MASTER

Collaborative planning in a high-tech industry with a make-to-forecast environment

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Award date:
2018

Eindhoven University of Technology
Department of Industrial Engineering & Innovation Sciences
Operations, Planning, Accounting and Control

– Master Thesis –

Collaborative Planning in a High-Tech Industry with a Make-To-Forecast Environment

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Eindhoven
November 22, 2018

TU\Eindhoven, Industrial Engineering and Innovation Sciences

Master Thesis Operations Management and Logistics

Subject headings: make-to-forecast, supply chain operations planning, collaborative planning (process), material requirements planning, constraint-based planning, capacity planning, synchronized base stock policy, inventory control, single echelon, counterfactual analysis

Abstract

Increased competition within high-tech supply chains demands for faster delivery of more customized products without increased costs. To enable a customer delivery lead time that is substantially shorter than the production lead time, companies apply a Make-to-Forecast (MTF) production strategy. The MTF strategy requires a proper alignment of the short-term execution cycle and the medium-term capacity planning, meaning that order releases should be aligned with the material availability upstream. The Supply Chain Operations Planning (SCOP) coordinates this release of orders in the supply network and an inadequate performance of the SCOP will lead to material coordination issues and subsequent material unavailability.

In this master thesis, a Collaborative Planning (CP) model is developed that generates a material feasible order release plan and indicates future material shortages. This model ensures a proper alignment of the short- and medium-term planning in a MTF business environment, based on a case study at Thermo Fisher Scientific and VDL Enabled Technologies Group. Subsequently, a CP process is defined how to utilize the output of the CP model to improve the SCOP and either avoid or resolve material-coordination issues.

Executive Summary

This report presents the results of a master thesis on Collaborative Planning (CP) in a Make-to-Forecast (MTF) environment. It is the result of a research and a case study with two leading high-tech organizations, Thermo Fisher Scientific (TFS) and VDL Enabled Technologies Group (ETG). TFS is a microscopy equipment producer and VDL ETG is a Tier-1 supplier. The project was initiated by both organizations while having a shared incentive to improve supply chain planning, and was carried out in collaboration with Eindhoven University of Technology (TU/e).

Problem Statement

TFS applies a MTF production strategy, whereby production is started based on forecast and then the partially completed units are matched and modified as actual orders arrive. This enables a customer delivery lead time that is substantially shorter than the production lead time. The Sales and Operations Planning (S&OP) cycle initiates the planning process which eventually results in a new Material Requirements Planning (MRP) and a corresponding forecast for suppliers. A monthly rolling forecast is applied by TFS to provide a better insight into future material and capacity requirements. VDL ETG plans production based on these forecasts and the production lead time of its items.

The short-term execution cycle and the medium-term capacity planning are currently not aligned at TFS. The short-term planning does not consider what is, or should be, currently present in the Work-In-Process (WIP) at VDL ETG based on what is forecasted. The Supply Chain Operations Planning (SCOP)¸ which is a planning framework to ensure material and resource feasibility for released orders, has a substandard performance. Furthermore, the MRP logic, currently used by TFS, neither provides a clear insight of the impact of late deliveries nor gives the system support to solve these issues. As a result, too often the deliveries of VDL ETG are not in line with the actual demand and a lot of control load is needed to catch up with shortages and to coordinate the schedules.

The main research objective is to develop a CP model that solves material coordination issues and subsequent material unavailability. The model should incorporate material constraints, and is therefore able to create feasible order releases and perform a satisfactory SCOP. The main research question is defined as follows:

"How can a MTF SCOP be improved by a CP model in order to create material feasible order releases, avoid material-coordination issues, and ultimately resolve material unavailability?"

The deliverable of this research is a CP model that generates an order release plan which is checked with respect to material availability. Immediate order releases should be aligned with the material availability upstream, and future shortages should be noticed and linked to its root causes. The supporting CP tool should ultimately result in reduced information lead time, greater visibility based on accurate information and enable informed decision making based on facts.

Mathematical Model

The planning procedure in the Philips case of De Kok et al. (2005) is used as a baseline for developing the CP model. An important dissimilarity between the Philips case and the current research is that the VDL ETG items which are used in modules cannot be pre-allocated to final products. Consequently, the CP model from the Philips case cannot be identically reproduced. To deal with this pre-allocation issue it is chosen to design the CP model as two consecutive stages.

The first stage of the CP model is applied for a single echelon where VDL ETG items are considered as final products. It is checked whether sufficient material will be available at VDL ETG to meet the demand of TFS. The goal of this first stage is to generate a feasible order release plan and to indicate (future) backlogs at VDL ETG (which implicates a late delivery at TFS). To indicate the impact of late deliveries on the production process at TFS, it is required to consider the successor(s) of the VDL ETG items.

The second stage of the CP model describes a value network with the VDL ETG items, now considered as child items in the Bill-Of-Material (BOM) of TFS, and their immediate successor(s). The output of the first stage is used to determine the expected shipment dates for each planned delivery at TFS. The objective of this second stage is to determine whether these shipments will result in material unavailability at TFS, and to indicate whether alignment of demand and supply could solve such future shortages.

CP process

A CP process is defined how to utilize the output of the CP model and eventually improve the SCOP. The goal of this CP process is to solve the misalignment of the short- and medium-term planning. To do so, it is recommended to perform the CP process periodically in short-term cycles such as a week. The objective of the CP process is that both organizations come to an agreement about the order release plan. The resulting coordinated plan should be feasible with respect to material availability. The supporting CP model enables rapid informed decision making based on facts, enables “what-if” analysis, and therefore supports speedy problem solving. The proposed CP process comprises four stages executed in a tightly-managed weekly cycle:

Stage 1 – Gather data; Stage 2 – Decide; Stage 3 – Escalate; Stage 4 – Deploy

Following this CP process should give planners control and let them discuss the tactical and strategic implications of their decisions (De Kok et al., 2005). This should reduce their time and efforts to prioritize MRP violations and perform rescheduling activities. The CP model supports to synchronize order release plans and to indicate potential problems.

Simulation

A simulation is carried out to indicate how different configuration of the CP model would have performed, had the model been used in the past. The results of the simulation reveal a remarkably low delivery performance for the configuration corresponding to the current situation. The order release quantities for this configuration would have been inaccurate and structurally too low, implying that forecasts were also inaccurate and too low. Based on the simulation it is expected that the configuration with a weekly cycle length that applies the move rate policy with a relatively low inventory threshold value would result in the greatest supply chain performance. However, this would only be true if the demand trends remain constant. Therefore, it is recommended to identify the cause of the inaccurate forecast and improve the forecast method instead of relying on patterns in the past.

Reflection

Concrete recommendations for improving the SCOP include improving the forecast accuracy, defining flexibility agreements that allow up- or downscaling within the lead time and incorporating the relevant resource constraints to improve the CP tool. A disadvantage of the proposed CP model is that it only considers immediate successors of VDL ETG items. It would be useful to consider the complete value network of items including the sales products of TFS to truly identify the most important bottlenecks.

Preface

This thesis concludes my research project conducted for the Eindhoven University of Technology in collaboration with Thermo Fisher Scientific (TFS) and VDL Enabled Technologies Group (ETG), both located in Eindhoven. Moreover, this report is the final product of my student life and marks the end of my master Operations Management and Logistics. Hereby, I would like to express my gratitude to everyone who supported me during the project.

First of all, I would like to thank my mentor Dina Smirnov. I want to thank you for your effort, support and precision. Your door was always open and your constructive feedback greatly helped me in structuring this research and my thesis report. Second, I want to thank Ton de Kok as second supervisor of this project. Your systematic approach for conducting a research really helped me in the early stages of this project. Furthermore, I was able to gain a lot from your experience and knowledge in this line of research.

Next, I would like to say thanks to Paul van Uden and Cees Bogers, my company supervisors at respectively TFS and VDL ETG. Initially for creating the possibility of conducting this study, thereafter for the pleasant collaboration and guidance during this project. Our discussions kept challenging me to look for the opportunities of taking the project to the next level.

I would like to thank two people whose feedback and support was particularly valuable in the final phase of this project. At first Mike, who helped to create a tool that can be applied immediately by TFS and VDL ETG. Secondly, my sister Elian who performed a final check and paying a great deal of attention to details.

I would also like to thank my family and friends. My family for their unconditional support and the guys from Duçibus and Pleintje for making this an unforgettable time. We have shared a lot of great memories and you have made my (student) life a great experience.

Finally, I would like to thank my girlfriend Anouk. You gave me the freedom to fully enjoy my student life in Eindhoven and even Taiwan. Thanks for your help, support and love!

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List of Symbols

Item Sets

M:	Set of all items
N:	Set of all end items, i.e., items sold to customers of the value network
$C_i(t)$:	Set of immediate successors or parent set of item i with $i \in M$
$P_i(t)$:	Set of immediate predecessors or child set of item i with $i \in M$
$F_i(t)$:	Set of end items delivered by item i with $i \in M$
U_k:	Set of items that can be processed on resource k

Variables for all items $\boldsymbol{i}$ with $\boldsymbol{i \in M}$ and $\boldsymbol{t \geq 1}$ and/or resource $\boldsymbol{k}$

$B_i(t)$:	Backlogs of item i at the start of period t
$C_i(t)$:	Consumption for item i in period t
$D_i(t)$:	Demand for end item i in period t
$EMR_i(t)$:	Expected move rate of item i at the start of period t
$FC_i(t)$:	Forecast orders for end item i in period t with $FC_i(t) \subseteq D_i(t)$
$I_i(t)$:	Net stock of item i at the start of period t
$IP_i(t)$:	Inventory position of item i at the start of period t
$PU_i(t)$:	Purchase orders for end item i in period t with $PU_i(t) \subseteq D_i(t)$
$S_i(t)$:	Target base stock level of item i at the start of period t
$SH_k(t)$:	Shortage of resource k at the start of period t
$SR_i(t)$:	Scheduled receipt of item i planned to arrive at the start of period t
q_i:	Quantity of item i processed in period t
$UWO_i(t)$:	Unconstrained work order release quantity of item i at the start of period t
$WO_i(t)$:	Work order release quantity of item i at the start of period t

Decision Variables

R:	Length of the time interval between subsequent review periods
M:	Number of periods t ahead to determine the expected move rate
Z:	Number of periods t used to calculate the inventory constraint
ρ:	A percentage of the lead time demand used to calculate the safety stock

Parameters associated to each item $\boldsymbol{i} \in \boldsymbol{M}$ and/or a resource $\boldsymbol{k}$

c_i:	Time required to process one unit of item i on its resource k
C_k:	Available capacity of resource k per period
DLT_i:	Delivery lead time of a purchase order of item i with $DLT_i \subset LT_i$
F_k:	Number of periods for which a resource k can up- or downscale order release quantities
LT_i:	Lead time of a work order of item i
ST_i:	Safety lead time associated with item i
T_i:	The planning horizon of item i

List of Abbreviations

APS	Advanced Planning and Scheduling
ATO	Assemble-To-Order
CE	Cause-Effect
CLIP	Confirmed Line Item Performance
CAS	Consistent Appropriate Share
CODP	Customer Order Decoupling Point
CP	Collaborative Planning
CRM	Custom Relationship Management
ERP	Enterprise Resource Planning
ETG	Enabled Technologies Group
ETO	Engineer-To-Order
GBO	Global Business Operations
KPI	Key Performance Indicator
MOQ	Minimum Order Quantity
MPS	Master Production Schedule
MRP	Material Requirements Planning
MTF	Make-To-Forecast
MTO	Make-To-Order
MTS	Make-To-Stock
OEM	Original Equipment Manufacturer
(P)BOM	(Percentage) Bill-Of-Material
RLIP	Requested Line Item Performance
SBS	Synchronized Base Stock
SCOP	Supply Chain Operations Planning
StrAP	Strategic Action Plans
S&OP	Sales and Operations Planning
TFS	Thermo Fisher Scientific
WIP	Work-In-Process

1 Introduction

This report presents a Collaborative Planning (CP) procedure for a high-tech organization in a Make-To-Forecast (MTF) environment. During the study, the Supply Chain Operations Planning (SCOP) problem has been addressed in order to create a feasible order release plan and eventually increase material availability. The project is carried out at Thermo Fisher Scientific (TFS), a world leading microscopy company, and its supplier VDL Enabled Technologies Group (ETG), a Tier-1 manufacturer.

The first chapter starts by introducing relevant background information to understand the problem context. From the problem context, the current situation is described to elaborate on relevant planning processes, agreements and performance measures. The introduction is concluded with the outline of this report.

1.1 Problem Context

A first step in determining the goal of the research is to understand the problem context. This research is focused on the interplay between TFS, formerly FEI company, and VDL ETG. This section provides relevant background information for both companies, as well as a short description of the relationship between the two.

1.1.1 Background Thermo Fisher Scientific

Thermo Fisher Scientific Inc. is a world leader in serving science by offering a unique combination of innovative technologies, purchasing convenience and comprehensive services. This combination of products, services and technologies helps customers of TFS to accelerate life sciences research, solve complex analytical challenges, improve patient diagnostics, deliver medicines to market and increase laboratory productivity. In this way, TFS pursues its mission to enable their customers to make the world a healthier, cleaner and safer place. Revenues are over 20 billion dollars per year and circa 65,000 employees are currently active at TFS.

In September 2016, Thermo Fisher Scientific Inc. completed its acquisition of FEI Company, an Original Equipment Manufacturer (OEM) in the high-tech sector. This company designs, manufactures and supports the broadest range of high-performance microscopy workflows that provide images and answers in the micro-, nano- and picometer scales. A worldwide team of 3200+ employees combines hardware and software expertise in electron, ion, and light microscopy with deep application knowledge of 4 different areas. These are materials science, life sciences, semiconductors and oil and gas. This part of TFS has a yearly revenue of approximately 1.5 billion dollars.

TFS is a worldwide company, but this research focuses on the supply chain of one specific factory of the former FEI company, which is the Eindhoven factory. In this factory, they produce Transmission Electron Microscopes, which are TFS its most complex microscopes.

1.1.2 Background VDL Enabled Technologies Group

VDL Enabling Technologies Group is part of the VDL Group and is a Tier-one contract manufacturing partner. It is a global supplier of high-quality mechanical components, modules and finished systems. Customers of VDL ETG are OEMs that are leaders in high-tech production equipment and users of advanced production lines. VDL ETG is active in the following markets: equipment for the semiconductor industry, thin-film deposition equipment for photovoltaic solar cells, analytical instruments, medical systems, mechanization projects, and aerospace and defense.

The services offered by VDL ETG companies include engineering, prototyping and serial production of products characterized by high complexity and relatively low production volumes. In addition, they also provide client-specific business mechanization, especially from VDL ETG Projects. VDL ETG has production locations in Eindhoven, Almelo, Trübach (Switzerland), Singapore and Suzhou (China). This research concerns the location in Eindhoven.

1.1.3 Relationship TFS and VDL ETG

Both companies originate from Philips and have been cooperating since, whereby VDL ETG supplies high-tech mechanical components and modules to TFS. Examining both revenue and production capacity, TFS is recognized as an important customer of VDL ETG.

