingly. This proactive approach ensures that the parts are of higher priority in the warehouse, while restricting the transport mode to road, which reduces the need for air freight. The part is then delivered to the dealership well in time for the planned service. As a result of this initiative, approximately 2% of rush orders have been converted into automatic Order Class 4 orders, replacing manually issued day orders or

VOR orders. Despite the limited volumes transferred to the new order class, Order Class 4 may still contribute to increased trust in stock orders and the DIM system.

However, pre-planning is not always feasible, as customers may arrive through over-the-counter visits or trigger the VAS button unexpectedly. For example, Dealer 3 shares that approximately 80% of their customers have pre-planned visits, while 20% consists of major part failures and breakdowns. Such events are very difficult to forecast, meaning that rush orders are required to some extent to meet service levels.

It is also important to discuss the potential significance of rush orders within the network. Spare parts operations exist to ensure that vehicles and machines continue to operate with as little downtime as possible. The customer is at the heart of operations and must be served as quickly as possible. It is also necessary to consider the tradeoff between the cost of holding stock and the cost of rush orders. Thus, the goal is not to minimize rush orders at all costs, but rather to reduce unnecessary ones and ensure that each order class is used appropriately.

However, rush orders issued when the same part is already in transit to the dealer are considered unnecessary and could be avoided through better utilization of information within the system. A key finding from the interviews is that the current systems already hold much of the relevant information, it is just not easily accessible to the dealers. For example, additional information on day orders can be provided by the Service Center upon request, and VOR orders are monitored. Thus, based on insights presented in this chapter, a policy that utilizes pipeline information on incoming stock orders has been selected for further investigation through a simulation analysis. The details of this policy is presented in the following chapter.

# 6 SIMULATION STUDY

This chapter introduces the analytical model that is representative of Volvo SO&T's spare part distribution network, on which the simulation model is based. The simulation model and the extensions made are briefly described, as well as the set of items used to evaluate the effect of the rush order policy. The simulation scenarios are also introduced.

## 6.1 Presentation of Analytical Model

The simulation model of Volvo's spare part system is based on an analytical model developed by Professor Johan Marklund and other researchers at the division of Production Management at LTH. The principles of the analytical model are described in the conference paper Marklund et al. (2025), and a working paper by Marklund (2026). An earlier version is also described in Frölund and Hjortstam (2024). This section will provide an overview of the model - for more details the reader is referred to the above mentioned sources.

The adapted model fit for Volvo's distribution channel is referred to as the EM-model (Extended Model). The EM-model is a One-Warehouse-Multiple-Retailers (OWMR) model with three separate demand channels to allow for service differentiation. Non-controllable dealers, neither owned by Volvo nor under DIM, are represented by direct demand to the warehouse, channeled through one of two separate distribution channels, $VR_1$ or $VR_2$, depending on the required service level. Capacitated dealers refer to dealers that Volvo has some, but not full, control of. The controllable dealers are modeled as installations in the multi-echelon system with $(R, Q)$ policies.

The total warehouse stock is divided into general stock and reservation stock, with the general stock being used to replenish all dealers, including the virtual retailers. The reservation stock is reserved for demand entering through the virtual demand channels. The EM-Model is conceptually presented in Figure 9.

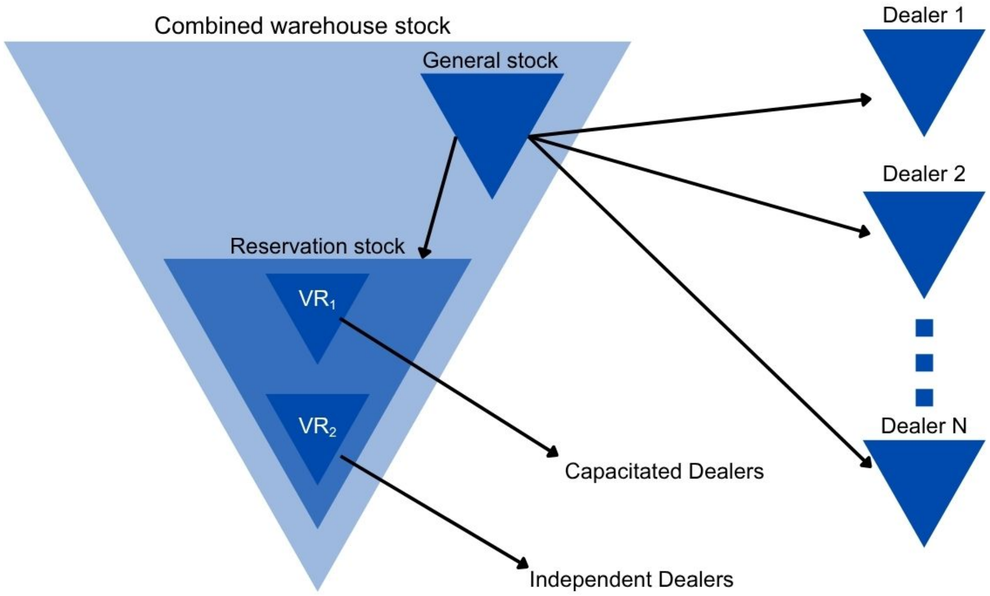

***Figure 9.*** *A conceptual representation of the EM-model.*

All lead times are assumed to be positive and constant. To account for uncertainties in transportation it is possible to use approximation techniques, such as replacing stochastic lead times with its mean. For more details on this, the reader is referred to Marklund, Mårtensson, et al. (2025), Marklund (2026), and Frölund and Hjortstam (2024). All inventory installations use continuous review $(R, Q)$ policies for replenishment. The virtual channels are replenished from the general stock according to a $(S-1, S)$ policy, meaning that as soon as demand occurs, a replenishment order for the same number of unit is placed. The order-up-to levels are denoted $S_1$ and $S_2$ for the two virtual retailer channels. All demand that is unsatisfied is backordered in the model, and satisfied on a first-come-first-served basis. All installations have a fill rate constraint, denoted ${\gamma_i}^*$, and a holding cost per unit and time unit is considered at each installation.

The objective is to coordinate and optimize the reorder point $R_0$ for the warehouse, the reservation stock levels $S_1$ and $S_2$, and the reorder point $R_i$ for each controllable dealer, such that the expected holding cost per time unit is minimized, while fulfilling the fill rate constraints, according to (27).

$$\begin{aligned}\min TC(R_0, S_1, S_2, R_i, \ldots, R_N) = h_0 E(IL_{CW})^+ + \sum_{i=1}^{N} h_i E(IL_i)^+ \\ s.t.\ \ \gamma_{VR(j)}(R_0, S_i) \geq \gamma^*_{VR(j)}\ \ \forall j \\ s.t.\ \ \gamma_i(R_0, R_i, \ldots, R_N) \geq \gamma^*_i\ \ \forall i\end{aligned} \tag{27}$$

The procedure for solving the optimization problem is described in Marklund, Mårtensson, et al. (2025), Marklund (2026) and to some extent in Frölund and Hjortstam (2024).

## 6.2 Presentation of Simulation Model

The discrete event simulation model used for the analysis in this thesis is based on assumptions consistent with the analytical model, with some modifications to allow for rush orders. The simulation model was developed by Professor Johan Marklund and other researchers at the Division of Production Management at LTH. The simulation model replicates the OWMR structure with an RDC that supply regular (controllable), capacited, and independent dealers through three channels. The regular retailers and $VR_1$ are replenished by a central warehouse, while $VR_2$ is replenished by $VR_1$. $VR_1$ is replenished by the central warehouse with a transportation time of zero, see Figure 9.

The original simulation model accommodates rush orders with a simple decision rule for placing a rush order, often used by dealers, henceforth referred to as "RushDirect". If a dealer is out of stock when demand occurs, a rush order is requested. In the simulation model, this is modeled as two separate transportation queues. If it is a regular order, the delivery is delayed by the specified lead time. If it is a rush order, the delivery is routed through a separate queue with a delay of 1 day. See Figure 10 for a conceptual depiction of the RushDirect decision rule in the simulation.

The simple RushDirect decision rule was extended as part of this thesis, to consider pipeline information before requesting a rush order, henceforth referred to as "RushPipe". In the model, this decision rule was implemented by splitting the regular transportation queue into two parts. The delay of the two queues adds up to the regular transportation lead time, while the last queue is set to have a delay equal to the rush order lead time, in this case 1 day as most day orders are expected to arrive within one day. When demand occurs, the dealer checks if the demand can be satisfied from stock on hand. If there is a stock out, the dealer then check if a stock order will be delivered within one day, i.e., there is an item in Queue 2. If empty, a rush order will be triggered. The RushPipe concept is seen in Figure 11.

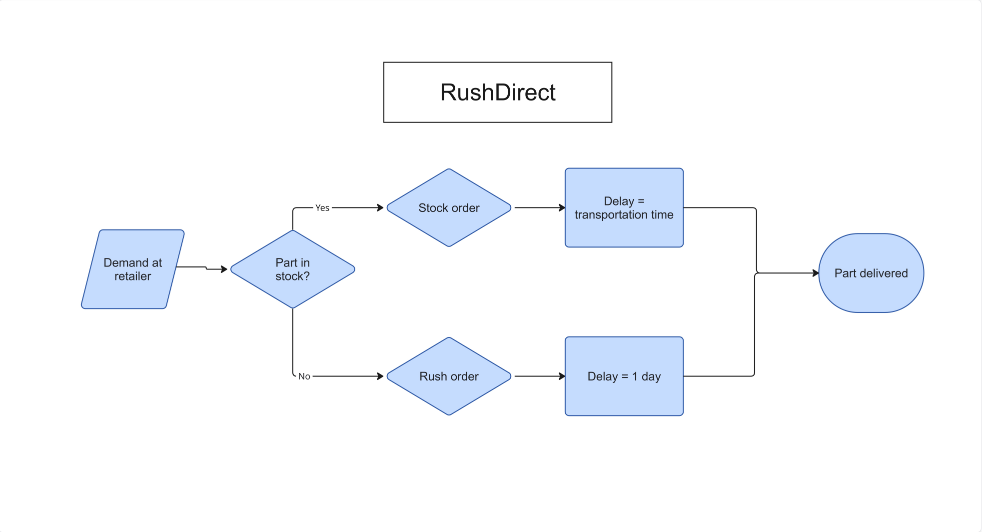

***Figure 10.*** *Conceptual description of the RushDirect policy as implemented in the simulation model.*

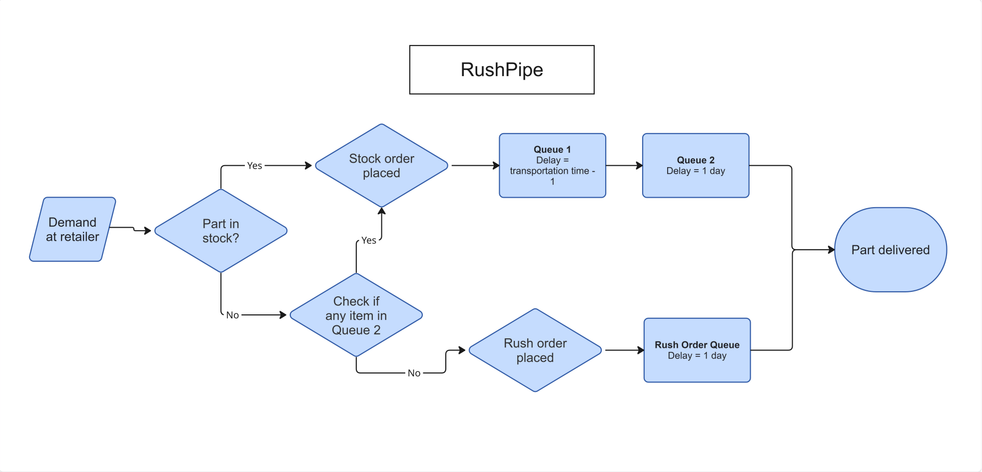

***Figure 11.*** *Conceptual description of the RushPipe policy as implemented in the simulation model.*

## 6.3 Data Collection

As this thesis is part of a larger research collaboration between Volvo SO&T and the division of Production Management at the Faculty of Engineering at Lund University, there was available data used in previous simulation studies. The same data was used for this thesis, as the process of collecting new data is time-consuming and complex. The discrete event simulation was based on data collected from the market in Johannesburg, South Africa, provided by Volvo SO&T. The simulation study investigated a set of 23 VCE items, see Table 3. This set of items was selected to capture items with varying characteristics, such as mean demand and lead time. The input data for each item include order quantities, transportation times, and holding costs, as well as the optimal reorder points obtained both from the analytical EM-model and Volvo's current single-node system.

The input demand data consist of an empirical demand size distribution, as well as mean and variance from the Volvo forecast system. In the simulation model, the input demand data is utilized as follows: Demand is generated in demand blocks, where the time between arrivals follows a Gamma distribution. The number of units a customer requests upon arrival is according to the given demand size distribution. The parameters of the Gamma distribution are adapted based on the demand size distribution such that the generated demand is in accordance with the mean and standard deviation provided by the forecast.

***Table 3.*** *List of items with mean demand and RDC lead time. Note that Item 14 and 16 are excluded because of inconsistencies in demand data.*

| **Item** | **Mean Demand** | **RDC Lead Time** |
|---|---|---|
| **1** | Low | High |
| **2** | High | High |
| **3** | Medium | High |
| **4** | Low | High |
| **5** | High | High |
| **6** | Low | High |
| **7** | High | Low |
| **8** | Low | High |
| **9** | Low | High |
| **10** | Low | High |
| **11** | Low | High |
| **12** | Medium | High |
| **13** | Medium | High |
| **15** | Low | Low |
| **17** | Medium | High |
| **18** | High | High |
| **19** | Low | High |
| **20** | Low | Low |
| **21** | Medium | High |
| **22** | Medium | High |
| **23** | Low | High |
| **24** | Low | High |
| **25** | High | High |

## 6.4 Simulation Scenarios

The simulation study explores the effect of implementing the rush order policy utilizing pipeline information by comparing RushDirect with RushPipe, by running two simulation scenarios per item and model. The simulation scenarios are presented in Table 4.

***Table 4.*** *Definition and description of the four simulation scenarios.*

| **Scenario** | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| **System** | SE | MEIO | SE | MEIO |
| **Description** | Volvo's reorder points | EM-Model with stochastic lead times | Volvo's reorder points | EM-Model with stochastic lead times |
| **Policy** | RushDirect | RushDirect | RushPipe | RushPipe |

Scenario 1, RushDirect (SE), models Volvo's current reorder points and distribution network for the Johannesburg RDC. Scenario 3 uses the same reorder points, but applies the RushPipe policy. Scenario 2 and 4 use reorder points determined using the analytical model described, under the RushDirect and RushPipe policy respectively.

Through this comparison, the effect of implementing a pipeline rush order policy can be examined under both single-echelon and multi-echelon inventory control systems. Additionally, the single-echelon and multi-echelon systems can be compared under this policy. The focus is analyzing the effect on the number of rush orders, fill rates and expected inventory in the network.

# 7 RESULTS AND ANALYSIS

The following chapter discusses and analyzes the results of implementing a policy utilizing pipeline information. Mainly, the numerical results are presented, which are complemented by some qualitative insights.

## 7.1 Numerical Results

In this section, the numerical results of the simulation study are presented and discussed. The primary objective of the simulation study was to investigate the impact of introducing a policy that uses pipeline information to determine whether a rush order should be placed. The policy is first evaluated in the transition from a single-echelon to a multi-echelon system. Then, the RushDirect and RushPipe decision rules are compared in isolation both in the single-echelon and multi-echelon systems.

### 7.1.1 Single-Echelon to Multi-Echelon

To investigate the policy's effect on the transition from single-echelon to MEIO, Scenario 3 is compared to Scenario 4, i.e., RushPipe (SE) is compared to RushPipe (MEIO). The expected number of rush orders per year is presented in Figure 12.

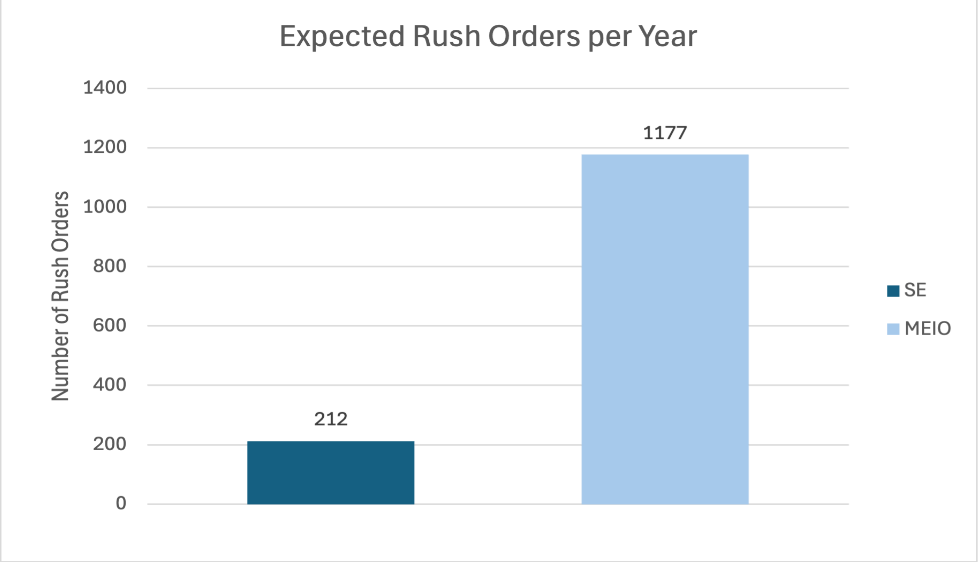

***Figure 12.*** *Expected rush orders per year across all items, for both the single-echelon and MEIO system, under the RushPipe policy.*

In Figure 12, it is apparent that the number of rush orders increases in the MEIO system compared to the single-echelon system. The increase is 965 rush orders per year (456%). Figures 13 and 14 illustrates the effect that the transition from single-echelon to MEIO has on expected inventory, and the average fill rate deviations in the MEIO system.