1.2 Current Situation

This section describes the processes related to the planning and production of MTF items at TFS and VDL ETG. This monthly process is depicted in Figure 1 and starts when TFS converts its Sales and Operations Planning (S&OP) into a new Master Production Schedule (MPS) and corresponding Material Requirements Planning (MRP). Customer-Supplier agreements between both companies and Key Performance Indicators (KPIs) for the supply chain are also described in this chapter.

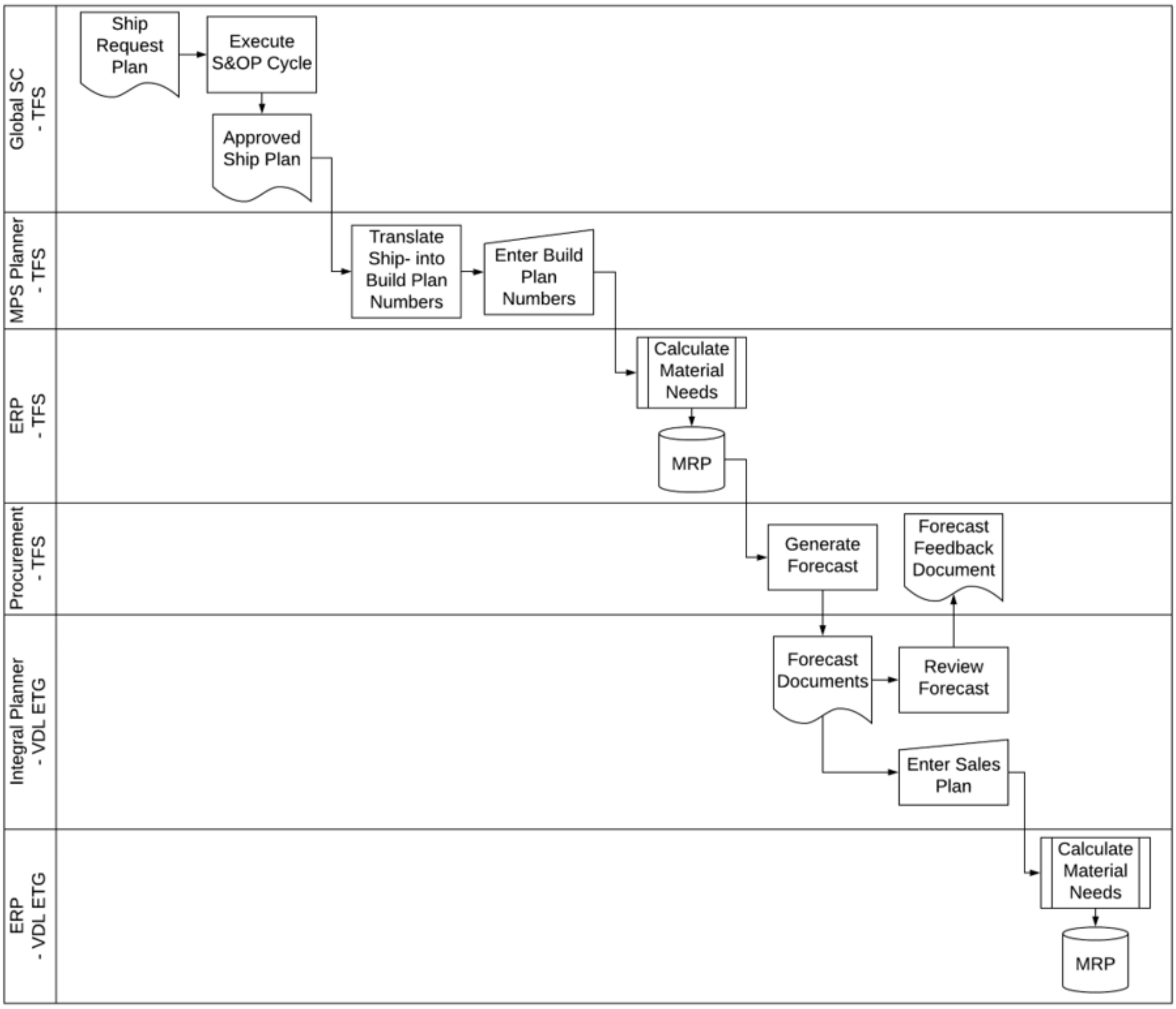


Figure 1: Monthly planning process that converts the S&OP into an MRP for MTF items

1.2.1 Sales and Operations Planning

The planning process starts with the S&OP cycle which is executed in the Global Supply Chain department of TFS. The goal of the S&OP cycle is to combine multiple plans into one aligned plan, such that different departments reach an agreement on the number of products TFS aims to sell. The S&OP plan has a planning horizon from the current quarter till 6 quarters ahead. The plan is updated each month following a standard cycle of approximately 2.5 weeks.

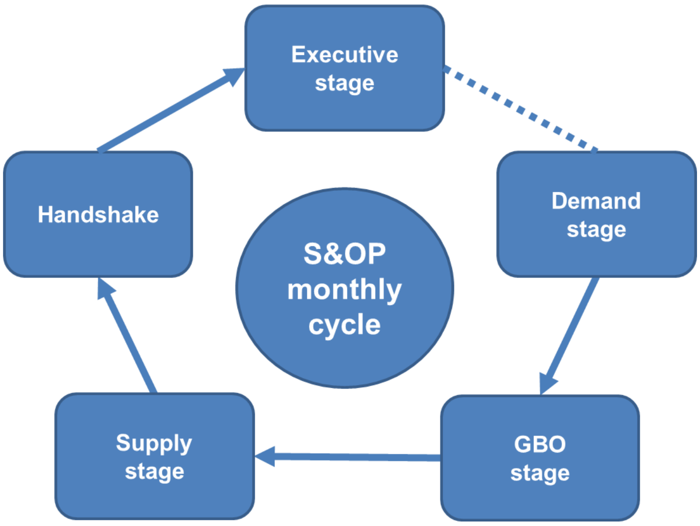


Figure 2: Monthly S&OP cycle

The cycle is initiated by the business units of TFS submitting a ship request plan. Global Business Operations (GBO) checks the ship request plan based on Custom Relationship Management (CRM) data and forwards the GBO request plan to the factories. In the second stage, the factories review this plan based on the factory planning and capacity. Based on this review, the ship plan is either approved or an alternative plan is proposed. A handshake meeting is then arranged to reach consensus between supply and demand. During this meeting potential issues are identified, which are further discussed in the executive meeting. The goal of this last meeting is to get an approved ship plan or to agree on actions where needed. The ship plan will be approved after these actions have been performed. This approved ship plan shows per product the amount that TFS aims to ship each quarter, for the next 6 quarters (including the current). Products may already be linked to a customer with a certain probability.

1.2.2 Aggregate Material Requirements Planning

As can be seen in Figure 1, the Enterprise Resource Planning (ERP) system automatically calculates material needs. Each product is divided into a base part and a configuration part. Items for the base part are generic, while each product has a unique configuration part. Material requirements for configuration items are forecasted with a certain probability based on statistical data and internal knowledge of business unit managers, forming a Percentage Bill-Of-Material (PBOM) (Berry, Tallon and Boe, 1992).

Several control parameters are incorporated in the ERP system and these parameters impact the amount and timing of material requirements. Two groups of parameters are present: classification parameters and sourcing parameters. The first group consists of the order policy, order period and a safety time. Sourcing parameters include supplier lead time, minimum/maximum order quantity and order multiplicity. After the MRP is calculated, the procurement department of TFS generates the forecast and shares this forecast with VDL ETG.

1.2.3 Customer-Supplier Agreements

Several customer-supplier agreements are established between TFS and VDL ETG to ensure delivery reliability. The terms and conditions are related to Minimum Order Quantities (MOQ), rolling forecasts, commitment agreements and delivery lead times. Most machines at VDL ETG have a rather high utilization rate and set-up times can be high in the high-tech industry. Producing in batches reduces the number of setups and may increases efficiency. The MOQ allows VDL ETG to produce in batches, which results in lower costs and therefore lower sales prices. On a monthly rolling forecast is agreed to provide more insight on future material- and capacity requirements for MTF items.

For the MTF items VDL ETG initiates its production based on the forecasted delivery dates. A management order is a production order based on a forecast (see Figure 1), without an associated purchase order. For these management orders VDL ETG and TFS have commitment agreements to ensure production of forecasted quantities for TFS on one hand, and cost coverage for consumed resources for VDL ETG on the other hand. For each item, a separate agreement is made and these commitments are fixed.

At a certain point in the production process VDL ETG receives purchase orders from TFS. Each item has a ‘forecast call-off lead time’, which is defined as the period of time within which VDL ETG should deliver its products. This ‘forecast call-off lead time’ corresponds to the supplier lead time in the MRP of TFS (mostly 6 weeks) and is significantly shorter than the production lead time at VDL ETG (20-50 weeks). When VDL ETG receives a production order it is manually checked whether the requested delivery date is within the ‘forecast call-off lead time’ of the item. Other steps in the order fulfillment process are depicted in the following figure.

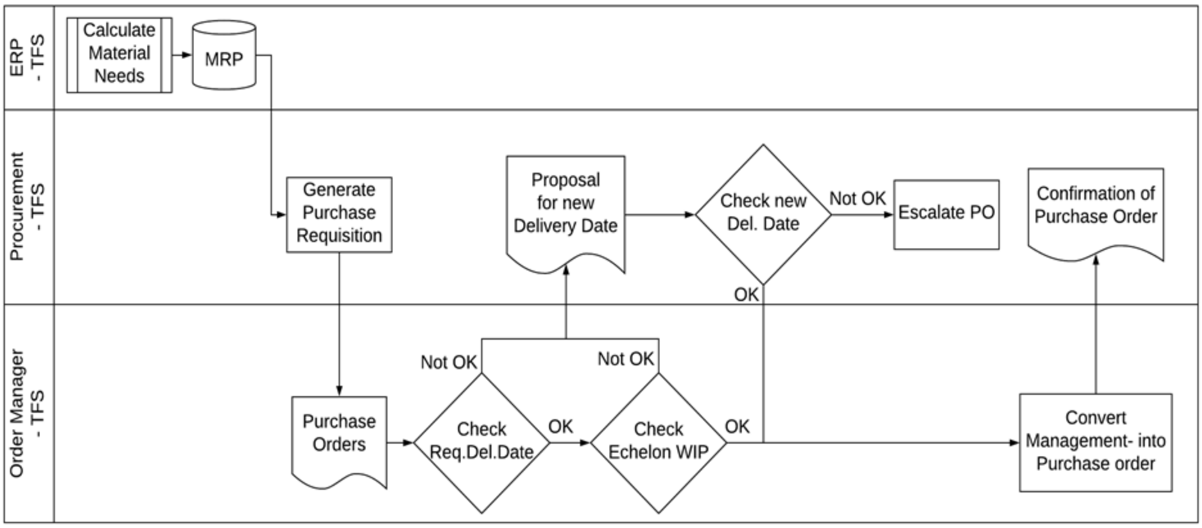


Figure 3: Order fulfillment process

1.2.4 Key Performance Indicators for Supply Chain Control

The KPI that is used by TFS to evaluate the supply chain performance is the supplier delivery reliability, which can be measured as the Requested Line Item Performance (RLIP) and the Confirmed Line Item Performance (CLIP). The RLIP measures the delivery reliability for the requested date defined by the purchaser. The CLIP date is the confirmed date by the supplier at which they can deliver and is leading for TFS in the assessment of its suppliers. TFS collects delivery data to assess these delivery reliability measures. Both KPIs are related to the execution cycle of TFS and do not consider the quality of the planning.

1.3 Outline of the Report

The remainder of this thesis is structured as follows. Chapter 2 defines the problem statement, including the problem description, methodology, research scope and research questions. Then, a literature study is performed in Chapter 3 to find suitable planning approaches for the CP model that will be designed. This mathematical CP model is completely designed in Chapter 4. The related CP process that utilizes the CP model is defined in Chapter 5. Subsequently, Chapter 6 describes a simulation to determine what configuration of the CP model is expected to perform best. Finally, Chapter 7 reflects on the current work by answering the research questions defined in Chapter 2, by presenting recommendations for TFS and VDL ETG, and by discussing limitations of the current work as well as directions for future research.

2 Problem Statement

The first section of this chapter describes the main problem and subsequently elaborates on the causes and the effect of this problem. An exploratory data analysis and a multitude of qualitative interviews are conducted with both TFS and VDL ETG personnel to derive the problem statement and identify its causes. The problem statement is defined first, after which the root-causes of the encountered problem are analyzed. The first part of section 2.1 describes a problem and its causes, while the presence nor the size of this problem is indicated. Therefore, this section is concluded with a quantitative data analysis to determine the severity of the problem. The second section of this chapter describes the methodology that is followed during this research, where after the research scope is explained in section 2.2. Research questions and deliverables are specified in the last section.

2.1 Problem Description

TFS applies a MTF production strategy, which enables a customer delivery lead time that is substantially shorter than the production lead time (Meredith and Akinc, 2007). TFS starts production based on forecast and then matches and modifies the partially completed units as actual orders arrive. Figure 1 shows how the S&OP cycle initiates the planning process which eventually results in a new MRP and corresponding forecast for suppliers. A monthly rolling forecast is applied to provide a better insight into future material and capacity requirements. VDL ETG plans production based on these forecasts and the production lead time of its items. Section 1.2.3 explains that VDL ETG is fully committed to these forecasts. It should be noted that VDL ETG also produces several items as Make-To-Order (MTO). It is proven in section 2.1.2 that these items do not significantly contribute to the following problem description.

When VDL ETG produces the forecasted quantities without any delays, and TFS synchronizes their purchase orders with the forecasts, demand and supply should be aligned resulting in a high supplier delivery reliability. However, poor planning results in poor performance on the execution side, while poor execution causes challenges in planning, essentially creating a vicious cycle. TFS and VDL ETG both encounter such problems, partly caused by TFS generating purchase orders without considering the upstream material availability. As a result, too often the deliveries of VDL ETG are not in line with the actual demand and a lot of control load is needed to catch up with shortages and to coordinate the schedules. In addition, VDL ETG uses various suppliers who are equally affected by these problems, although the current work entirely focuses on the interaction between TFS and VDL ETG. Concluding, the problem statement is defined to be:

"Infeasible purchase orders causing material unavailability at TFS, high control load to coordinate the schedules, and general supply chain nervousness"

2.1.1 Root-Causes for the Problem

The exploratory data analysis resulted in the Cause-Effect (CE) diagram provided in Figure 4. The problem statement focuses on material coordination in the supply network, while the CE diagram also indicates other possible causes. A subset of the causes, e.g., the ones related to product design, the production process and capacity limitations cannot be solved by an improved supply chain planning and are therefore left out of scope. Despite the fact that capacity limitations cannot be solved or adapted within the project, it is vital to consider them in the supply chain planning. If these limitations are not considered, planned production may require more capacity than available. The two relevant blocks in the CE diagram are yellow-colored, the relevant processes for this research are demarcated with a red dotted line, and root-causes should be addressed to solve the mentioned problems.