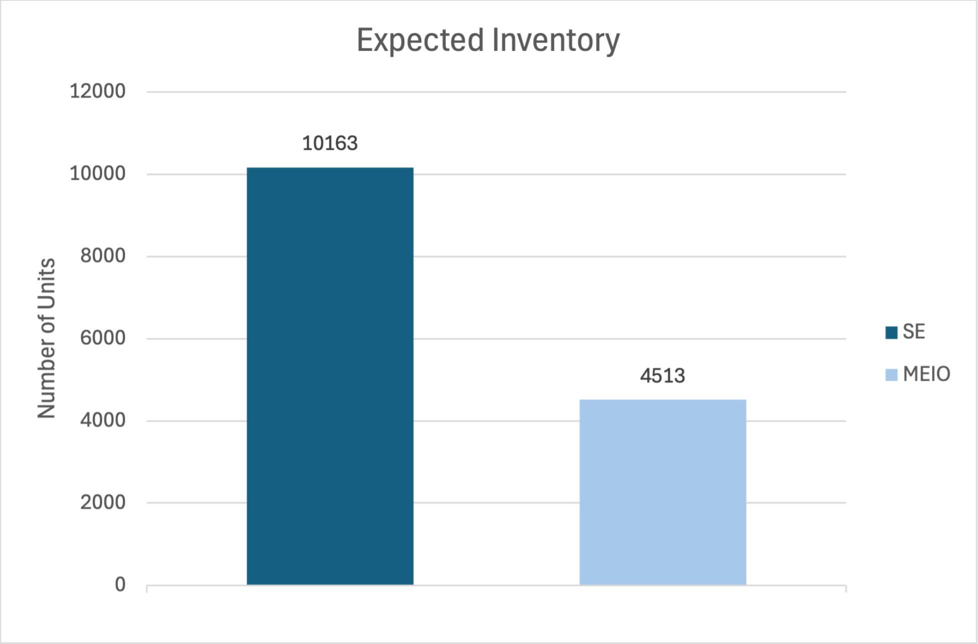

***Figure 13.*** *Expected inventory in both single-echelon and MEIO, under the RushPipe policy.*

As illustrated in Figure 13, the expected inventory level is drastically reduced (-5650 units) in the transition from single-echelon to MEIO. Figure 14 illustrates that the MEIO system exceeds the target fill rates for the majority of items, on average by 0.97%. The largest undershoot of -1.31% is for Item 5. This suggests that even with inventory reduced by more than half, service levels toward dealers are maintained. The expected number of rush orders per item and year is presented in Figure 15.

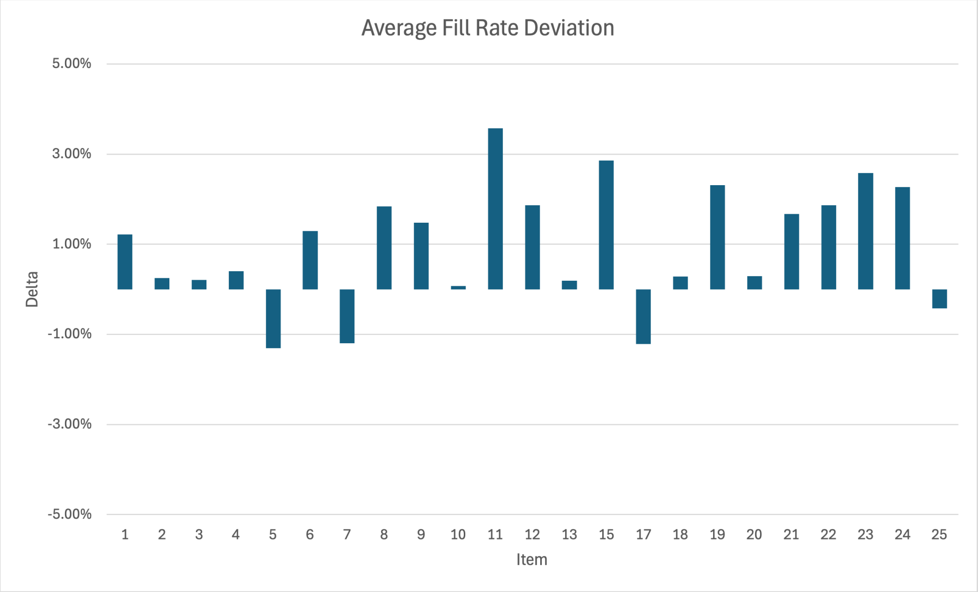

***Figure 14.*** *Average fill rate deviations from the TSL per item in the MEIO system, under the RushPipe policy.*

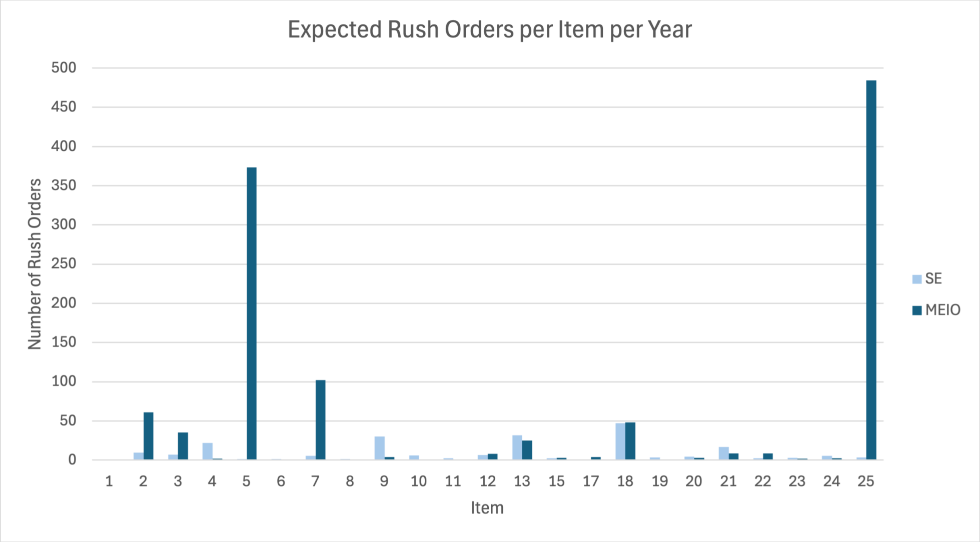

***Figure 15.*** *The expected number of rush orders per item per year, under the RushPipe policy for single-echelon and MEIO.*

Figure 15 showcases that there are a few items, mainly Item 5, 7, and 25, that contribute to the majority of the increase in rush orders for the MEIO system, compared to the single-echelon system. These are all items of high demand, which entails a larger impact on the system. To investigate the cause of this large increase, these three items will be analyzed further. Only three items are selected due to limited time frame, and to have a low impact in comparison to the three mentioned items. The fill rates obtained in the single- and multi-echelon simulations under RushPipe are presented in Figures 16, 17, and 18, compared to the TSLs determined by Volvo SO&T.

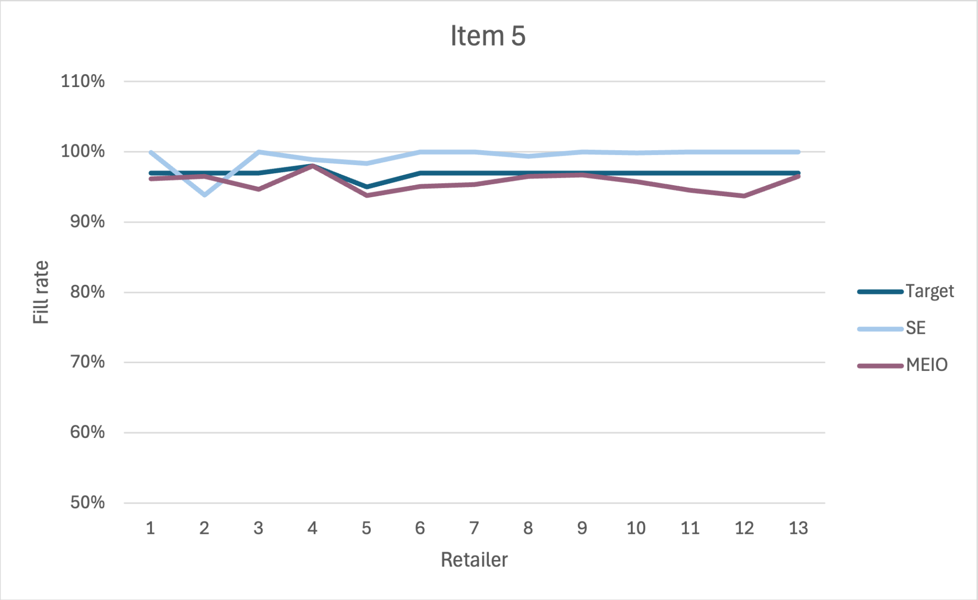

***Figure 16.*** *Fill rate per Retailer for Item 5. The target fill rate is represented in dark blue, the single-echelon case in light blue, and the MEIO case in purple, under RushPipe.*

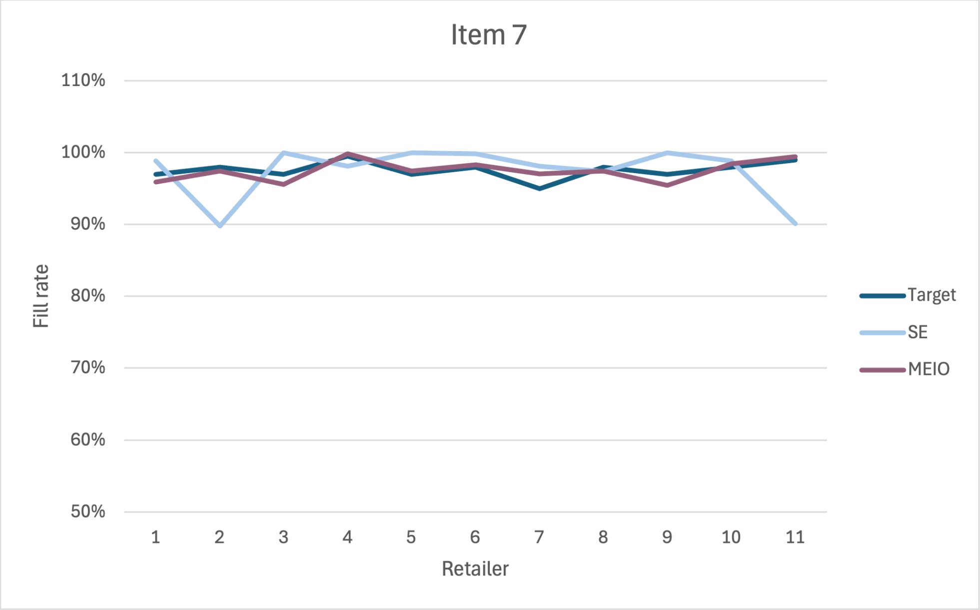

***Figure 17.*** *Fill rate per Retailer for Item 7. The target fill rate is represented in dark blue, the single-echelon case in light blue, and the MEIO case in purple, under RushPipe.*

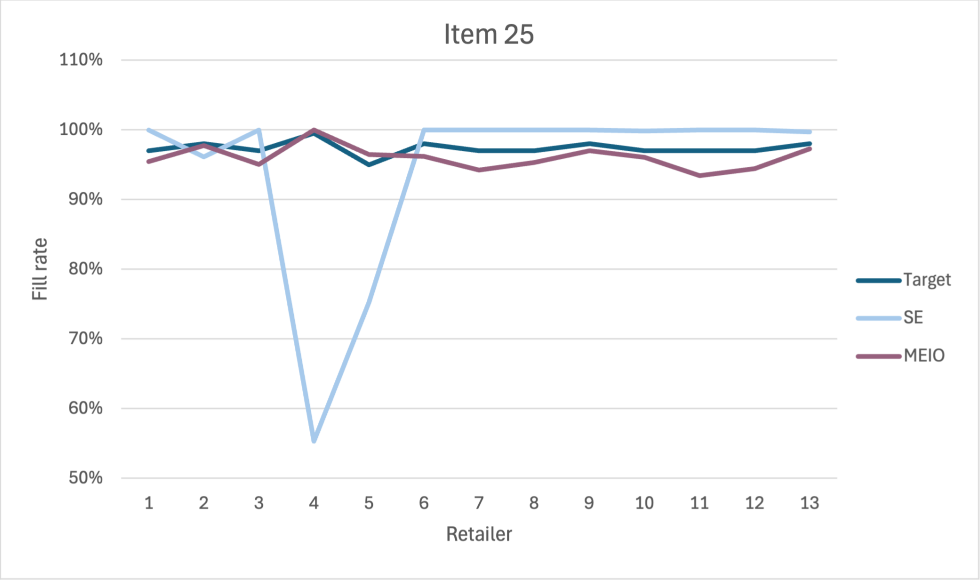

***Figure 18.*** *Fill rate per Retailer for Item 25. The target fill rate is represented in dark blue, the single-echelon case in light blue, and the MEIO case in purple, under RushPipe.*

In Figure 16, it can be seen that the simulated fill rates using the reorder points determined through single-node optimization (currently used by Volvo) overshoot the target fill rates for nearly all retailers. The simulated fill rate under MEIO is closer aligned to the target, although below for a few retailers, but generally with small deviations. Similarly, in Figure 17, the single-echelon fill rates exceed the target for the majority of the retailers, while the MEIO fill rates are closely aligned to the target, with some small deviations. This is also showcased for Item 25, as seen in Figure 18. Two exceptions are observed for Retailer 4 and 5, where the Volvo reorder points result in significant fill rate deviations from the TSL in the SE case, while it is reached under MEIO. The underlying reason for this deviation will not be further investigated, as it is not central to the analysis.

Overall, the reorder points in the single-echelon case overshoot the determined target fill rates for many retailers, sometimes even reaching 100%. The comparison between the single-echelon and MEIO system is therefore rather unfair. With a very high fill rate, stock-outs are rarely observed, leading to very few rush orders placed. In the MEIO scenario, the target fill rates are reached more precisely, which leads to a greater amount of stock outs, and thus rush orders. The average fill rate deviations for each scenario are presented in Table 5. The negative deviations for Item 7 and 25 in the SE case are driven by outliers with large negative deviations. When excluding Retailers 2 and 11 for Item 7, and Retailers 4 and 5 for Item 25, the average fill rate deviation instead becomes +2% for Item 7 and +2.2 % for Item 25. This shows that, generally, the fill rate deviations are larger in the SE case, while MEIO remains closer to the TSL, with only some minor negative deviations.

***Table 5.*** *Average fill rate deviation compared to target service level for Item 5, 7, and 25.*

| **Item** | **Average Fill Rate Deviation SE** | **Average Fill Rate Deviation MEIO** |
|---|---|---|
| Item 5 | 2.3% | -1.3% |
| Item 7 | -0.2% | -0.1% |
| Item 25 | -3.0% | -1.3% |

To analyze the transition from single-echelon to MEIO under more comparable conditions, the reorder points for the MEIO scenario were re-optimized for Items 5, 7 and 25, under the fill rates obtained from simulating for Volvo's current solution. This was done using the analytical model presented in

Section 6, using the single-echelon fill rates as the constraint instead of the previous target fill rates.

#### 7.1.1.1 Single-Echelon to Multi-Echelon Under New Reorder Points

New simulations were conducted for a new scenario for Item 5, 7, and 25, named MEIO NRP (new reorder points), to evaluate the performance of MEIO in comparison to Volvo's current single-echelon solution. The resulting fill rates are compared to the single-echelon fill rates, which in this case are also the target fill rates used for optimization of the MEIO NRP reorder points. See Figures 19, 20, and 21.

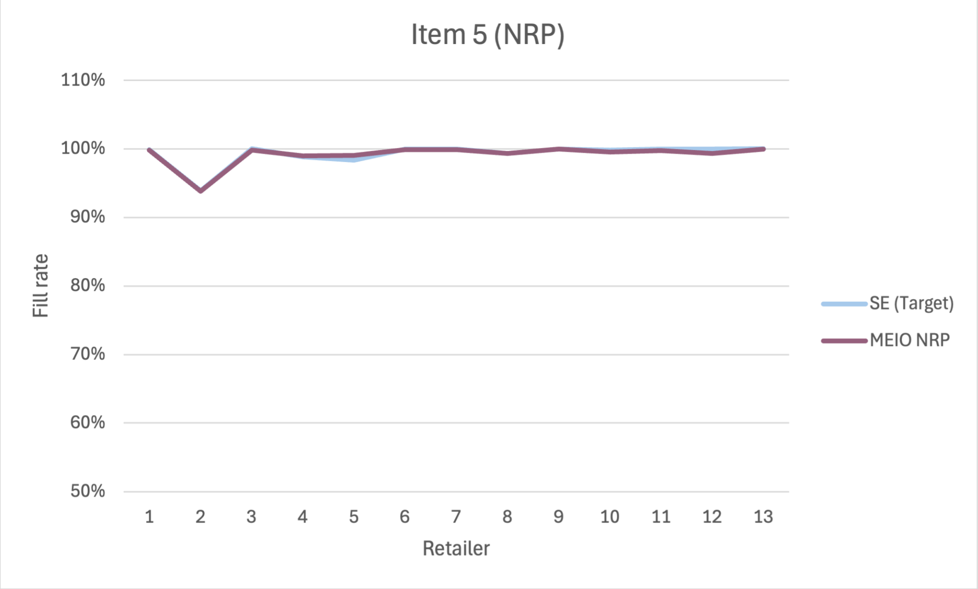

***Figure 19.*** *Fill rate per retailer for Item 5, after re-optimizing the MEIO reorder points. The single-echelon (target) is light blue, and the MEIO NRP case purple, under RushPipe.*

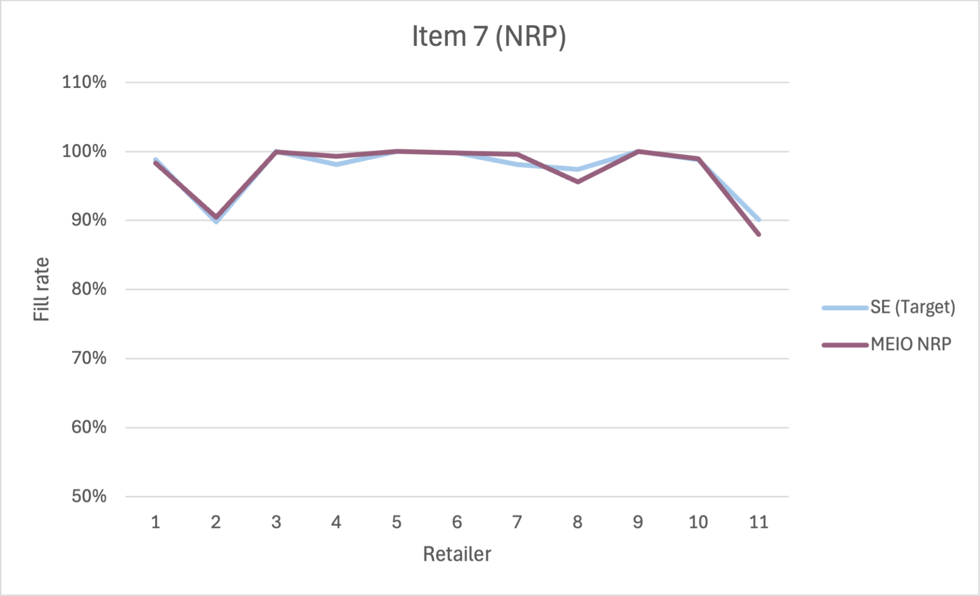

***Figure 20.*** *Fill rate per retailer for Item 7, after re-optimizing the MEIO reorder points. The single-echelon (target) is light blue, and the MEIO NRP case purple, under RushPipe.*