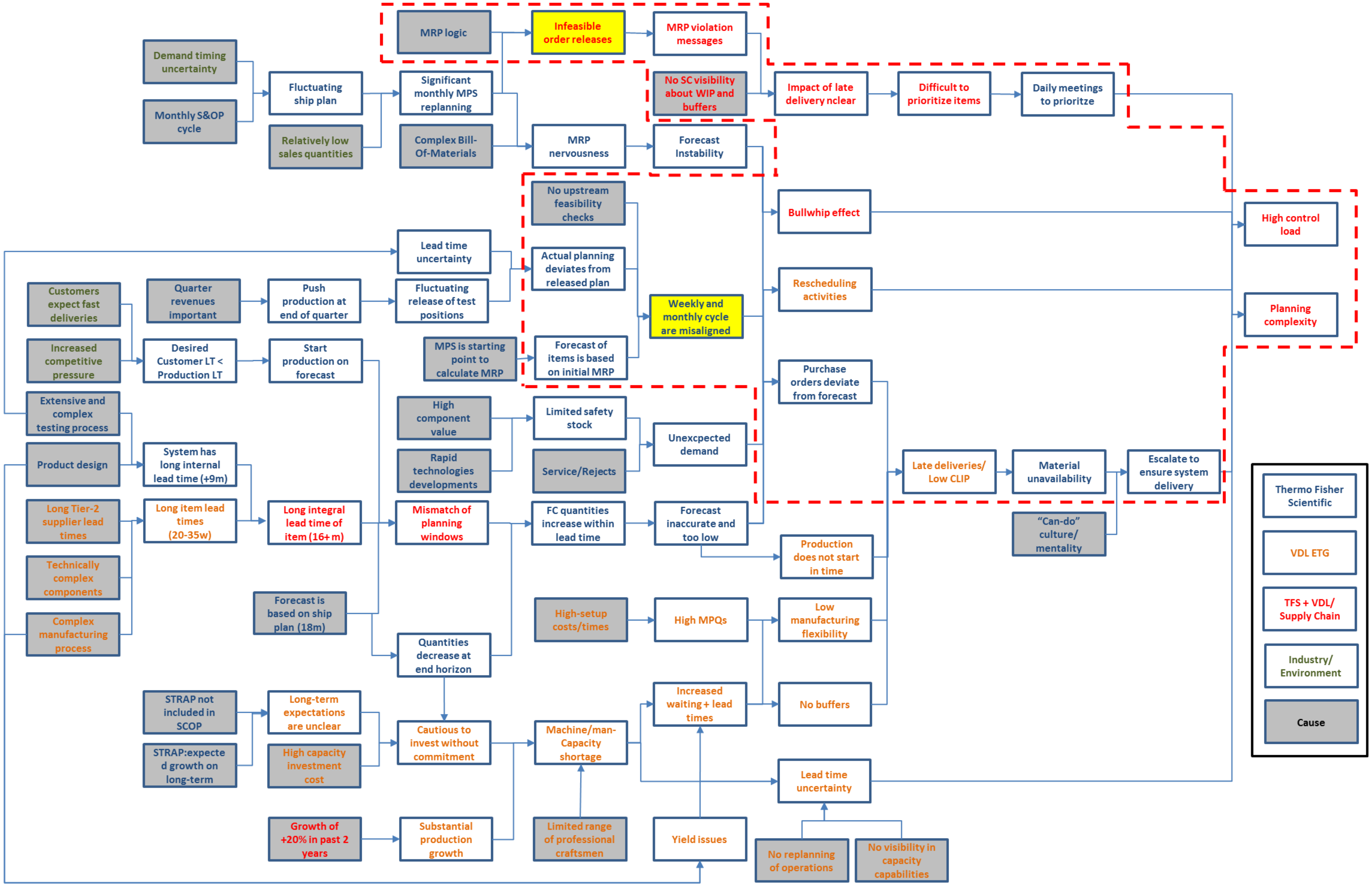


Figure 4: Cause-effect diagram that followed from the explanatory data analysis

Forecast inaccuracy

It is explained by Towill (1997) that parameter settings, such as reorder levels and batch sizes, contribute to demand uncertainty for upstream supply chain nodes. The detrimental effect of a lack of demand visibility is called the bullwhip effect (Lee, Padmanabhan and Whang, 1997). The parameter settings usually depend on the demand forecast, such as using safety lead times, which is one of the root causes of this bullwhip effect. Upstream partners need to "play a guessing game" and anticipate on decisions of the downstream partner. Therefore, it can be concluded that the forecasts of TFS, which are based on the MRP, are performed on an incorrect hierarchical level. To enhance information integration in the supply chain it would be better to provide demand visibility and transparency, which can be accomplished via data sharing activities supported by information systems (Reichhart and Holweg, 2007). This provides suppliers of information about the actual consumption of items per time interval, which helps to identify possible future shortages at an early stage.

The second disadvantage of the current forecast method is that for some items, a truncated horizon effect has been present. The forecast horizon of an item should be at least equal to the internal lead time of a system at TFS plus the production lead time of an item at VDL ETG (Federgruen and Tzur, 1994). For some items, this cumulative lead time is longer than the time interval of an approved ship plan. The forecasted quantities for these items seem to decrease towards zero at the end of the horizon, while precisely these are the quantities that the supplier uses to plan new production. Subsequently, the demand increases within the cumulative lead time and planning problems immediately arise. When forecast quantities change within the cumulative lead time of an item, VDL ETG needs to reschedule or take actions to conform to these changes. However, no flexibility agreements are established whether VDL ETG should comply with up- or downscaling of forecasted quantities within the production lead time.

This truncated horizon effect was clearly visible till forecasts of November 2017, after which an extra step was initiated in the MRP. From then on, the ship plan has been extrapolated before the MPS was updated, which results in a longer time interval for material requirements and subsequent forecasts. An example of this truncated horizon effect is provided in Appendix A. Despite the extrapolation of the ship plan and the subsequent forecasts, the material requirements will still decrease towards zero at the end of the planning horizon. As a result, the relevant forecasted material requirements for VDL ETG items with cumulative lead times longer than the ship plan will at its maximum remain equal to the requirements at the end of the ship plan. This contradicts with the long-term (1-5 years) Strategic Action Plans (StrAP), which indicates a positive trend of the demand for the next years.

Missing link short-term execution cycle and medium-term capacity planning

Modifications in a new ship plan and several other internal and external causes can change the MRP. Think about rescheduling activities of the MPS, modifications in sales orders (e.g. configuration adjustments), unplanned demand due to rejects and yield issues at the supplier. Another possible cause for changes in the MRP is the fact that production of sub-modules at TFS, in which multiple VDL ETG items are consumed, is planned manually for a certain time window ahead. In section 1.2.2 it is explained that the aggregate MRP is directly linked to the MPS of final products. Consequently, the production of sub-modules may not be synchronized with the production of these final products. In other words, the operational planning may differ from the strategic planning. The deviant production planning of modules may trigger immediate demand that will not be available based on the initial aggregate MRP. Furthermore, an essential feature of the MRP logic is that safety stocks are not consumed, whereby each (small) modification of the MPS or any deviation in scheduled receipts yields a change in order releases when running the MRP. In other words, the MRP logic considers safety stocks as outcomes instead of planning parameters or targets.

At TFS the MRP is used to perform the SCOP and a MRP-run starts planning at the highest level with the MPS as starting point. The MRP does not necessarily satisfy resource- and material constraints (Wiers and De Kok, 2018). More information about this deficiency will be given in section 3.3.1. In addition, the MRP only considers the forecast call-off lead time and not the actual production lead time of VDL ETG items. A change in the MRP could immediately trigger a demand based on the forecast call-off lead time without checking upstream material availability. As a result, it is possible that infeasible planned orders are created. If at any point in the MRP an infeasible planned order is created or a lead-time or resource constraint is violated, the system gives an exception message to notify the user. No feedback is provided how to resolve the violation and what possible effect the violation will or can have in future. There is no information whether a violation directly delays a subsequent work order, or simply relates to a buffer being temporarily below its safety stock.

The MRP-supported processes are executed by material planners who do not know the impact of their rescheduling actions on other planning activities. Solving one violation mostly results in one or more other violations in the dependent orders and/or capacities (De Kok and Fransoo, 2003). Typically, informal communication is needed to align rescheduling actions. Currently, no structured procedure is in place to handle violations, nor is this incorporated in the ERP system. Upper management involvement is required on a weekly- or sometimes even daily basis to prioritize the violations. It can be concluded that the MRP logic rather generates material requirements than it creates feasible order releases.

Concluding, the short-term execution cycle and the medium-term capacity planning are currently not aligned at TFS. The short-term planning does not consider what is, or should be, currently present in the Work-In-Process (WIP) based on what is forecasted. The SCOP, which is a planning framework to ensure material and resource feasibility for released orders, has a substandard performance. This results in many late deliveries and subsequent material unavailability at TFS. Furthermore, the MRP logic does not provide a clear insight of the impact of late deliveries nor gives the system support to solve the issues. Hence, a high control load and many rescheduling activities are required.

2.1.2 Severity of the Problem

Deliveries for which VDL ETG is the default supplier with an order date from 01-01-2016 till 12-03-2018 are analyzed to determine the severity of the problem. Analyzing this data provides insight to what extent items are not delivered on time, and which type of items significantly contribute to these late deliveries.

In total, 2044 purchase orders have been placed within the specified period and 1876 have been shipped. TFS compares the confirmed delivery date of VDL ETG with the actual shipping date to measure the CLIP. A delivery is measured to be either ‘Early’, ‘On time’ or ‘Late’. When a delivery is shipped at least 7 days before its confirmed date, it is defined to be ‘Early’, when it is shipped within 5 days after its confirmed date it is defined ‘On time’ and otherwise it is defined to be ‘Late’. The CLIP is defined as the percentage of orders which are not late and is 64.7%. This percentage shows that approximately 1 out of 3 purchase orders is delivered too late, which results in material unavailability and a subsequent delay in the production process of TFS.

As mentioned in section 2.1, VDL ETG is driven by forecast and orders. To narrow down the scope of the project, it is investigated which type of items significantly contribute to the late deliveries. Not surprisingly, the vast majority of the late deliveries is caused by MTF items (614 deliveries = 92.7%). This research is therefore focused on this category of items.

2.2 Methodology

The current work is a design study. The mission of such a study is described by Van Aken (2005) as developing knowledge that can be applied to solve field-specific problems. Such prescriptive knowledge is developed by defining technological rules or creating solution concepts. This research follows the design-oriented and theory-informed methodology proposed by Van Aken, Berends and Van der Bij (2012), recommended to use in business problem solving projects with a significant technical-economic component. The proposed problem-solving cycle is derived from a model of Van Strien (1997), who termed the model as a regulative cycle.

This project is initiated by an observed business problem. Such a business problem, which can be defined as the problem mess, is often a set of interrelated problems (Ackoff, 1981). This problem mess should be identified and structured to complete the first step of the problem-solving cycle and provide a clear problem statement. The cycle consists of four more steps, together forming an iterative process depicted in Figure 5.

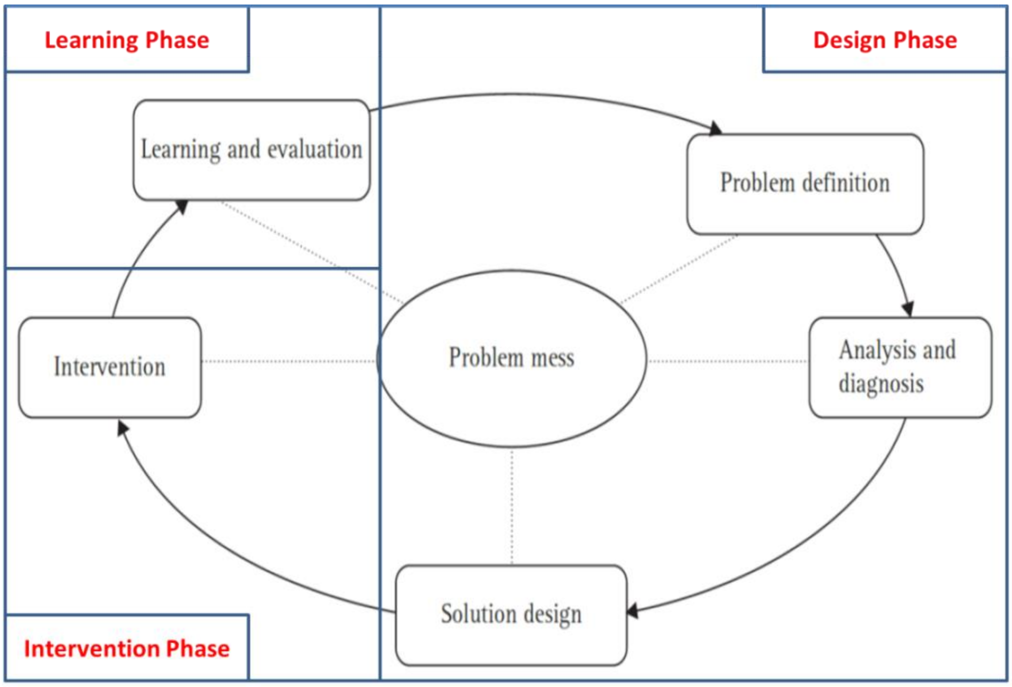


Figure 5: Problem solving cycle (van Aken, 2012)

Besides the five different steps depicted in Figure 5, the problem-solving cycle can also be categorized in three phases: design phase, intervention/change phase and learning phase. The design phase consists of (i) the problem definition, including identification and structuring of the problem mess, (ii) an analysis and diagnosis of the problem and (iii) a solution design. Due to time restrictions, the thesis project will focus on the design phase. Nevertheless, recommendations will be drawn about the intervention and learning phases, because both are highly relevant for the involved business organizations.

2.3 Research Scope

The relevant scientific research areas for this project are defined in this section. Based on the root-causes for the problem, two streams of research are found to be relevant for this current work. In section 2.1.1 is explained that TFS currently applies the MRP logic for its SCOP, which not necessarily satisfies material- and resource constraints. Without these constraints, the SCOP function cannot ensure proper material coordination and release of feasible production orders (Wiers and De Kok, 2018). To ensure that only feasible plans are created and violations at lower levels are identified at an early stage, it is crucial to include such constraints at the first step of the planning. The research scope for this part is defined as constraint-based planning and/or material feasible order releases.

Furthermore, it is given in section 2.1.1 that the short-term and medium-term planning are misaligned, meaning that the short-term cycle does not consider upstream material availability. Therefore, an approach should be defined in which information about both the medium-term planning and short-term cycle are synchronized and data is shared amongst supply chain partners. It would be beneficial for both parties to continuously compare echelon WIP and scheduled receipts to reduce information lead time and create a greater visibility. An improved visibility would help to early determine the actual material bottlenecks in the chain. Collaborative (planning) activities should improve the pipeline alignment, which results in more stability and responsiveness. Concluding, the second part of the research scope is defined as supply chain collaboration.