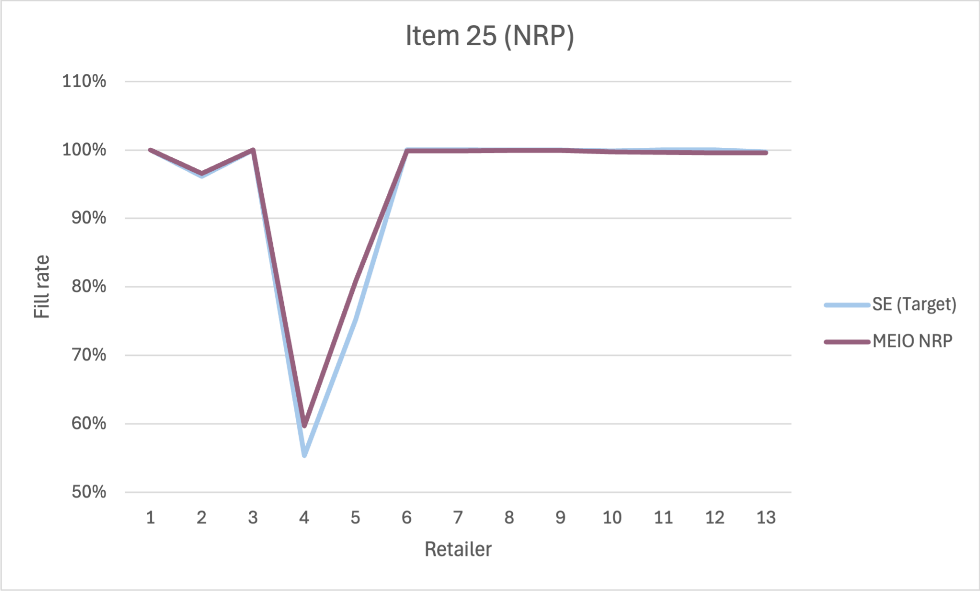

***Figure 21.*** *Fill rate per retailer for Item 25, after re-optimizing the MEIO reorder points. The single-echelon (target) is light blue, and the MEIO NRP case purple, under RushPipe.*

***Table 6.*** *Average fill rate deviation from the SE fill rate in the MEIO NRP scenario, for Item 5, 7, and 25.*

| **Item** | **Average Fill Rate Deviation MEIO NRP** |
|---|---|
| Item 5 | -0.07% |
| Item 7 | -0.10% |
| Item 25 | 0.68% |

Figures 19, 20, and 21 showcase that the MEIO NRP scenario accurately reaches the target fill rates for almost all retailers, with some small deviations, see Table 6. Note that for Retailer 4 for Item 25, the MEIO reorder point is optimized under the low fill rate in Figure 18, explaining the large reduction in the MEIO fill rate for this particular retailer and item. With the fill rates being closely aligned in the SE and MEIO NRP cases, the effect on the number of rush orders can be analyzed under more comparable conditions. The expected number of rush orders per item for each scenario is presented in Figure 22.

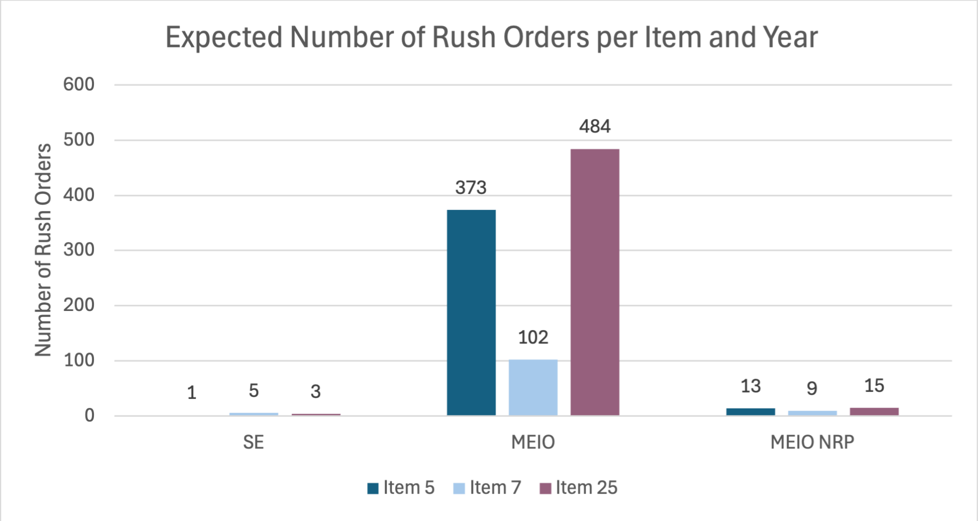

***Figure 22.*** *Expected number of rush orders for Item 5, 7, and 25, under single-echelon, MEIO and MEIO NRP, under the RushPipe policy.*

It is obvious from Figure 22 that the initial increase in rush orders when transitioning from single-echelon to MEIO is largely driven by the overachieved fill rates in the current system, and not by the transition to the MEIO system itself. Table 7 highlights the difference between the number of rush orders in the MEIO and MEIO NRP case compared to single-echelon.

***Table 7.*** *The increase in number of rush orders per year for both MEIO and MEIO NRP, compared to single-echelon. The last column indicates the relative improvement of MEIO NRP over MEIO in terms of rush order increase.*

| Item | Increase MEIO vs. SE | Increase MEIO NRP vs. SE | Difference (%) |
|---|---|---|---|
| **Item 5** | 372 | 12 | -97% |
| **Item 7** | 96 | 4 | -96% |
| **Item 25** | 481 | 11 | -98% |

As shown in Table 7, the re-optimized reorder points significantly limit the increase in rush orders, reducing them by at least 96% compared to the original MEIO case. However, there is still a small increase in the expected number of rush orders per year in the MEIO NRP scenario compared to the single-echelon case. Due to the high demand of the three selected items, even a small fill rate deviation for a few retailers will trigger an increase in rush orders. However, it should be noted that the expected number of rush orders in Figure 22 is expressed annually. Although there is a small increase in the MEIO NRP case, the absolute number of rush orders remains very low in relation to the total number of orders, and is therefore not expected to significantly affect daily operations.

It is also of interest to analyze whether the overachieved fill rate has an effect on the expected inventory by introducing the MEIO NRP case. Figure 23 and illustrate the expected inventory for the three items.

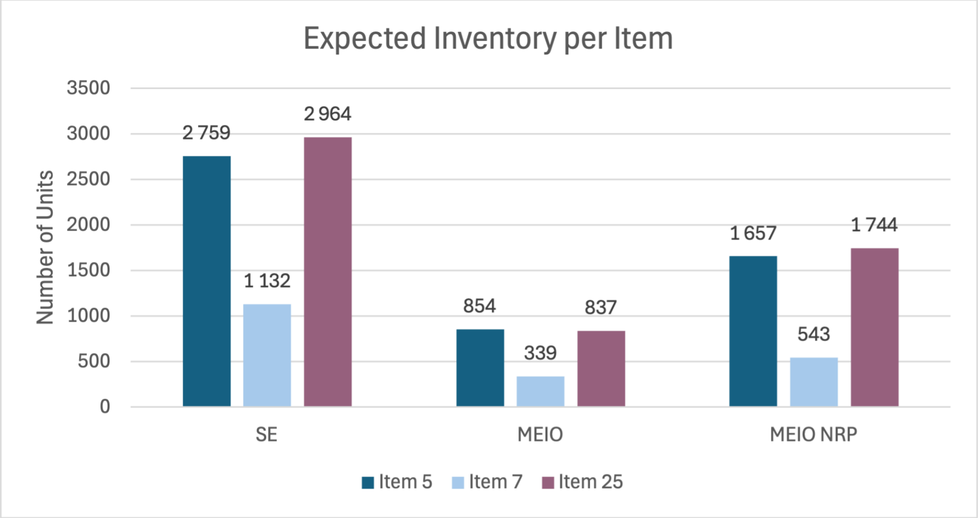

***Figure 23.*** *Expected inventory for Item 5, 7, and 25, under single-echelon, MEIO and MEIO NRP, under the RushPipe policy.*

In Figure 13, it was demonstrated that the inventory level drastically reduced in the MEIO system. Similarly as for the number of rush orders, some of this effect can be attributed to the over-achieved fill rate. In Figure 23, it is apparent that the true reduction of inventory is smaller for MEIO NRP than MEIO, when compared to the single-echelon system. However, a drastic reduction in inventory is an expected consequence of transitioning from a single-node optimized system to a MEIO one. The percentage reduction is 40%, 52%, and 41% for Item 5, 7, and 25, respectively, when comparing SE to MEIO NRP. The average reduction across all three items is 42%.