2.4 Assignment and Deliverables

In this section the main research question and several sub-questions are defined.

2.4.1 Main Research Question

The main research question is derived by combining the research scope (supply chain collaboration and feasible order releases) to solve the main problem (material coordination issues and subsequent material unavailability). A CP model should incorporate material constraints, and is therefore able to create feasible order releases and perform a satisfactory SCOP. The main research question is defined as follows:

"How can a MTF SCOP be improved by a CP model in order to create material feasible order releases, avoid material-coordination issues, and ultimately resolve material unavailability?"

2.4.2 Sub-Questions

In section 2.2 it is explained that this research will mainly focus on the design phase of the problem-solving cycle. The first step of this cycle, the problem definition, is already completed in this chapter. The first 5 sub-questions are defined to cover the analysis & diagnosis step and the solution design step. It should be noted that this project depends on iterations. The sub-questions in this research project are not necessarily answered in an exact consecutive order, but answering may include going back and forth between the questions.

In section 2.1.1 it is explained that direct infeasible order releases can be created by the MRP, because it starts planning at the highest BOM and does not include material constraints. The first sub-question aims to search literature for suitable planning approaches that can be used in the CP model. This question includes a literature review related to relevant constraint-based planning approaches and applied planning approaches in other CP models. One or a combination of approaches can be used for the CP model in this research. Which model will be selected depends on the specific business environment, mathematical formulations and available data, so an iterative process may take place.

The second sub-question relates to the functional requirements, constraints and decision variables that need to be properly formulated in the CP model. The mathematical CP model is designed by answering this sub-question. The selected planning approach from the first sub-question is applied in the CP model. To actually use and run the model, it is necessary to collect appropriate data and prepare this data when necessary, which is captured in the third sub-question.

When the mathematical model is completed and all data is gathered, the CP model can be executed. The goal of the CP model is to generate an order release plan and provide insight into possible future issues. It should be noted that this order release plan is not the final outcome of the SCOP. The CP model is used as support tool, but does not perform any actual actions. This means that a CP process should be defined what and how to utilize the output of the CP model, which covers the answer to sub-question 4. The goal of this CP process is to solve the underlying problem that the short- and medium-term planning are misaligned. To do so, it is recommended to perform the CP process periodically in short-term cycles such a week. The objective of the CP process is that both organizations come to an agreement about the order release plan. The resulting coordinated plan should be feasible with respect to both material and resource availability.

The fifth sub-question aims to predict the expected impact of the CP model on the supply chain performance. The CP model will purely be used as a support tool, hence it is complicated to predict or hypothesize what impact the model will have on the supply chain performance. Its impact particularly depends on how well the users of the CP model follow the defined CP process. One needs to speculate how well planners of both organizations would have aligned the supply and demand. Furthermore, these alignment decisions are not automatically deployed by the CP model. Therefore, the simulation does not include any alignment of supply and demand within lead time. What can be measured though, is the accuracy of the order release decisions made by the CP model. Several decision variables will be present in the CP model and this simulation checks whether adjustments to these variables result in more or less accurate order release decisions. The simulation shows which configuration(s) of the CP model would have performed the best in the past. The results provide insight about the forecast accuracy of TFS and indicate what configuration is currently recommended for the CP tool.

- **Sub-Q1:** Which planning approach(es) can be used for the CP model to create a feasible order release plan and identify bottlenecks at an early stage?
- **Sub-Q2:** What decision variables and (material/ resource) constraints need to be included in the model?
- **Sub-Q3:** What data needs to be collected and how should it be gathered and/or prepared to run the model?
- **Sub-Q4:** How should the output of the CP model be used to improve the SCOP and eventually increase material availability?
- **Sub-Q5:** Which configuration(s) of the CP model would have performed best based on historic data, and what can be concluded from these findings?

The design phase is completed by answering these five sub-questions. The main research question can, in fact, be answered by combining these sub-questions.

2.4.3 Deliverables

The deliverable of this research is (i) a CP model that generates a feasible order release plan with respect to material and resource availability. Immediate order releases will be aligned with the material availability upstream, and future shortages should be noticed and linked to its root causes. (ii) A collaborative planning process that describes how the outcomes of the CP model should be used to eventually improve the SCOP. (iii) A supportive CP tool will ultimately result in reduced information lead time and greater visibility, and will enable informed decision making based on facts.

3 Literature Review

This chapter presents an overview of current literature focusing on collaborative processes and concepts, and more specifically the SCOP. Section 3.1 explains which relevant literature about supply chain collaboration has been published and section 3.2 explains the MTF environment. Then follows a comprehensive review on SCOP, the deficiencies when applying MRP logic as SCOP, and an overview which planning logic or models can be used to create material feasible order releases. Section 3.4 describes a specific case that is closely related to this research and can be used as starting point for the CP model. As a conclusion of this review, the contribution of this research to the current literature is highlighted.

3.1 Supply Chain Collaboration

This section consists of three parts and the first part is about the definition of supply chain collaboration. Then one of the main rationales for supply chain collaboration, called the bullwhip effect, is elaborated. Lastly, the most relevant form of collaboration related to this research is highlighted.

3.1.1 Definition

A literature review conducted by Soosay and Hyland (2015) elaborates on the definition of supply chain collaboration. They state that many definitions for supply chain collaboration are present in the literature, but some common features are noticeable. Collaboration concerns multiple business organizations cooperating and establishing relationships with the goal to share improved outcomes and benefits. To accomplish such benefits it is crucial to establish an appropriate level of trust, exchange relevant information and take joint decisions. Depending on the situation, it can also be necessary to integrate supply chain processes (Soosay and Hyland, 2015).

Different models to cover supply chain collaboration are present in the literature. One of these models, which contains seven attributes related to both collaborative processes and relationships, is proposed by Cao, Vonderembse, Zhang, and Ragu-Nathan (2010). These seven attributes (information sharing, goal congruence, decision synchronizations, incentive alignment, resources sharing, collaborative communication and joint knowledge creation) are described as means to reduce cost and risks. Simatupang and Sridharan (2005) introduce another model which consists of five aspects: collaborative performance system, information sharing, decision synchronization, incentive alignment and integrated supply chain processes. The only collaborative activity that is currently performed between TFS and VDL ETG is information sharing in the form of forecast (feedback) documents. It should be noted that no follow-up actions are defined what to do with these documents.

3.1.2 Bullwhip Effect

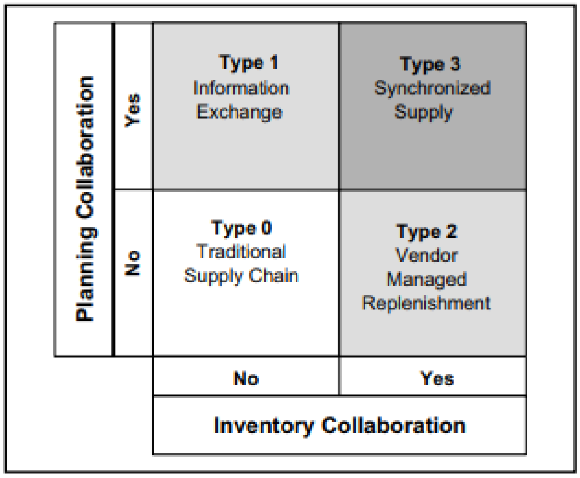
It is already explained in section 2.1.1 that the parameter settings contribute to demand uncertainty, and this lack of demand visibility has a detrimental effect called the bullwhip effect. In addition, De Kok (2012) explains that besides upstream links, also downstream links suffer from the bullwhip effect. He illustrates that information distortion caused by the bullwhip effect results in deterioration of customer service at the most downstream link of the supply chain, or requires a higher safety stock to meet the requested customer service level. The bullwhip effect can result in several negative implications such as; excess inventory, inadequate forecasts, insufficient or excess capacity, poor customer service, unreliable product planning and high costs for corrections throughout a supply chain (Lee et al., 1997).

Parameter settings in the ERP-system of TFS currently impact the amount and timing of MRP, and therefore also the forecasts that are shared with VDL ETG. These settings result in the above defined bullwhip effect. Some of the negative effects mentioned by Lee et al. (1997) are also present and highly relevant for this research, namely inadequate forecasts, unreliable (supplier) product planning and high costs for corrections throughout a supply chain.

Several collaborative activities can be performed to reduce the bullwhip effect. Lee et al. (1997) proposes three activities; information sharing, channel alignment, and operational efficiency. Innovative information systems can be used as a means to provide demand visibility and transparency in order to enhance collaboration (Reichhart and Holweg, 2007). This provides suppliers with information about the actual consumption of items per time interval, which helps to identify possible future shortages at an early stage. Many other studies confirm the positive effects of information sharing to mitigate the bullwhip effect (cf. Lee, So, and Tang, 2000; Cachon and Fisher, 2000). As already mentioned in the previous section, information is only shared in the form of forecast documents. Furthermore, none of the other proposed activities to reduce the bullwhip effect are currently performed.

3.1.3 *Synchronized Supply*

Several activities can be performed to achieve certain degrees of supply chain collaboration. Holweg, Disney, Holmström and Småros (2005) provide a framework to classify different concepts of collaboration. Four different supply chain configurations are identified based on two dimensions; ‘Planning Collaboration’ and ‘Inventory Collaboration’. It is noted that it is possible to distinguish collaboration between more dimensions, but these are discussed as contingent factors. The basic configurations are provided in Figure 6, which shows that the ‘Synchronized Supply’ considers both inventory and planning collaboration.



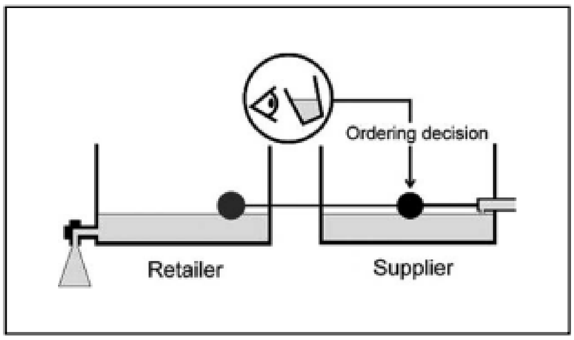


Figure 6: Supply Chain Configurations

Figure 7: Synchronized Supply

Holweg et al. (2005) describe that a synchronized supply “eliminates one decision point and merges the replenishment decision with the production and materials planning of the supplier” (see Figure 7). They also describe that in many cases companies exchange information, but not align their production planning process, which hinders a significant improvement of the supply chain performance. The goal of the thesis is to align order releases (replenishment decisions) with the upstream material availability, which corresponds to supply synchronization. So, it is important that not merely one or two collaboration activities are encouraged, but to alter replenishment and planning decision structures besides the exchange of information.

Achieving a fully synchronized supply is a complex task, but Holweg et al. (2005) mention some key factors that enable success: short geographical distances, stable demand patterns, long shelf life or selling period and high value products. The characteristics of the supply chain under consideration correspond to two of the key factors, namely the first and last one. The shelf life is relatively short due to rapid technological developments and downstream demand to the supply chain appears to be unstable, otherwise there would be no forecast inaccuracy.

It can be concluded that supply chain collaboration may result in reduced excess inventory and avoidance of the bullwhip effect, although it is crucial to align the collaboration practices to the individual settings that the supply chain has to deal with. Due to the mismatch of key factors, it is recommended not to focus on a fully synchronized supply, but on another dimension of supply chain collaboration. It is more reasonable to implement a collaborative planning model and/or a proper SCOP, which also should have a positive impact on the supply chain. This could be a first step into the direction of a synchronized supply.

3.2 Make-to-Forecast Production Environment

The MTF production strategy is typically applied in industries that manufacture very large and heavily engineered products with a significant degree of customization early in the production process (Meredith and Akinc, 2007). This corresponds to the industry that TFS and other high-tech OEM's are currently in. The reason to apply a MTF strategy is to "achieve customization while maintaining quick delivery to customers" (Akinc and Meredith, 2015). This strategy enables a customer delivery lead time that is substantially shorter than the production lead time. Production strategies can be mapped as a trade-off between 'delivery time' and 'degree of customization'. Akinc and Meredith (2015) present a conceptual model to illustrate this trade-off for the following strategies: Engineer-To-Order (ETO), MTO, MTF, Assemble-To-Order (ATO) and Make-To-Stock (MTS).

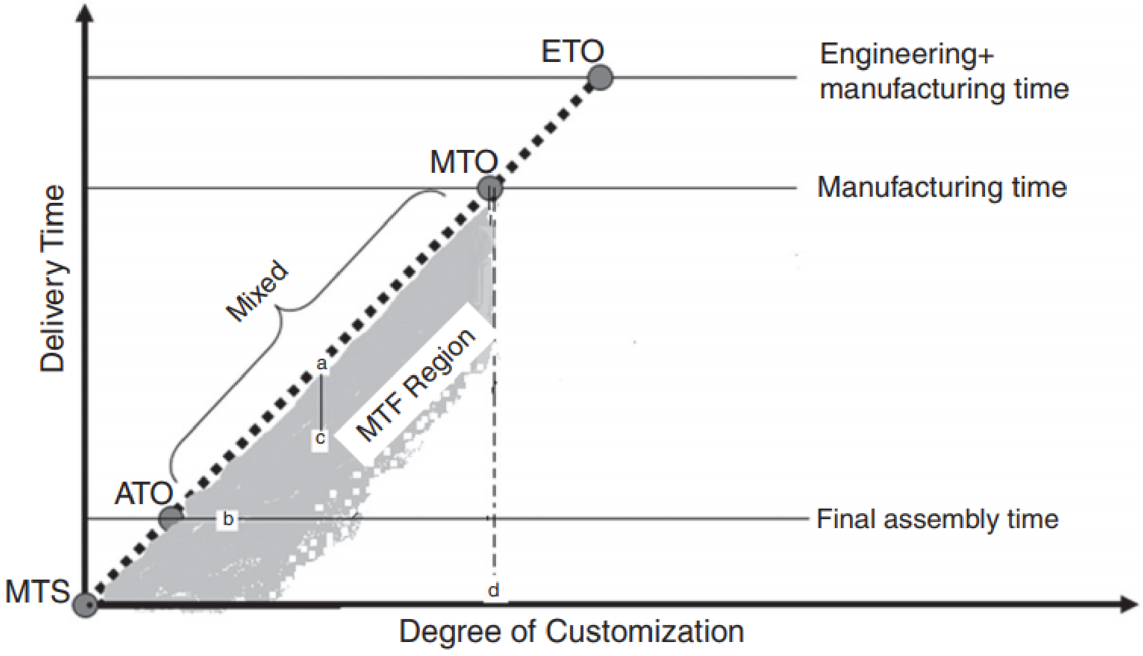


Figure 8: Trade-off between 'Delivery time' and ' Degree of Customization' for several production strategies

Meredith and Akinc (2007) describe the MTF strategy as a hybrid of the MTO and MTS production strategies. The effectiveness of such a strategy depends on the location of the Customer Order Decoupling Point (CODP) (Akinc and Meredith, 2015). A CODP located at the end of the production process enables some product variety while having a relatively short delivery time. The difference between the MTF and the ATO strategy, which is also a hybrid strategy of MTS and MTO, reveals itself that MTF allows both early and late customization, where ATO only allows limited customization by stocking end-stage components (Meredith and Akinc, 2007). A manufacturer starts production based on forecast, which conforms an MTS strategy, and then matches and modifies the partially completed units as actual orders arrive (MTO). Whether an order is matched to a unit early or late in the production process, depends on the variety of semi-finished units and the order description. In other words, a MTF strategy applies a ‘floating’ CODP, where ATO has a fixed CODP.

It is earlier mentioned that a manufacturer starts its production in the MTF environment based on a forecast. A complete BOM must be produced and scheduled prior to the time a unit is released into the production system. This production schedule is based on a forecast and demand uncertainty is unavoidable due to the high level of customization. Akinc and Meredith (2015) recognize this and define MPS as one of the day-to-day challenges within MTF. The challenge is to release a unit into production in a configuration which has the highest probability to be ordered. TFS currently releases units with configurations proportional to the historical demand, which is called the mixed release rule (Meredith and Akinc, 2007).

3.2.1 SCOP Problem in the MTF-environment

One of the deficiencies in the model of Meredith and Akinc (2007) is that the SCOP-problem is not accurately addressed. A part of this problem, how to release and configure orders in de MPS, is discussed by Akinc and Meredith (2015). However, they do not elaborate on order release decisions towards the supplier nor discuss material coordination in the supply chain. Especially these matters are highly relevant for the case of TFS and VDL ETG. The model of Meredith and Akinc (2007) assumes that configurations can be applied immediately after a customer order arrives, even if such a configuration differs from the initial release decision in the MPS.

Many of the VDL ETG items have significant production lead times, even up to 8 months, which means that TFS requires buffers to be able to respond quickly to changes in demand. On the other hand, such items have high values which results in high undesired holding costs. It is important to adapt the SCOP to the characteristics of the environment and consider several aspects as buffering, responsiveness and material/resource feasibilities. The model of Meredith and Akinc (2007) lacks a discussion about aggregate MRP, but could be a good starting point for more research.

3.3 Supply Chain Operations Planning

This section starts with a basic description about the SCOP and what should be included in the framework to ensure a proper material coordination flow. Then the MRP logic, which is currently used for the SCOP, and its deficiencies are further elaborated. The last sub-section describes the Synchronized Base Stock (SBS) policy, which is a suitable procedure to perform the SCOP.

De Kok and Fransoo (2003) describe the SCOP as a planning framework that ensures material and resource feasibility for released orders. The objective of the SCOP is to “coordinate the release of materials and resources in the supply network under consideration such that customer service constraints are met at minimal cost” (De Kok and Fransoo, 2003). The SCOP covers both medium-term and short-term planning, i.e. it translates medium-term planning decisions into short-term execution decisions. Wiers and De Kok (2018) state that the SCOP function coordinates the release of production orders to all the production units within the supply chain.

They mention three assumptions that have to be satisfied to ensure proper coordination:

1. Production unit guarantees (close-to) 100% lead time delivery reliability.
2. Resource availability is explicitly formulated as a constraint in the SCOP model
3. Material availability is explicitly formulated as a constraint in the SCOP model

Satisfying all constraints (assumption 2 and 3) enables the production units to perform close-to the 100% due date reliability (assumption 1), which is confirmed by De Kok et al. (2005) and a number of empirical studies (cf. De Kok, 2015). ERP systems are the most common planning and control concepts currently used in businesses. The MRP logic is incorporated in such systems and this logic can be seen as a method to perform the SCOP (De Kok and Fransoo, 2003). It is remarkable that MRP, even though it is widely accepted, does not satisfy assumptions 2 and 3. This results into the creation of infeasible plans (Wiers and De Kok, 2018). Hence, assumption 1 will neither be satisfied. Not satisfying the resource and material constraints results in a lower delivery reliability, which indicates the importance of a planning logic that incorporates the constraints and satisfies all assumptions.

TFS currently uses its ERP system to perform the SCOP, which means that the MRP logic incorporated in this system does not satisfy resource- and material constraints. This research mainly focusses on material availability constraints, specifically upstream at VDL ETG. The MRP logic does not consider whether purchase orders match relevant forecasts from the past or the current WIP at VDL ETG. The ERP system allows to create infeasible order releases that cannot be met, resulting in material unavailability at TFS. Therefore, TFS should apply one of the two suitable procedures mentioned by Boulaksil, Fransoo and Van Halm (2009).

One procedure is based on the multi-echelon stochastic inventory theory. However, it is proven by De Kok and Fransoo (2003) that pure base stock policies violate one of the feasibility constraints that they defined. Namely, the pure base stock policies allow an increase in backlog that can exceed exogenous demand. In this same paper, a modified base stock policy is proposed which does not violate any of the feasibility constraints. This planning system, initially proposed by De Kok and Visschers (1999), creates material-feasible order releases and is later termed as SBS policies (De Kok and Fransoo, 2003).

The alternative procedure is based on mathematical programming principles. These procedures mostly originate from MRP modelling, and Advanced Planning and Scheduling (APS) is currently one of the most prominent forms. Wiers and de Kok (2018) present how above constraints can be formulated in mathematical terms, possibly implemented in an APS. A rolling forecast is used to insert demand into the model, safety stocks are set as input parameters and the allocation of inventory quantities at the stock points is defined as a decision variable (Boulaksil et al., 2009). Later in this thesis it will be proven that the proposed CP model satisfies the mathematical material- and resource constraints of Wiers and De Kok (2018).

3.3.1 MRP logic

The logic of the MRP is based on: what, how much, and when material is needed? (Hopp and Spearman, 2000). The MRP-run is executed to get a detailed replenishment schedule that answers these three questions. Input for the MRP-run is an MPS which refers to the overall production plan for final products and this MPS is based on actual demand and/or forecasts. Other data that is required as input are the BOM, which holds information about what and how many components are needed to produce a final product, and the updated inventory records.

Wiers and De Kok (2018) summarize the planning functionality of the MRP logic as a 'material explosion' and 'lead time offsetting'. In the 'material explosion' the BOM is used to generate demand for components based on the demand for a final product. The 'lead time offsetting' refers to a fixed lead time, needed to produce an item from its components, which is used to determine the production or procurement date of components by offsetting the date that the item is needed.

The MRP logic is easy to understand and manage and the calculation time per MRP run is negligible, which makes it a very popular planning and control concept. However, several limitations are mentioned in the literature even after the MRP-II extension was introduced. Wiers and De Kok (2018) clarify three of the main deficiencies: Planning Resource and Material Availability, Allocation and Synchronization and Capacity Planning. Another deficiency is that the MRP logic does not provide assistance in determining the MPS (Shapiro, 2001).

Planning Resource and Material Availability

It is already explained that the MRP logic does not include resource- and material availability constraints to generate a SCOP solution. Consequently, it allows the function to create infeasible plans. Wiers and De Kok (2018) describe two types of infeasibilities created by the MRP; violations of resource- and material availability constraints. The first type concerns future violations that can be prevented by rescheduling activities, while the second type concerns detailed infeasibilities on immediate order releases. A resource constraint concerns a planned shortage within the lead time. The MRP notifies the planner with a message, who can manually check the possibilities to reschedule such that the planned shortage is resolved.

The second type of infeasibilities concerns the violation of material availability constraints. The highest level MPS assumes that such issues are resolved, while in practice it is not clear whether this is possible. The negative inventory on hand that is created by the MRP results in immediate, within lead-time, demand towards child items in the first-period. This immediate demand can most probably not be satisfied, which requires a reduction of the planned order releases to conform to the material availability constraint. Consequently, order releases of the parent items need to be adjusted, which possibly affects plans further downstream up and until the MPS. Resolving the infeasibilities requires manual plan modifications and extensive communication between the planner and shop floor, since all these actions need to be taken immediately (Wiers and De Kok, 2018). As mentioned in section 2.1.1, solving one violation mostly results in one or more other violations in the dependent orders and/or capacities. This deficiency has a major impact in a production environment with complex BOM structures, such as the one at TFS.

Capacity Planning

Resource constraints are not considered in the original MRP, hence a MRP-II extension was introduced which included capacity checks, aggregate planning functions and short-term scheduling together with some closed loop feedback mechanisms (Wight, 1981). Wiers and De Kok (2018) mention in their research that the addition of Capacity Requirements Planning or Rough-Cut Capacity Planning to the MRP-I gives the impression that capacity planning is incorporated in the MRP-II. It is explained that this is true to some extent, hence the techniques visualize and detect potential capacity problems. However, the techniques neither resolve nor give support to resolve the problems. In other words, the MRP-II extension identifies and notifies the user about capacity issues based on the material requirements, but infeasibilities can still be created and are not solved by the framework. From the fact that capacity issues are not resolved, it can be concluded that the MRP-II framework merely includes capacity checks rather than capacity planning (Wiers and De Kok, 2018).

Allocation and Synchronization

The allocation and synchronization issues that MRP creates are discussed by Wiers and De Kok (2018) by illustrating a stylized case. This case is not illustrated in this literature review, but the results are discussed briefly. Suppose that in a certain week the net demand for the final product is higher than expected, which results in negative inventories for the child items. The MRP recognizes and notifies the user about infeasibilities, but does not automatically reschedule the planned production orders. The additional gross requirements are scheduled to be received as soon as possible, while lead times differ per child. One child item will arrive too early and result in excess inventory, which shows that the MRP logic not synchronizes item order releases for the same parent.

The same case is used to illustrate the fact that MRP does not allocate child items. Suppose now the situation that a certain child item is used in more than one parent, and the net requirements for these parents exceed forecasted demand and result in a shortage for the child. This implies that material availability must be allocated among these parent items. However, this is not included in the MRP logic, neither is solving the issue.

Assistance

Whether the MRP run results in feasible order releases depends considerably on its input, which is normally the MPS. One of the deficiencies of the MRP is that it not provides any assistance to the user in determining a (sub-)optimal MPS. No support is provided to minimize cost, achieve feasibility or help adjusting production capacities to meet goals (Shapiro, 2001).

3.3.2 Synchronized Base Stock Policies

This planning concept is described by De Kok and Visschers (1999) as a decomposition method for general assembly systems. Such a system is firstly decomposed into divergent multi-echelon systems. De Kok and Visschers (1999) show how the order-up-to levels can be calculated for these divergent systems, based on a fill rate constraint that needs to be defined. These order-up-to-levels, for which it is stated that they are near-optimal, can then be applied in the original assembly system. The SBS policy pre-allocates common components of these assembly systems to (sets of) final products.

De Kok and Fransoo (2003) term the pre-allocation policies of the De Kok and Visschers (1999) as SBS policies, and use this concept to perform the SCOP. It is explained that in contrast to pure base stock policies, SBS policies can be found to satisfy any set of customer service level constraints. Furthermore, simulation results show that the SBS concept outperforms an alternative linear programming concept. The superiority seems to increase for more complicated product structures, such as the microscopes at TFS. Furthermore, it is mentioned that SBS policies can be applied on large assembly systems, which is again true for systems at TFS. On the other hand, it is emphasized that the SBS policies are not cost-optimal, and that in certain situations the pure base stock policies can outperform the SBS policies. The latter issue is probably caused by allocating common components too early (De Kok and Fransoo, 2003).

Another study conducted by De Kok (2015) highlights the applicability of the SBS policies as the planning procedure for the forecast-driven part of a supply chain, which corresponds to the supply chain of TFS and VDL ETG. Applying this concept ensures material feasible order releases, so that only process uncertainty must be accounted for when setting the item-dependent planned lead times. This paper of De Kok (2015) refers to some empirical studies, such as master theses performed at the TU/e, to show that the SBS policies explain the empirically measured performance in a wide range of different multi-item multi-echelon systems.

3.4 Collaborative Planning in the Philips Case

The SBS policy is used to develop a CP tool to successfully support weekly planning of operations at Philips Electronics (De Kok et al., 2005). This sub-chapter describes the rationales to create the CP tool, summarizes the planning logic behind the tool and subsequently elaborates on the results.

3.4.1 Rationales and Problem Definition

Organizations like Philips Electronics, which have short product life cycles, long lead times and high-volume production, have problems coordinating their supply chain. TFS also must deal with short product life cycles and even longer lead times, but operates in a low-volume instead of high-volume environment. The project was initiated, because Philips and its supply chain experienced significant bullwhip effects. Negative implications of this effect are already explained in section 3.1.2.

The main problem in this Philips case is defined to be a SCOP problem. The problem is described as a missing link between the short-term execution cycle and the medium-term capacity planning. In the original planning process, the short-term planning was decentralized and disconnected from the medium-term planning. These independent processes caused both information latency and distortion. Consequently, involved companies tried to safeguard against uncertainty by creating stocks, while remaining the risk of obsolescence in the process. Despite the safety stocks, delivery reliability was still unsatisfactory.

The goal of the project was to reduce the bullwhip effect through an innovative planning concept and a supporting software system, expressing itself in a CP tool. The CP tool aimed to synchronize the short-term execution with the medium-term capacity planning. Ultimately, such an integrated supply chain planning and control concept resulted in reduced inventory and increased customer-service levels. These characteristics correspond to the current research which indicates that the Philips project is closely related to this research.

3.4.2 Planning Logic and the Collaborative Planning Process

It is already mentioned that the CP tool adopted the planning logic of SBS policies. The basic idea of these policies is explained in the previous sub-chapter. The planning logic is adapted to the specific dynamics of the case study. The tool combined three different types of input: sales plans based on new market information, WIP and stock data from various ERP systems and planned lead times of work orders. Furthermore, safety lead times were incorporated to capture the stochastic behavior of the system. These lead times were set by planners based on experience.

The tool enables a weekly CP process, which links monthly capacity agreements, weekly production-planning activities and daily operational execution. The process consists of four stages: Gather data, Decide, Escalate and Deploy. The critical outcomes of the process are related to the number of products to fabricate, test and ship. Liability agreements were established to adhere to these outcomes.

3.4.3 Results of the Project

The new planning process supported by the collaborative tool resulted in the desired effects. The project resulted in three significant improvements: reduced information lead time, greater visibility based on accurate information and enabled decision making based on facts. With these improvements the CP process enabled Philips to: “quickly address and intelligently resolve complex material-coordination issues, reveal and capture profitable opportunities, and build trustful relations between independent partners in a supply chain”. These improvements show that the negative implications of the bullwhip effect are solved with the new collaborative process.

The results of the Philips case are strongly related to the proposed deliverables discussed in section 2.4.3. The current study should result in a proposed planning procedure supported by a CP tool which creates a material feasible order release plan and provides insight in future shortages. The intended effects are similar to the results accomplished in the Philips case: reduce information lead time, create a greater visibility based on accurate information and enable informed decision making based on facts. This should ultimately increase material availability.