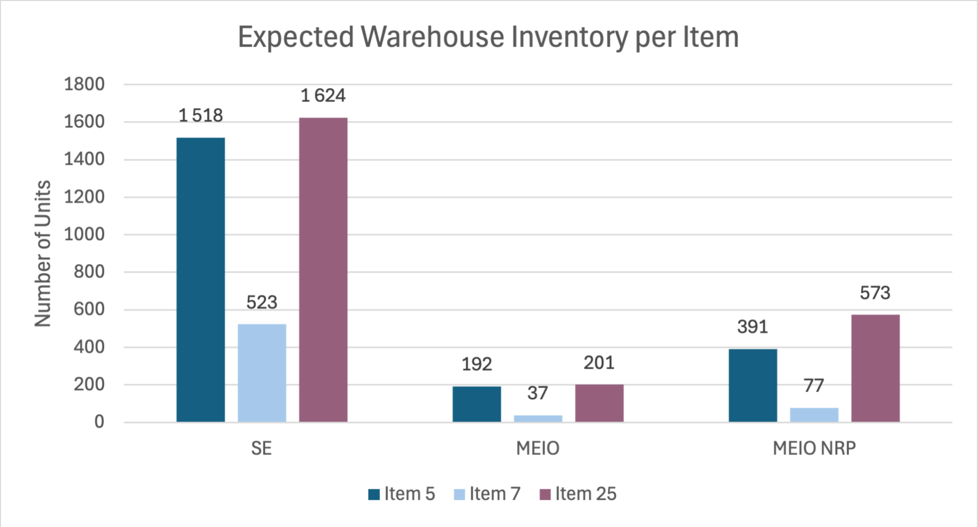

***Figure 24.*** *Expected inventory at the Warehouse for Item 5, 7, and 25, under single-echelon, MEIO and MEIO NRP, under the RushPipe policy.*

The inventory reduction in MEIO (and MEIO NRP) is largely driven by a lower fill rate at the warehouse, which significantly reduces warehouse inventory. This is because simultaneous optimization across all installations allows inventory levels to be minimized throughout the system, see Figure 24. The reduction in warehouse inventory is greater in the MEIO case than in the MEIO NRP case, which can be explained by the lower target fill rates. Nevertheless, the decrease in warehouse inventory remains significant in the MEIO NRP case, reducing it by 74%, 85%, and 65%, for Item 5, 7, and 25, respectively. The average reduction is 72% across the three items.

Note that the three items analyzed deeper are the ones where the transition from single-echelon to MEIO has the biggest impact, due to them being of high demand compared to the other parts. For other parts with lower demand, the number of rush orders for MEIO may be slightly lower or higher compared to SE.

### 7.1.2 RushDirect vs RushPipe

In addition to analyzing the transition from a single-echelon to a multi-echelon system, the simulations compare the two policies RushDirect and RushPipe. This comparison is conducted in both systems and across all items to properly assess the efficiency of the new policy. In the MEIO case, the comparison is based on the original MEIO scenario rather than MEIO NRP, as NRP has only been applied to a subset of items. Since the objective is to compare RushDirect and RushPipe within each system independently, the relationship between SE and MEIO is not considered. Instead, the focus lies on the relative changes within each system.

The reduction in the number of rush orders per item when introducing RushPipe in the single-echelon system is illustrated in Figure 25. Since the majority of the simulated items are low-volume and the initial number of rush orders is low, the reduction is also presented in percentage terms, see Figure 26.

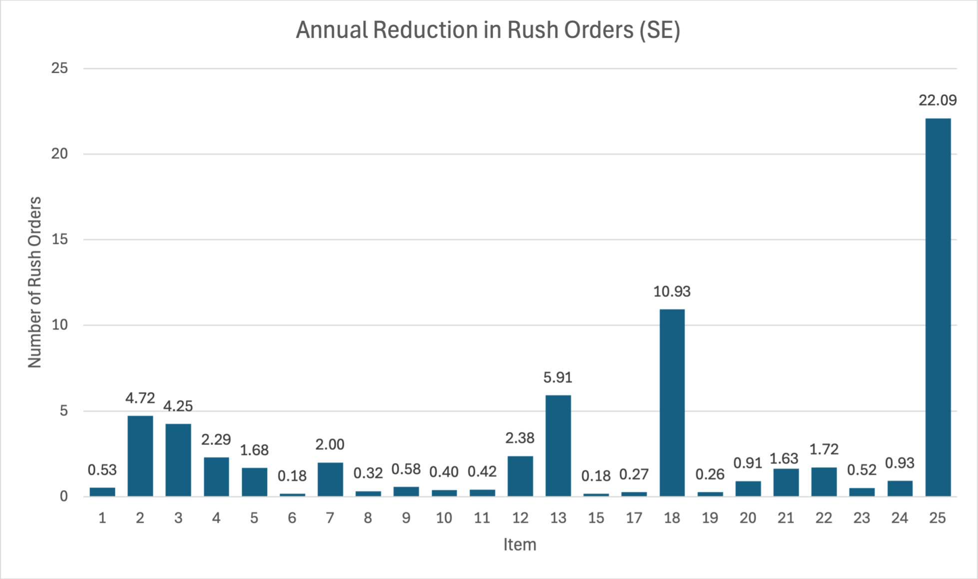

***Figure 25.*** *Expected annual reduction in the number of rush orders per item in the single-echelon system, changing from RushDirect to RushPipe*

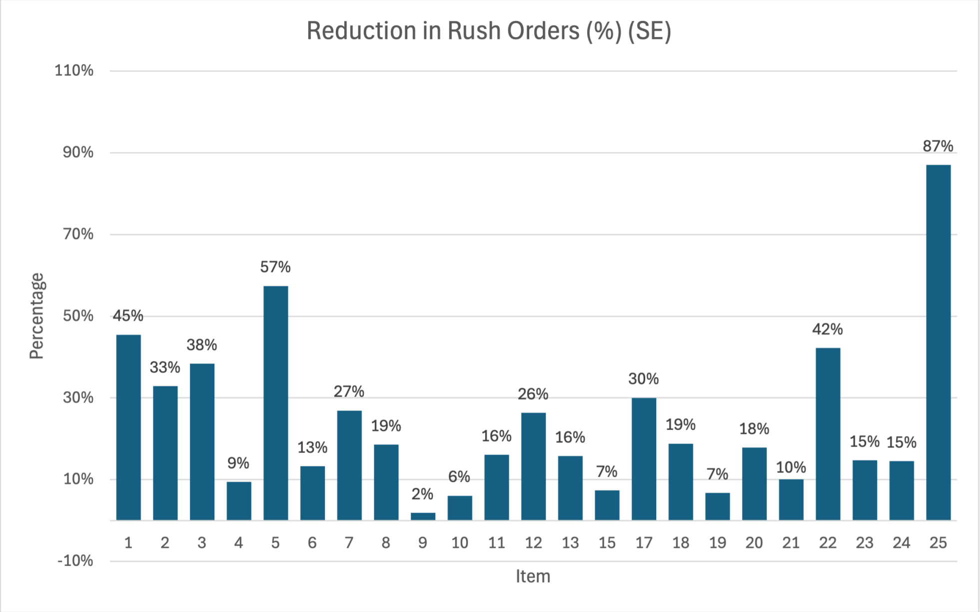

***Figure 26.*** *Expected annual percentage reduction in rush orders in the single-echelon system, changing from RushDirect to RushPipe*

All items show a reduction in the number of rush orders when RushPipe is introduced in the single-echelon system, with an average reduction of 2.83 rush orders per item. The largest reduction is observed for Item 25, with a decrease of 22 units per year. The relatively small absolute reductions are expected, given the low number of rush orders in the initial, which limits the potential magnitude of the decrease.

In percentage terms, the reductions in rush orders are more significant, reaching up to 87% for Item 25. It is important to note that the initial low number of rush orders for most items results in large percentage decreases, even when the absolute reductions are small. The expected number of rush orders per year decreases from 277 to 212 when moving from RushDirect to RushPipe, as illustrated in Figure 27. This corresponds to a 23.5% reduction in rush orders across the entire simulated system.

The positive effects of introducing RushPipe can also be seen in the MEIO system. As shown in Figure 27, the total number of rush orders in the MEIO system amounts to 1177 with the RushPipe policy, compared to 1459 in the RushDirect case. This represents a 19.4% reduction in the number of rush orders when introducing RushPipe. Note that the MEIO reorder points are optimized to satisfy the specified target service levels, while the Volvo reorder points overshoot the target service levels, explaining the increase in the number of rush orders between the two inventory systems.

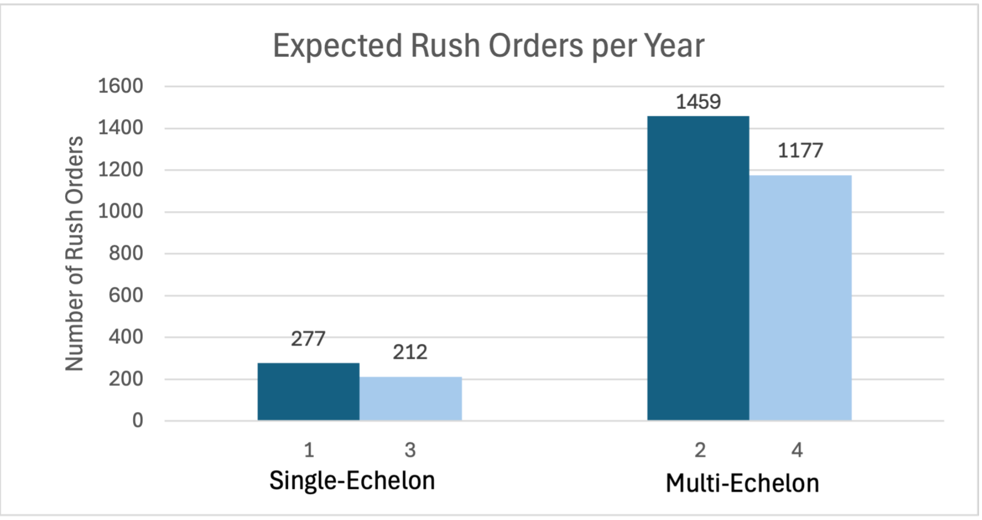

***Figure 27.*** *Expected number of rush orders per year across the different scenarios. The dark blue is RushDirect and the lighter blue is RushPipe.*

The absolute reductions per item per year in the MEIO system are presented in Figure 28. Considerable variations across items can be observed, with most items showing marginal reductions and a few showing substantial decreases, such as Items 5, 7, and 25. The average reduction is 12.28 rush orders per item. The percentage reductions are more consistent, with most items displaying reductions between 15% and 25%, see Figure 29. However, with a low initial number of rush orders, even minor absolute changes result in relatively large percentage increases, while having almost a negligible impact on the overall system. For example, Item 19 showcasing a reduction of 44% is in numerical values only a reduction of 0.14 rush orders per year. Meanwhile, for items of high demand (such as Item 5, 7, and 25), the percentage reduction is more representative of the policy's overall effectiveness.