3.4.4 Dissimilarities between Philips and TFS/VDL ETG case

In section 3.1.3 it is mentioned that the SBS policy pre-allocates common components of general assembly systems to (sets of) final products. Most of the VDL ETG items are consumed in modules, which are sub-assemblies of the final products. These modules are generic per system family and they are on the critical path of the production planning. To increase flexibility in production planning and allocation, TFS has decided to produce these modules via a supermarket principle (Kanban). To support the applicability of the eventual CP model, it is chosen to consider this specific planning characteristic.

The production of these modules is manually planned for three months ahead, based on the work orders in the ‘supermarket’, available capacity and inventory levels. Modules are produced ‘anonymously’, which means that the production planning of a module is not one-on-one linked to the production of a final product. As a result, VDL ETG items are neither directly linked to final products, hence it is impossible to pre-allocate these items. This indicates that the model that is applied in the Philips case cannot be identically copied and used for this project.

It should be noted that the CP model in the Philips case only performs material, and not resource, feasibility checks. This model will perform well with ample capacity, because order release quantities will not be rejected due to limited resources. However, as already mentioned in section 2.1.1, limited capacity is a relevant issue at VDL ETG. Consequently, the model in the Philips case should be extended and resource constraints need to be incorporated. These constraints are based on the mathematical resource constraints of Wiers and De Kok (2018).

3.5 Contribution to Current Scientific Literature

Although the literature indicates the SBS policy is most suitable, it should be noted that very little studies are present in which a SBS policy is actually applied to perform the SCOP and/or synchronize supply. The CP tool in the case of De Kok (2005) is based on the SBS policies. It is neither argued why this procedure is chosen, nor which factors indicate a good environment for such policies. The environment in this case study differs by several aspects from the current master thesis: high-volume/low-volume; cumulative lead times of VDL ETG items are significantly longer than the considered lead times at Philips; decoupled production planning of modules; and lead time uncertainty (especially in the production process of TFS). These are indications that implementation of the existing CP tool not automatically results in positive effects.

To conclude the chapter, this research is positioned against the observed literature to identify one or several gaps. Such gaps automatically indicate the contribution to the current literature. This work aims to (partly) fill these gaps and contribute to:

- The field of SCOP in a MTF environment
- Collaborative planning in a MTF environment
- Case studies which implement an SBS-policy, or any variants of this modified base stock policy.

4 Mathematical Model

The mathematical CP model is fully designed and formulated in this chapter. It is concluded from the literature study that the CP model from the Philips case of De Kok et al. (2005) is a good starting point for the CP model in this research. However, the model should be adapted to deal with the dissimilarities mentioned in the section 3.4.4. Section 4.1 describes how these dissimilarities are resolved and elaborates on the structure of the mathematical CP model. The mathematical CP model will consist of two different stages and these stages are discussed section 4.2 and 4.3 respectively. The last section of this chapter proves that the order release calculation procedure satisfies the material- and resource constraint of Wiers and De Kok (2018).

4.1 Structure of the Mathematical CP model

To deal with the pre-allocation issue of modules to end-items it is chosen to design the CP model as two consecutive parts. The first stage is applied for a single echelon and VDL ETG items are considered as final products. This model compares the stock levels and WIP at VDL ETG with the planned deliveries in the ERP of TFS. These planned deliveries are considered to be exogeneous demand. In other words, it is checked whether sufficient material will be available at VDL ETG to meet the demand of TFS. The goal of this stage is mainly twofold, whereby the first goal is to generate a feasible order release plan. The model from the Philips case (section 3.4) is adapted to this single echelon case and already performs material feasibility checks. Section 4.2.1 fits the first stage of the CP model to the rolling schedule concept. Subsequently, several resource constraints are discussed to solve the issue of limited capacity at VDL ETG. These resource constraints are formulated to prevent the CP model from generating an order release plan that requires more capacity than available. When the required capacity exceeds the available capacity of a certain resource, some items need to be rejected. Section 4.2.3 describes an appropriate allocation procedure.

The first stage of the CP model applies a standard base-stock policy to calculate the order release quantities. These quantities are based on the latest sales information and the inventory position at VDL ETG. TFS currently considers switching to a move rate policy instead of merely calculating the order release quantities based on the most recent forecasts. To do so, the first stage is extended with an alternative decision rule in section 4.2.4. This alternative rule is defined with the objective to increase production stability and possibly improve delivery performance. This decision rule allows an order release of the expected average demand per time period, the move rate, even though the inventory position covers the lead time demand. This rule allows to create infinite capacity, hence a constraint is added. The second goal of the first stage is to indicate (future) backlogs at VDL ETG, which implicates a late delivery at TFS. Whether such a late delivery results in material unavailability at TFS cannot be determined in this stage, because all successors of VDL ETG items are left out of consideration.

To indicate the impact of late deliveries on the production process at TFS, it is required to compare the deliveries with the planned production and stock levels of the concerning successor(s). The second stage of the CP model describes a value network with the VDL ETG items, now considered as child items, and their immediate successor(s) at TFS. The output of the first stage is used to determine the expected shipment dates for each planned delivery at TFS. The second stage of the CP model is described in section 4.3.1 and performs two state-updating procedures. The first procedure compares the shipments with the stock levels and the planned consumption of VDL ETG items. This comparison indicates whether a late delivery will result in material unavailability at TFS. If no material shortages are expected, then it is desired to align the planned deliveries with the shipments.

The first comparison of the second stage could also indicate actual future shortages at TFS. In section 4.3.2 another state-updating procedure is performed to indicate whether such future shortages could be avoided with the inventory levels at VDL ETG. It is checked whether sufficient material would be available at TFS when all finished products would immediately be shipped, independent of demand orders. If so, the planned deliveries should be aligned with the scheduled receipts at VDL ETG. Otherwise, it should be assessed whether the scheduled receipt at VDL ETG should be advanced. Advancing the due date of a scheduled receipt within the lead time of an item is defined to be an escalation. A disadvantage of this CP model is that it does not show the impact of material shortages on subsequent parent items. Planners at TFS should manually check whether a material shortage also impacts higher levels of this item.

The planning logic of the CP model does not involve an optimization procedure, but a calculation procedure. De Kok et al. (2005) explain that the planning logic originates from stochastic multi-echelon inventory theory, which focuses on optimizing planning parameters to cope with uncertainty in demand, lead times, and yields. The calculation of the order release decisions is relatively straightforward once planning parameters are set. In this case, the parameters correspond to the MRP control parameters that are mentioned in section 1.2.2 and the decision variables included in the mathematical model.

4.2 First Stage of the CP Model

The value network can be described by means of the sets and relationships defined in the List of Symbols. It is explained in section 4.1 that the CP model of the Philips case is used as starting point and adapted to a single echelon case. In the first stage all VDL ETG items are therefore temporary treated as final products, so $M = N$. This means that the set of immediate successors and predecessors is empty for each item, cumulative lead times are not considered and the echelon inventory position equals the local inventory position of an item. The objective of the first stage of the CP model is to determine work order release quantities which are material- and resource feasible. Material constraints are already present in the adapted model of the Philips case, while resource constraints are defined in section 4.2.2. Here is a table with the most relevant variables for this section:

Table 1: Most Relevant Variables in the CP Model

Variable	**Description**
$WO_i(t)$	Work order release quantity of item i at the start of period t
$IP_i(t)$	Inventory position of item i at the start of period t
$I_i(t)$	Net stock of item i at the start of period t
$SR_i(t)$	Scheduled receipt of item i planned to arrive at the start of period t
$D_i(t)$	Demand for end item i in period t (equal to the planned supplies at TFS)
$S_i(t)$	Target base stock level of item i at the start of period t
$SS_i(t)$	Safety stock of item i at the start of period t

There are no lot-sizing restrictions for released quantities and the inventory position is defined as:

$$\boldsymbol{IP_i(t) = I_i(t) + \sum_{s=0}^{LT_i-1} SR_i(t+s)} \qquad \boldsymbol{i \in M} \qquad \boldsymbol{t \geq 1} \qquad \boldsymbol{A.1}$$

It is assumed that demand which is not satisfied from stock is backlogged. The exogenous input to determine the initial state of the system, which corresponds to the start of period 1, is described as:

$$SR_i(t) \qquad i \in M \qquad t = 1, \dots, LT_i - 1$$

$$D_i(t) \qquad i \in M \qquad t = 1, \dots, T_i$$

$$I_i(t) \qquad i \in M \qquad t = 1$$

The planning horizon T_i should be long enough to accommodate all immediate planning decisions. This implies that the horizon should at least be equal to the production lead time LT_i plus one period. Increasing the planning horizon results in planned order release decisions, which can provide insight in possible future item shortages and overages. These insights are relevant in environments with short product life cycles and high volatility in demand and supply (De Kok et al., 2005).

$$T_i \geq LT_i + 1 \qquad i \in M$$

In what follows, (planned) events occur in the following order:

1. Facilities receive scheduled or planned items immediately at the start of a period t.
2. Work orders are released for each item immediately after this.
3. Customer-demand and internal work orders are fulfilled just before the end of the period t.

It is first explained how to calculate the $WO_i(t)$, where after the state-updating procedure is defined. The first step to calculate the $WO_i(t)$ is to determine the target base stock levels S_i. These base stock levels indicate the cumulative stock that is required to cover demand during the production lead time LT_i plus 1 period t. A safety stock SS_i can be included to cover uncertainty in demand.

$$S_i(t) = \sum_{s=0}^{LT_i} D_i(t+s) + SS_i(t) \qquad i \in M \qquad t \geq 1 \qquad A.2$$

One possibility to define the safety stock is to calculate demand during the safety lead time ST_i. Safety lead times are applied to capture the system's stochastic behavior, implying the uncertainty with respect to future sales, actual lead times, and yields of work orders.

$$SS_i(t) = \sum_{s=LT_i+1}^{LT_i+ST_i} D_i(t+s) \qquad i \in M \qquad t \geq 1 \qquad A.3$$

Another possibility to define the $SS_i(t)$ as a certain percentage ρ of the lead time demand. This last possibility will be applied in Chapter 5 and 6.

$$SS_i(t) = \rho * \sum_{s=0}^{LT_i} D_i(t+s) \qquad i \in M \qquad t \geq 1 \qquad A.3'$$

$$\boldsymbol{S_i(t) = \left\lceil (1 + \rho_i) * \sum_{s=0}^{LT_i} D_i(t+s) \right\rceil} \qquad \boldsymbol{i \in M} \qquad \boldsymbol{t \geq 1} \qquad \boldsymbol{A.2'}$$

No availability or allocation issues are present because child- and parent items are not yet considered and backorders are allowed. The released order quantity equals the target base stock level minus the inventory position of item i.

$$\boldsymbol{WO_i(t) = (S_i(t) - IP_i(t))^+} \qquad \boldsymbol{i \in M} \qquad \boldsymbol{t \geq 1} \qquad \boldsymbol{A.4}$$

The order release decision initiates the state-updating procedure. The state of the network is updated by 'executing' the order release decision, assuming that scheduled receipts arrive according to their planned lead times and assuming that demand realizations equal demand forecasts. The following steps are applied till the end of the planning horizon. An order release quantity in period t equals a scheduled receipt in $t + LT_i$. The state-updating procedure calculates all net inventories for the complete planning horizon of an item. These net inventories may indicate a backlog at VDL ETG and a corresponding late delivery for TFS. The second run of the CP model should indicate whether these backlogs will have an impact on the work orders at TFS.

$$\boldsymbol{SR_i(t + LT_i) = WO_i(t)} \qquad \boldsymbol{i \in M} \qquad \boldsymbol{t \geq 1} \qquad \boldsymbol{A.5}$$

$$\boldsymbol{I_i(t + 1) = I_i(t) - D_i(t) + SR_i(t)} \qquad \boldsymbol{i \in M} \qquad \boldsymbol{t \geq 1} \qquad \boldsymbol{A.6}$$

The following example is introduced to further explain and visualize the planning procedure. This example is based on the planning- and order fulfillment processes in section 1.2. The planning procedure is performed each month and demand D_i is divided into purchase orders PU_i with a delivery lead time DLT_i, and forecasted demand FC_i. Furthermore, the lead time LT_i is assumed to be 8 months. Only immediate order release decisions are relevant, thus the planning horizon $T_i = LT_i + 1 = 9$. The first planning cycle, $W = 1$, starts at the beginning of January 2018. The net stock at the start of the first planning cycle is assumed to be zero and no safety stock is included.

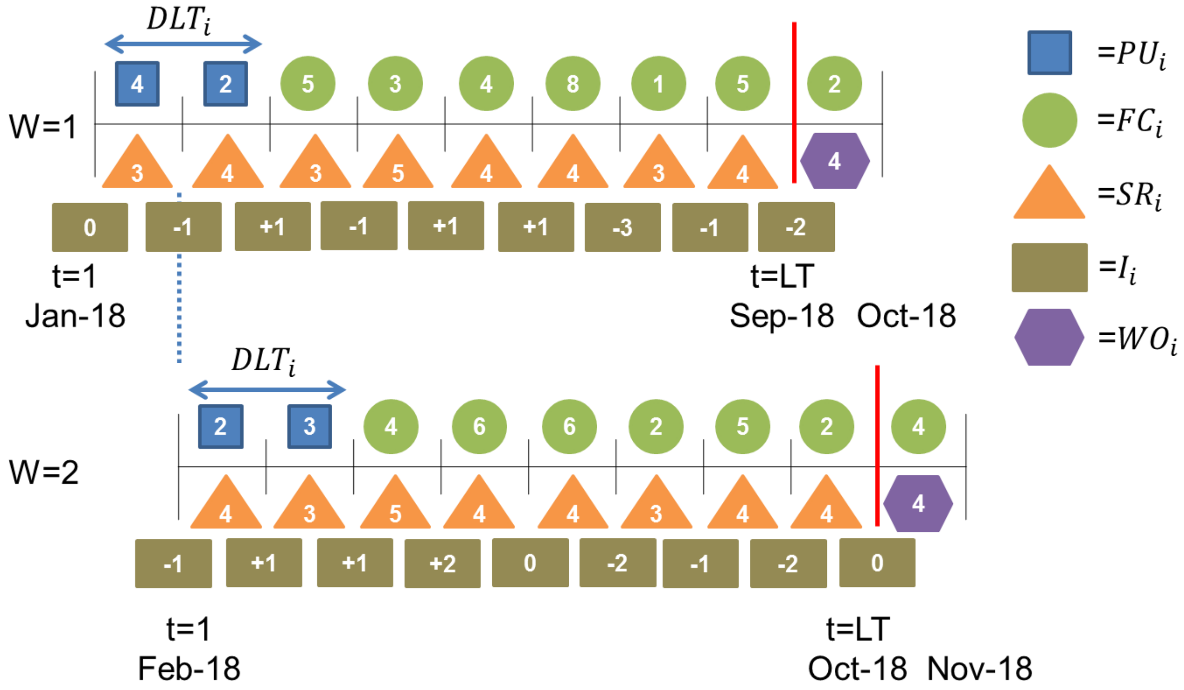


Figure 9: Basic example of a planning cycle

The order release decision for the first planning cycle is calculated with equations $A.1$, $A.2'$ and $A.4$.

$$IP_i(1) = I_i(1) + \textstyle\sum_{s=0}^{8-1} SR_i(1 + s) = 30$$
$$S_i(1) = \left\lceil (1 + 0) * \textstyle\sum_{s=0}^{8} D_i(1 + s) \right\rceil = 34$$
$$WO_i(1) = \left(S_i(1) - IP_i(1)\right)^{+} = (34 - 30)^{+} = 4$$

Applying the state-updating procedure results in the following scheduled receipt and net inventory:

$SR_i(9) = WO_i(1) = 4$
$I_i(2) = I_i(1) - PU_i(1) + SR_i(1) \rightarrow I_i(2) = 0 - 4 + 3 = -1$

The state-updating procedure is repeated to calculate all net inventories for the complete planning horizon of an item. These net inventories are already incorporated in Figure 9 and indicate expected backlogs at the start of February, April, July, August and September. Adding a safety stock percentage, for example $\rho_i = 0.2$, on top of the target base stock level would result in different order release quantities. However, the calculations and state-updating procedure remain identical. The order release quantity for this example would immediately increase due to the safety stock:

$S_i(1) = \left\lceil (1 + 0.2) * \sum_{s=0}^{140} D_i(1 + s) \right\rceil = \lceil (1 + 0.2) * (34) \rceil = 41$
$WO_i(1) = \left(S_i(1) - IP_i(1)\right)^+ = (41 - 30)^+ = 11$

4.2.1 Rolling Schedule Concept

In the initial model it is assumed that all scheduled receipts arrive immediately at the start of a month, subsequently the order release quantity is determined and demand is fulfilled just before the end of the period. These are unrealistic assumptions in this specific case, hence both scheduled receipts and demand are planned on specific dates while the status is currently reviewed each month. Consequently, not only the immediate order release decision is relevant, but order release quantities need to be determined for each day of the concerning month.

The above procedure remains the same, but in the example each period t now equals 1 day instead of 1 month and the state-updating procedure needs to be performed so that all order release quantities are calculated for the complete month. As a result, the current situation can be modeled as a rolling schedule-based SCOP function. Jansen (2012) further explains the rolling schedule concept with Figure 10. Note that the R in Figure 10 corresponds to WO_i in the model.

In a rolling schedule-based SCOP function it is assumed that there is time-dependent information over a finite amount of time in the future (Jansen, 2012). This is a periodic review policy in which the status of the system is observed at the start of each review cycle. The interval over which information is available is called the planning horizon. As mentioned earlier, the planning horizon should be long enough to accommodate all immediate planning decisions. Order release decisions are made for the complete review cycle by following the state-updating procedure. Therefore, the length of the review cycle R should be incorporated into the planning horizon, which results in:

$$T_i \geq LT_i + R \qquad i \in M$$

Each review cycle starts with gathering information about the current status of the WIP and stock points together with the newest sales information, in this case the planned deliveries in the ERP of TFS. With this information as input, the CP model generates an order release plan for the complete cycle. All order release decisions are taken at the start of the cycle. Subsequently, all operations are executed and during this review period no interaction takes place between the SCOP and the production unit. At the beginning of the next review cycle, the system is observed again, sales information is updated, and a new order release plan is generated. Consider again the planning cycle with $t = 1$ at the first day of January 2018. For this review moment the R equals 31 days and all $WO_i(t)$ for at least $t = 1, \dots, 31$ need to be determined.

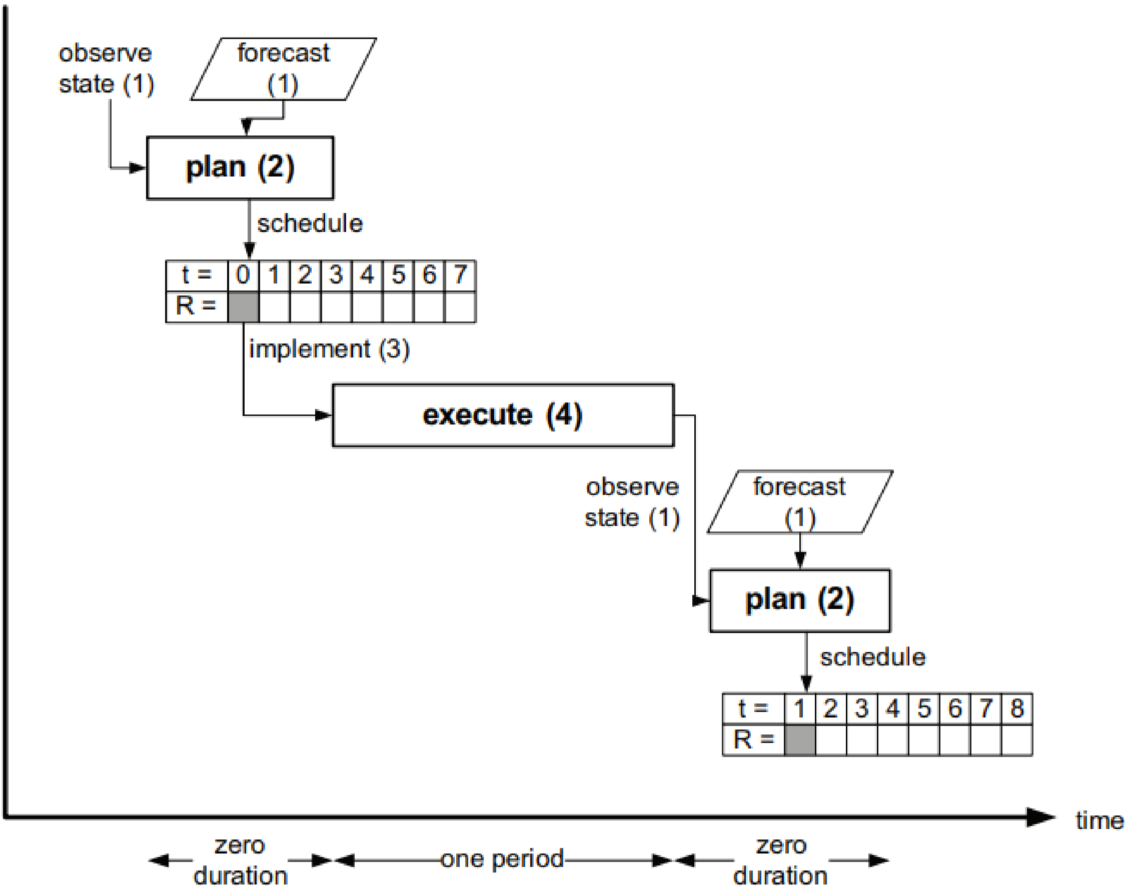


Figure 10: Rolling Schedule Concept

4.2.2 Resource constraints

To have a better projection of the reality and to prevent order release quantities that require more capacity than available at VDL ETG, it is inevitable to add resource constraints to the CP model. The following set of constraints is based on the mathematical resource constraints defined by Wiers and De Kok (2018). The second assumption to ensure a proper SCOP (section 3.3) is automatically satisfied when these constraints are included in the CP model. The first two constraints are related to the cumulative processed- and cumulative released amounts. Subsequently, several options are defined for a third constraint, which compares the required (cumulative) capacity with the available (cumulative) capacity. The first option is the easiest to implement, although this option most likely results in unjustified rejections. Each of the subsequent options get closer to reality, but also increases in complexity. Consequently, these options are more complicated to implement.

The first constraint compares both the processed (q_i) and released (WO_i) cumulative amounts for a time window up to and including period t. It states that the cumulative processed amounts can never exceed the released amounts, which indicates that material always has to be released before it can be processed.

$$\sum_{s=1}^{t} WO_i(s) \geq \sum_{s=1}^{t} q_i(s) \qquad B.1$$

It is assumed that the system is empty at the start of the first period, meaning that no orders are released before time 1 and stocks are zero. Resources must be available to ensure that an order released in period t will be completed in period $t + LT_i$. The following constraints comprises this statement.

$$\sum_{s=1}^{t} WO_i(s) \leq \sum_{s=1}^{t+LT_i-1} q_i(s) \qquad B.2$$

Each of the constraints $B.3.1 - B.3.4$ compares the required capacity of released orders with the available capacity of the resource. The first option assumes that each item is processed on 1 resource only, and each resource only processes 1 item. It is also assumed that both the available capacity per resource k (C_k), and the time required to process one unit of item i (c_i), remain constant over time. Thus, both variables are independent of t. The constraint states that the capacity requirements for released orders per period t must be less than the nominal capacity of the resource per period. This constraint implicates that for each item an upper limit can be determined for the order release quantity per period.

$$c_i * WO_i(t) \leq C_k \rightarrow WO_i(t) \leq \frac{C_k}{c_i} \qquad k = 1, \dots, K \qquad t \geq 1 \qquad B.3.1$$

Most of the machines at VDL ETG process more than one item, which means that this first constraint is too restricted and results in many unnecessary infeasibilities. This is clarified with the following example. Take a certain resource k with a total available capacity per period equal to 60 hours, and this resource processes two different items with the same demand rate and with the same required process time per item of 1 hour. To comply with above constraint and the assumption that each resource only processes one item, it is required to model the resource as two different resources. The resource is split into two resources with an equal available capacity of 30. Assume that the unconstrained order release quantity equals 40 for item 1 and 20 for item 2. Applying constraint $B.3.1$ will result in final order release quantities of 30 and 20 respectively. Therefore, only 50 of the 60 available hours are utilized and 10 items are unnecessarily rejected. The assumption that each resource can only process 1 item is now relaxed to prevent such situations from happening. The variable U_k equals the set of items that can be processed on resource k and the resource constraint is now defined as:

$$\sum_{i \in U_k} c_i * WO_i(t) \leq C_k \qquad k = 1, \dots, K \qquad t \geq 1 \qquad B.3.2$$

This constraint shows that the total capacity requirements for all relevant released orders in period t should not exceed the available capacity of the resource per period. However, this constraint may still lead to other avoidable rejections of work orders. Jansen (2012) explains in his paper the benefit of modelling capacity over a planned lead time of multiple periods. Selecting longer planned lead times allows to achieve a higher throughput on a resource, which indicates that the resource is used more efficiently (Selcuk, 2007). Wiers and De Kok (2018) also consider planned lead times and they explain that this concept is a method to create certainty about future material availability. Their SCOP constraints are formulated to reflect on the ideas behind the planned lead time concept. They implicate that a resource can be utilized at any moment during the lead time of an item, which provides maximum flexibility within the decision space. The cumulative available capacity over $[1, t + LT_i - 1]$ should exceed the cumulative required capacity of released orders over $[1, t]$:

$$\sum_{s=1}^{t} \sum_{i \in U_k} c_i * WO_i(s) \leq \sum_{s=1}^{t+LT_i-1} C_{ks} \qquad k = 1, \dots, K \qquad t \geq 1 \qquad B.3.3$$

It should be noted that most of the VDL ETG items have a long lead time in which several production steps are performed in a fixed sequence. Even though a considerable part of the lead time consists of waiting times, this fixed sequence of multiple resources reduces the flexibility within the decision space. Resource constraint $B.3.3$ should be adapted to deal with this reduced flexibility. The critical step in the production process regarding resource constraints is the bottleneck resource. In each period the throughput rate at this resource should be less than C_k. However, some flexibility may be possible in the processes before this bottleneck resource due to waiting times and less utilized resources.

Assume that in period t the required capacity for released orders is less than C_k. The flexibility parameter allows to release orders that exceed the capacity of C_k in the subsequent period(s). The cumulative available capacity is defined as the available capacity per period times a flexibility parameter F_k, which indicates the integer number of periods for which it is possible to up- or downscale order release quantities. This fourth alternative most accurately describes the current situation at VDL ETG and is therefore preferred to include in the CP model. Contrarily, it is more complex to implement this option. Furthermore, abundant and reliable information about both the available capacity of resources and the required capacity to process items must be present. Note that constraint $B.3.4$ is equal to $B.3.2$ if $F_k = 0$.

$$\sum_{s=t-F_k}^{t} \sum_{i \in U_k} c_i * WO_i(s) \leq C_k * (F_k + 1) \qquad k = 1, \ldots, K \qquad t \geq 1 \qquad B.3.4$$

4.2.3 Allocation Procedure

It is explained in section 4.1 that the CP model already performs material feasibility checks. Consequently, all calculated order release quantities are material feasible, hence no allocation procedure is required for this part. The resource feasibility checks are performed after the work order release decisions are made. The (cumulative) required capacity should be less than the (cumulative) available capacity, otherwise an allocation procedure needs to be performed to determine the new order release quantities $WO_i^*(t)$. This section describes an allocation procedure to develop a material- and resource feasible order release plan. The formula for the capacity shortage is based on the preferred resource constraint $B.3.4$ and is defined as:

$$SH_k(t) = \left(C_k * (F_k + 1) - \sum_{s=t-F_k}^{t} \sum_{i \in U_k} c_i * WO_i(s)\right)^+ \qquad k = 1, \ldots, K \qquad t \geq 1 \qquad C.1$$

If there is a shortage in capacity, the order release quantities are allocated based on the inventory position of the concerning items. Since the goal of the CP model is to increase material availability, it is chosen to reject 1 product of the item with the highest expected net inventory after the lead time. This decision rule is repeated via a state-updating procedure till the shortage is zero. The state-updating procedure is defined as follows:

$$While\ SH_k(t) > 0 \qquad k = 1, \ldots, K \qquad t \geq 1$$

$$arg \max_i I_i(t + LT) = j \qquad i \in U_k \qquad t \geq 1 \qquad C.2$$

$$WO_j^*(t) = WO_j(t) - 1 \qquad j \in U_k \qquad t \geq 1 \qquad C.3$$

$$SR_j(t + LT_i) = WO_j^*(t) \qquad j \in U_k \qquad t \geq 1 \qquad C.4$$

$$I_j(t + LT) = I_j(t + LT) - 1 \qquad j \in U_k \qquad t \geq 1 \qquad C.5$$

This allocation procedure aims to minimize the total number of backorders and implies that the impact of a backorder is equal for all items. Another allocation procedure that could be applied is the Consistent Appropriate Share (CAS)-rationing policy. Van der Heijden, Diks and De Kok (1997) state that this policy performs well for general multi-echelon distribution systems with (R,S) order-up-to-policies. Such systems are comparable to the one discussed in this research. The CAS-rationing policy allocates the shortage of an item i according to the cumulative safety stocks of all immediate successor items. This policy is also applied in the Philips case of De Kok et al. (2005).