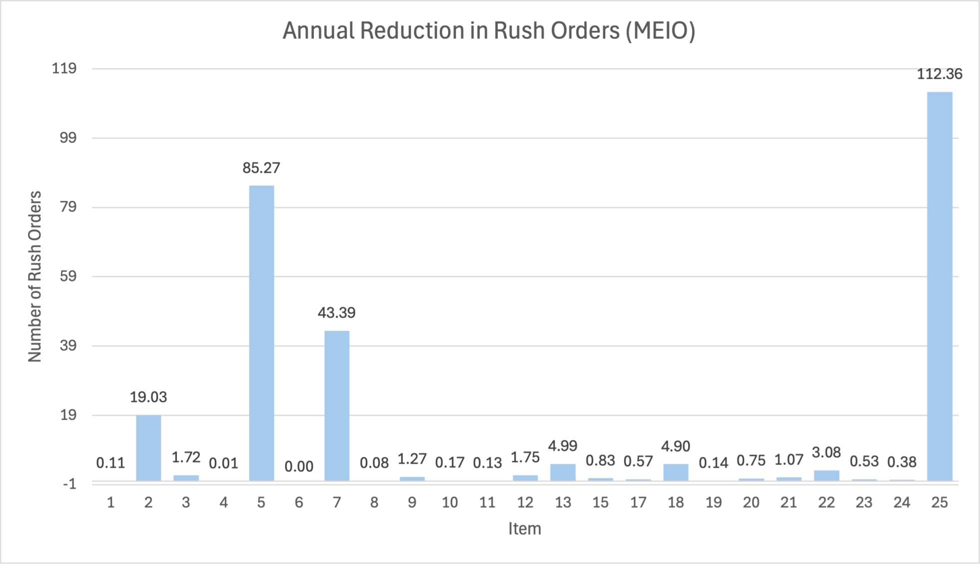

***Figure 28.*** *Expected annual reduction in the number of rush orders per item in the multi-echelon system, changing from RushDirect to RushPipe*

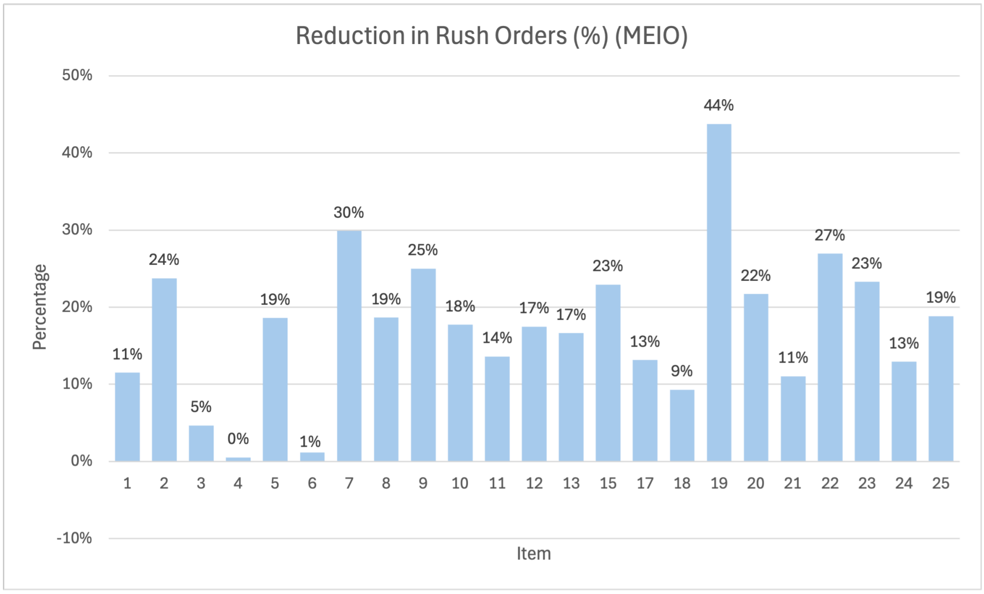

***Figure 29.*** *Expected annual percentage reduction in rush orders in the multi-echelon system, changing from RushDirect to RushPipe*

As previously stated, the introduction of the RushPipe policy reduces the number of rush orders regardless of the system. However, it is also important to evaluate the consequences of the policy on other parts of the system. The expected inventory across all scenarios are illustrated in Figure 30. The expected inventory does not change noticeably in the RushPipe case, for either the single-echelon or MEIO system. The small differences in actual numbers are most likely due to simulation variability.

***Figure 30.*** *Expected inventory and backorders for all four scenarios, both under RushDirect (dark blue) and RushPipe (light blue).*

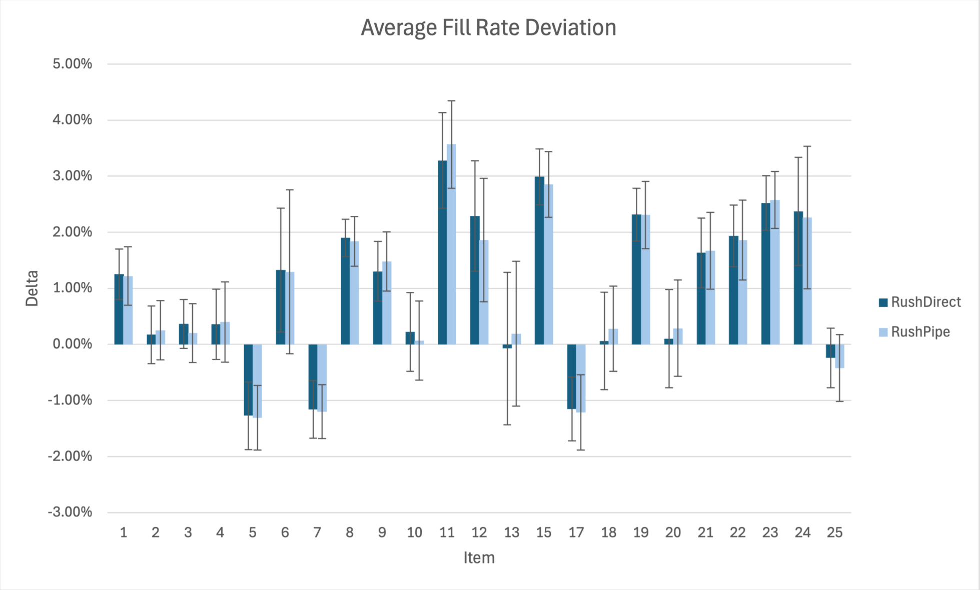

***Figure 31.*** *Average fill rate deviations per item in the MEIO system $\pm 3\sigma$, comparing RushDirect with RushPipe.*

Figure 31 illustrates the fill rate deviations in both the RushDirect and RushPipe policy, in the MEIO system. Generally, the expected service does not change noticeably when the policy is applied. The observed differences are small relative to the variability ($\pm 3\sigma$), which illustrates that no clear conclusion can be drawn regarding one policy outperforming the other. Minor deviations are due to simulation variability rather than attributable to the introduction of the policy, as indicated by the substantial overlap of the intervals in Figure 31. This suggests that the policy can be implemented without interrupting expected inventory and customer service.

## 7.2 Qualitative Analysis

### 7.2.1 Emissions

The effect on emissions when introducing the RushPipe policy have not been evaluated quantitatively through simulations. However, based on qualitative analysis and insights from interviews, it is possible to draw several conclusions. The RushPipe policy is expected to reduce the total number of rush orders. With fewer rush orders, the number of shipments made by air is expected to decrease. Although not all rush orders are shipped by air, a higher share is transported by air compared to regular stock orders. By shifting shipments from airfreight to road transport, transport-related emissions will decrease.

The effect on transport emissions when transitioning from a single-echelon to a MEIO system depend strongly on the choice of reorder points, i.e., which fill rates are obtained. The RushPipe MEIO case with the original reorder points results in a substantial increase in the total number of rush orders compared to the single-echelon case, due to fulfilling the original target fill rates, but not exceeding them. However, when using the reorder points from the MEIO NRP case, the increase in rush orders is very small, see Figure 22. Thus, the original MEIO case will result in higher transport emissions than the MEIO NRP reorder points, due to the increase in number of rush orders. The savings in transport emissions using MEIO NRP may, however, be offset by higher emissions associated with inventory holding. It is therefore uncertain whether MEIO or MEIO NRP yields lower total emissions, and it is solely dependent on the obtained fill rates.

Overall, the impact of the RushPipe policy on emissions will vary depending on which dealers that are able to achieve reductions in their rush orders. Not all dealers have the option to choose the transport mode for their orders, and not all rush orders are shipped by air. In cases where dealers receive all their orders by road, a reduction in rush orders will have less impact on transport emissions, as all types of orders will still be sent by truck or sea. However, the further away dealers are located, the larger the emissions reduction when avoiding unnecessary rush order transports. The impact on emissions is greatest for dealers whose rush orders are shipped by air while stock orders are transported by road. Nonetheless, by introducing the RushPipe policy, the total emissions will decrease.

As the introduction of the RushPipe policy is not expected to significantly affect inventory or customer service, neither emissions related to inventory holding or unmet customer demand are expected to change significantly. When investigating the impact on emissions in the transition from single-echelon to MEIO, the total inventory is expected to decrease significantly, while MEIO on average reach or exceeds the target fill rate, with a few small deviations. Whether total emissions increase or decrease therefore depends on the emissions associated with inventory holding and potential backorders. Conducting such an analysis is outside the scope of this thesis.

### 7.2.2 Cost Analysis

With the RushPipe policy, the number of rush orders decreases compared to the RushDirect policy, both in the simulated single-echelon and the multi-echelon systems. From a cost perspective, the reduced number of unnecessary rush orders will have a direct impact on the transportation cost, which are expected to decrease. As for emissions, freight by air is more costly than road freight, and the extent of the cost reduction will depend on the share of rush orders by air compared to road. As seen in Figures 30 and 31H, the effect of RushPipe on the expected inventory and fill rate deviation is almost zero compared to RushDirect. As a consequence, the difference in holding and shortage cost is expected to be negligible.

It is less clear what the cost difference will be in the transition from a single-echelon to a MEIO system, under the RushPipe policy. Usually in inventory control, one consider the holding and shortage cost, which will depend on the expected inventory and service, respectively. There is a tradeoff between these costs, which will depend on the relative cost size, as well as the value of each item. The transportation costs are expected to increase based on the simulated results. However, as discussed, the increase in rush orders is mostly attributable to the over-achieved fill rates in the single-echelon system, and not the transition to MEIO itself.

## 7.3 Validity of Results

The simulation study was conducted on a data set of 23 VCE items, with an RDC in South Africa, Johannesburg, and various dealers in different countries. To validate the results and draw certain conclusions, the study would need to be extended to additional items across different markets. The efficiency of the RushPipe policy should be evaluated for items with different characteristics than those that have been studied, particularly items with an initial higher number of rush orders.

The effects on costs and emissions have not been quantitatively studied. In the theory section, multiple methods for quantifying emissions and including them in cost calculations were proposed, however, associated costs are as of now not translated into the simulation model. Accurately capturing all relevant cost and emission components and including these in the simulation study would be very complex and subject to significant uncertainty, due to the limited time frame of the thesis, and has therefore been excluded from the study. Nevertheless, a cost and emission analysis is still necessary to understand the impact of the RushPipe policy on the system and to assess its feasibility.

The implementation of the RushPipe policy within the Volvo organization has not been evaluated in this thesis. Providing dealers with pipeline information to support improved decision-making and reduce rush orders is not expected to be straightforward in a global organization with complex systems. Even if the information exists somewhere within current systems, making it accessible to dealers is likely to be both time-consuming and complex in practice.

In the real system, the RDC may place rush orders to the CDC. This has not been studied as the simulation model does not explicitly include the CDC and all other connected RDCs. Rush orders placed by the RDC with the CDC may be affected by the suggested RushPipe policy, an effect currently unknown. An insight gained from the interview study is that currently, recovery orders from the CDC may be transported by air to the RDC in two situations. First, if a day order is placed for an item that is out of stock at the RDC, a recovery order may be placed with the CDC. Second, a recovery order may be initiated if a planner wants to proactively prevent a potential stock out at the RDC based on forecasted demand. A consequence of moving from single-echelon to MEIO is lower fill rates at the warehouse, i.e., the RDCs. This may result in planners issuing more recovery orders to RDCs to prevent potential stock outs. Meanwhile, stock outs at RDCs are not an issue for the dealers, as the customer fill rates are maintained by shifting more inventory towards the dealer. This indicates that the rush order strategies at the RDCs must change when transitioning to a MEIO solution. This has not been modeled or simulated.

# 8 CONCLUSION

The purpose of this thesis was to analyze the rush order processes at Volvo SO&T, and formulate potential rush order policies that could be implemented, to be evaluated through simulation.

Based on the information gathered on the current rush order processes, it was evident that access to accurate pipeline information may promote better decision making and fewer unnecessary rush orders. Thus, the RushPipe decision rule was formulated, and compared to the current decision rule, RushDirect, through simulation.

The introduction of the RushPipe policy in the transition from single-echelon inventory control to MEIO initially resulted in a substantial increase in the number of rush orders. However, upon further investigation, the increase could mainly be attributed to the single-echelon case exceeding the specified target fill rates for a few high demand items. When investigating the RushPipe policy in the single-echelon and MEIO system under comparable conditions with new reorder points, it only resulted in a marginal increase in the expected number of rush orders. The expected inventory decreased significantly while maintaining customer service, a consequence of the characteristics of MEIO, rather than an effect of the RushPipe policy.

The RushDirect and RushPipe decision rules were simulated in both single-echelon and multi-echelon systems. The policy reduced the expected number of rush orders by 23.5% in the single-echelon system and by 19.4% in the MEIO system, demonstrating its effectiveness in both settings. The expected inventory remained largely unchanged under the RushPipe policy, indicating that it can be implemented without significantly affecting inventory levels.

The numerical study demonstrates that the RushPipe policy performs well in both a single-echelon and MEIO system, for the tested items. A substantial decrease in rush orders is expected when applied to a larger sample size, however, the magnitude needs further research.

## 8.1 Future Research

For further research, it would be interesting to financially evaluate the RushPipe policy by incorporating different cost elements, in order to provide a comprehensive assessment of its impact on the total cost. Additionally, emissions related to transportation should be estimated and included in the simulation model, to enable a quantitative evaluation of the policy's environmental impact.

Moreover, there may be other policies that could prove even more effective than the RushPipe policy, either in isolation or as a complement. Based on the current process maps, such policies could be formulated and incorporated into the simulation model, and eventually in the organization.

Furthermore, the current simulation model could be extended to include a central warehouse, in addition to the regional warehouse and retailers. The investigated distribution network allows for rush orders to be transported directly from the central warehouse to the retailers, as well as recovery orders to the regional warehouse from the central warehouse. Incorporating a third echelon in the model would provide a more accurate evaluation of the policy under conditions that more closely reflect reality.

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# APPENDIX A: DEALER INTERVIEW GUIDE

- **General**
    - What type of customers does your dealership mostly face?
    - Do you follow the automatic stock order schedule or do you place manual orders for stock?
    - Do you usually receive your orders when they are scheduled?
    - Can you clearly observe orders incoming from stock replenishment?
- **Day order**
    - Describe the process of placing a day order - from "thought" to arrival
    - Who at the dealership decides if a day order should be requested?
    - How often do you place day orders?
    - When is a day order normally requested?
    - What kind of information do you consider before placing a day order?
        - Is there any information you would like to have that you currently don't?
    - What happens if a customer requests multiple units of a certain part, and you can only fulfill parts of the demand?
        - Do you day order the rest, or allow it to be backordered until next stock replenishment?
    - Does it incur an additional cost for you to place a day order?
    - What do you think would have the most impact at your dealership for placing less "unnecessary" day orders - incentives or cost punishment?
    - Do you work a lot with pre-planning for planned services?
- **VOR**
    - What makes you request a VOR instead of a day order?
    - How often would you say you need to place a VOR order?

  - The process of placing a VOR; would you say it is easy to understand/easy to execute?

- **Sustainability**
  - Do you know by which transport mode orders are shipped to you?
  - Do you have any say in which transport mode orders are shipped with?
  - Do you feel you have a good perception of how much emissions are connected with the different transport modes?
    - Does sustainability affect your refill decisions?

# APPENDIX B: INTERNAL INTERVIEW GUIDE

- **General**
  - Describe the refill process to the dealers
  - Describe the refill process from CDC to RDC/SDC
  - Who controls the refill flow to the SDCs/RDCs from the CDC?
  - Dealers request day orders and VOR - is there a similar order class that RDCs/SDCs request from CDC?
- **Rush order process from dealer**
  - To the best of your knowledge, when do dealers request day orders/VOR?
  - When a day order is requested at a dealer, how is this signaled at the RDC/SDC/CDC?
  - How is a rush order prioritized at the RDC/SDC/CDC?
    - ∗ Is it picked before other orders?
    - ∗ How much time is required to process the order?
  - How is a day order/VOR shipped?
    - ∗ Who decides on the transport mode?
    - ∗ How is this decided?
    - ∗ Is the order shipped on its own or consolidated with other regular orders?
  - Does a rush order incur additional costs (e.g. material handling, rush transport, etc?)
    - ∗ If so, for whom?
  - How do dealers communicate with RDCs/CDCs/SDCs?
  - What information is shared between dealers and the RDCs/CDCs?
    - ∗ Can dealers see incoming orders?
    - ∗ Can dealers observe the stock level at the RDC/CDC/SDC?
  - Is there any policies/rules for when a day order/VOR can be placed?
  - What information do you think dealers need to place fewer rush orders/place them in the right situation?
  - Is the order traceable for the dealer throughout the entire process?

  - Is there any information gaps between Volvo and the dealers?

- **Rush order process from RDC/SDCs**
  - To the best of your knowledge, when do RDC/SDC request a "rush order"?
  - How does the RDC communicate with the CDC?
  - What information is shared between the RDCs/SDCs and the CDCs?
    - Can RDCs/SDCs see incoming orders?
    - Can RDCs/SDCs observe the stock level at the CDC?
  - Are there policies/rules for when a "rush order" can be placed?
  - What information do you think RDCs/SDCs need to place less "rush orders"/place them in the right situation?