4.2.4 Move Rate Policy

It is mentioned in section 4.1 that TFS considers switching to a move rate policy. Implementing this move rate policy extends the order release decision rule from the first stage of the CP model, while the state-updating procedure and other calculations remain unchanged. The expected move rate $EMR_i(t)$ of an item is equal to the expected average demand per period t given a certain time interval of M periods ahead:

$$EMR_i(t) = \left\lceil \frac{\sum_{s=0}^{M-1} D_i(t+s)}{M} \right\rceil \qquad i \in M \qquad t \geq 1 \qquad A.7$$

The unconstrained order release quantity $UWO_i(t)$ is defined as follows:

$$UWO_i(t) = \max(EMR_i(t), (S_i(t) - IP_i(t))^+) \qquad i \in M \qquad t \geq 1 \qquad A.8$$

A constraint is added to prevent the accumulation of excess stock. The move rate will only be released when the inventory position minus the target base stock level of an item i is below a certain threshold. This threshold can be defined as the $EMR_i(t)$ times a positive integer number Z. This results in the following constraint:

$$IP_i(t) - S_i(t) \leq EMR_i * Z \qquad i \in M \qquad t \geq 1 \qquad A.9$$

Three different situations can be distinguished with this rule:

(1) $UWO_i(t) = (S_i(t) - IP_i(t))^+ \rightarrow WO_i(t) = UWO_i(t)$
(2) $UWO_i(t) = EMR_i(t)\ and\ IP_i(t) - S_i(t) \leq EMR_i * Z \rightarrow WO_i(t) = UWO_i(t)$
(3) $UWO_i(t) = EMR_i(t)\ and\ IP_i(t) - S_i(t) > EMR_i * Z$
This means that the constraint does not hold.
The quantity of the inequality $Q_i(t)$ is calculated and used to determine the $WO_i(t)$.
$Q_i(t) = IP_i(t) - S_i(t) - EMR_i * Z \rightarrow WO_i(t) = (UWO_i(t) - Q_i(t))^+$

Referring to the example of Figure 9, the expected move rate and unconstrained order release quantity can be determined for the first planning cycle at $t = 1$ with $M = 4$ and $Z = 2$.

$$EMR_i(1) = \left\lceil \frac{\sum_{s=0}^{4*1-1} D_i(1+s)}{4} \right\rceil = \left\lceil \frac{4+2+5+3}{4} \right\rceil = 4$$

$$UWO_i(1) = \max\left(EMR_i(t), (S_i(t) - IP_i(t))^+\right) = \max(4,4) = 4$$

Both situation (1) and (2) can be applied. The first situation immediately results in $WO_i(1) = 4$.

For the second situation it is proven that the constraint holds:

$$IP_i(t) - S_i(t) \leq EMR_i * Z \rightarrow 30 - 34 \leq 4 * 2$$

$$WO_i(1) = UWO_i(1) = 4$$

Applying this policy should result in a more stable production schedule and increase material availability. On the other hand, holding costs may significantly increase when a move rate quantity is produced while the eventual demand is less than forecasted.

4.3 Second Stage of the CP model

The second stage of the CP model considers a value network of the VDL ETG items and all their immediate successor items at TFS. All order release decisions for the complete review cycle are determined in the first stage, which means that all scheduled receipts are known for the lead time of an item plus a review cycle length. Furthermore, the first stage indicates future backlogs at VDL ETG, although it is unknown whether these backlogs truly delay production work orders at TFS. The output of this first stage is used as input for the second stage. The objective of this second stage is to determine whether late deliveries will result in material unavailability at TFS, and to indicate whether alignment of demand and supply could solve such future shortages.

The input to determine the initial state of the system is described as:

$SR_i(t)$	$i \in M$	$t = 1, \dots, LT_i + R_i$
$D_i(t)$	$i \in M$	$t = 1, \dots, LT_i + R_i$
$C_i(t)$	$i \in M$	$t = 1, \dots, LT_i + R_i$
$I_i(t)$	$i \in M$	$t = 1$
$I_i^{TFS}(t)$	$i \in M$	$t = 1$

In section 4.1 is mentioned that this second stage uses the output of the first stage to determine the expected shipment dates for each planned delivery at TFS. These shipments $SH_i(t)$ are determined with the following algorithm. It is assumed that a planned delivery, equal to a demand order, is never sent in partial shipments. Therefore, shipment quantities consistently correspond to the quantities of these demand orders. The shipment date corresponds to the requested delivery date if sufficient inventory is available at VDL ETG. Otherwise, the demand order will be shipped as soon as the complete quantity becomes available.

Algorithm to determine the shipment dates
For $t = 1, \dots, LT_i + R_i$

1. Check $D_i(t) > 0$
    - <u>If true</u>: Define $t = t_{demand}$ and go to Step 2
    - <u>Otherwise</u>: Next t and go back to Step 1

2. Check whether the cumulative finished products cover the cumulative demand until period t.
   → Check $CF_i(t) \geq CD_i(t)$ → $I_i(1) + \sum_{s=1}^{t} SR_i(s) \geq \sum_{s=1}^{t} D_i(s)$

    - <u>If true</u>: Define $t_{ship} = t_{demand}$ → $SH_i(t_{ship}) = D_i(t_{demand})$
      Next t and go back to Step 1

    - <u>Otherwise</u>: $SH_i(t_{demand}) = 0$
      Find the next t for which $CF_i(t) \geq CD_i(t)$
      Define that $t = t_{ship}$ → $SH_i(t_{ship}) = D_i(t_{demand})$
      Next t and go back to Step 1

4.3.1 Compare the Expected Shipments with the Planned Consumption at TFS

Subsequently, these shipments are compared with the planned consumption and stock levels at TFS. The state-updating procedure from the first stage is slightly adapted to check whether actual (future) material shortages will occur at TFS.

$$I_i^{TFS}(t+1) = I_i^{TFS}(t) - C_i(t) + SH_i(t) \qquad i \in M \qquad t \geq 1 \qquad A.6'$$

The state-updating procedure may show that, even though the first stage indicates future backlogs at VDL ETG, the stock levels at TFS are sufficient to cover the consumption during the time interval that deliveries will arrive late. If sufficient material is available at TFS, the planned deliveries should be aligned with the expected shipments. Otherwise, another comparison is drawn to check whether future shortages could be prevented with the WIP at VDL ETG.

4.3.2 Compare the WIP at VDL ETG with the Planned Consumption at TFS

The following state-updating procedure calculates the net inventories at TFS for the complete planning horizon of an item i when all finished products would immediately be shipped, independent of demand orders.

$$I_i^{TFS}(t+1) = I_i^{TFS}(t) - C_i(t) + SR_i(t) \qquad i \in M \qquad t \geq 1 \qquad A.6''$$

If the net inventories at TFS remain positive, the planners at TFS should align their planned supplies with the scheduled receipts of VDL ETG. On the other hand, a negative net inventory at TFS possibly initiates an escalation. The decision whether to escalate and therefore request an advanced delivery date is made by a planner of TFS. As stated in section 4.1, this planner should assess the impact of the delayed production order and decide whether to escalate the demand order.

4.4 Proof of Material Feasibility

As mentioned in section 3.3, the constraints in the framework of Wiers and De Kok (2018) are defined in such a way that they hold for any SCOP concept, and the framework can be seen as a basic model for supply chain planning. The resource constraints in section 4.2.2 are directly derived from Wiers and De Kok (2018) and adapted to the current situation, thus resource feasibility is automatically proven. Order release quantities are determined in the first stage of the CP model, hence it should be proven that this model incorporates the three material constraints of Wiers and De Kok (2018). The first one is defined as:

$$B_i(t+1) - B_i(t) \leq D_i(t) \qquad \forall i \qquad t \geq 1 \qquad D.1$$

This constraint states that the increase in back-orders cannot exceed the independent demand. In section 4.2 is mentioned that scheduled and planned receipts arrive according to their planned lead times and demand realizations equal purchase orders. As a result, no extra backorders can occur due to a delay in the production process nor can they occur due to an unplanned increase of demand. This proves that constraint $D.1$ holds for all end items $i \in N$. All items in the first stage of the CP model are treated as end items, thus the constraint holds for the complete model.

The second material constraint of Wiers and De Kok (2018) is related to the net inventory position. Variable $G_i(t)$ is defined as the dependent demand of an item.

$$I_i(t+1) = I_i(t) - G_i(t) - D_i(t) + SR_i(t), \qquad \forall i \qquad t = 1, \dots, T \qquad D.2$$

It is given that dependent demand for all end items, i.e. all items in the first stage of the CP model, is equal to zero.

$$\rightarrow I_i(t+1) = I_i(t) - D_i(t) + SR_i(t), \qquad i \in N \qquad t = 1, \dots, T \qquad D.2'$$

This rewritten constraint is equal to Equation $A.6$ which proves Constraint $D.2$.

The third constraint of Wiers and De Kok (2018) states that released quantities need to be nonnegative, which implicates that returns are not allowed in this model.

$$r_i(t) \geq 0 \qquad \forall i \qquad t = 1, \dots, T \qquad D.3$$

This constraint can be rewritten with the notation of the model in section 4.1.

$$\rightarrow WO_i(t) \geq 0, \qquad \forall i, \qquad t = 1, \dots, T \qquad D.3'$$

Equation $A.4$ immediately shows that this constraint is satisfied and order release quantities can never be negative. Therefore, all three constraints of Wiers and De Kok (2018) are proven.

5 Collaborative Planning Process

Recall that the CP model generates an order release plan and indicates, but not resolves, future shortages. Therefore, it is essential to define a CP process how the CP model should be used. This chapter formulates the CP process as a fixed cycle consisting of four stages, corresponding to the stages in the Philips case (section 3.4.2). Section 5.2 illustrates a CP process for one of the VDL ETG items and indicates how the CP model could be used in a CP meeting between TFS and VDL ETG.

5.1 Four-Stage CP process

The proposed CP process comprises four stages executed in a tightly managed weekly cycle.

Stage 1. Gather Data
Both organizations start with updating the status of their system. Then, they collect the required live data that is used as input for the CP model. Three types of input data are required at the start of a review cycle. First, demand is obtained from the MRP of TFS. This provides information about the due dates at which the ERP system of TFS expects to receive certain quantities of each item. Second, the state of the system is obtained by downloading the WIP and stock data from the ERP system of VDL ETG. The last input data that is required for the CP process equals the production lead times of items to ensure that the final order release plan could be executed on the shop floor of VDL ETG. These lead times are defined in a pricelist that is shared between VDL ETG and TFS. All data needs to be checked for correctness and consistency and then forwarded to a central database, or alternatively to the person conducting the CP meeting and running the CP model.

Stage 2. Decide
Material coordination decisions are made in the weekly meeting, which has a strict agenda and a knowledgeable moderator. The meeting starts with a review of the action points from previous week. Subsequently, the CP model generates an order release plan and indicates future shortages, showing the actual status of material flows and new demand information. One of the major contributions of the CP model is its fast calculation speed. The rapid CP model allows the planners to calculate and evaluate alternative scenarios during one CP meeting, creating an interactive planning environment.

Both organizations interactively view and share their thoughts about the output. The planned deliveries in the ERP of TFS may remain unchanged if no backorders are expected at VDL ETG. If the first stage of the CP model indicates expected late deliveries of a certain item, it should be checked whether these late deliveries will result in material shortages at TFS. If so, the second stage indicates whether these shortages could be avoided with the available stock levels at VDL ETG. The objective of the meeting is to jointly finalize an order release plan and agree on all due dates.

Stage 3. Escalate
It can happen that the planners disagree during the CP process meeting. It is possible that VDL ETG cannot deliver a certain order at its planned due date, which is unacceptable for TFS. Another possibility is that TFS requests to advance a certain order, while this cannot be accomplished by VDL ETG without any escalations. In such cases, the planners need to refer such issues to the appropriate managers. Upper management should come to an agreement and define action points before the end of the week. Following this procedure requires immediate action, while in the old situation the problem would not be recognized till an infeasible purchase order was forwarded to VDL ETG. This shows that the CP process significantly reduces information lead time and increases transparency throughout the chain.

Stage 4. Deploy
All decisions from the CP process need to be deployed in both organizations. VDL ETG should start production as defined in the joint order release plan and adapt its current production schedule to comply with the agreed due dates. TFS should either update the planned supplies in its MRP with the agreed due dates or manually check that purchase orders are aligned with the agreed due dates.

Following this CP process should give planners control and let them discuss the tactical and strategic implications of their decisions (De Kok et al., 2005). This should reduce their time and efforts to prioritize MRP violations and perform rescheduling activities. The CP model is a key factor to enable this change of activities. The model supports the synchronization of order release plans and indicates potential problems. The weekly CP process ensures that planners take appropriate action upon this information, which eventually should result in improved order fulfilment and increased material availability.

5.2 CP Process Example

The CP process is illustrated to indicate how the CP model should be used and what kind of decisions are made during a CP meeting. Actual data is collected from both ERP systems to determine the initial state of the system. The CP process is simulated for an item i with a lead time $LT_i = 140$.

A CP tool is developed that applies a weekly basic CP model, thus without a safety stock, move rate policy or resource constraints. The safety stock and move rate policy are not applied because this basic model best corresponds to the current commitment agreements between VDL ETG and TFS. As mentioned in section 1.2, VDL ETG starts production based on the forecasted quantities, and agreements are in place to cover the costs for the resources consumed. However, no agreements are made about the costs of producing on top of the forecast, which causes VDL ETG to be reluctant to add an extra safety stock or apply the move rate policy. Furthermore, limited accurate data is available at VDL ETG about the available (cumulative) capacity of resources for items of TFS. Due to this lack of data and the time constraints of this research it is chosen to disregard the resource constraints in this CP process example.

Stage 1. Gather Data
All relevant data is collected from the ERP systems of both organizations. The CP process is simulated on September 14th 2018 and the planning horizon is defined as $T_i = LT_i + R = 140 + 7 = 147$. All scheduled receipts are known until $SR_i(LT_i - 1) = SR_i(139)$, which corresponds to January 31th 2019. In addition, all demand is collected for the complete planning horizon, which is until February 7th. The last input data that is required for the CP model are the stock levels of the items at both organizations. All input data for this example is provided in Appendix B.

Stage 2. Decide
The first stage of the CP model determines the order release decisions for the next week, so until September 20th 2018. Furthermore, it provides insight in (future) backlogs at VDL ETG. This first stage shows that the inventory position is sufficient to cover demand during $LT_i + R$, hence no order releases are generated by the CP tool. Figure 11(a) depicts the net inventories, calculated via the state-updating procedure, at VDL ETG for item i during the planning horizon. Table 2 shows the time periods and quantities of the expected backlogs at VDL ETG.

The goal of the CP process meeting is to collectively agree on due dates in order to align demand and supply. The second stage of the CP model first compares the expected shipments from VDL ETG with the stock levels and planned consumption at TFS. Table 2 and Table 3 provide similar information about the net inventories.

Table 2: Net inventory at VDL ETG with requested deliveries during the planning horizon

t	1--6	7--12	13--62	63--97	98--147
I_i	0	-26	>=0	-30	>=0

Table 3: Net inventory at TFS with expected shipments during the planning horizon

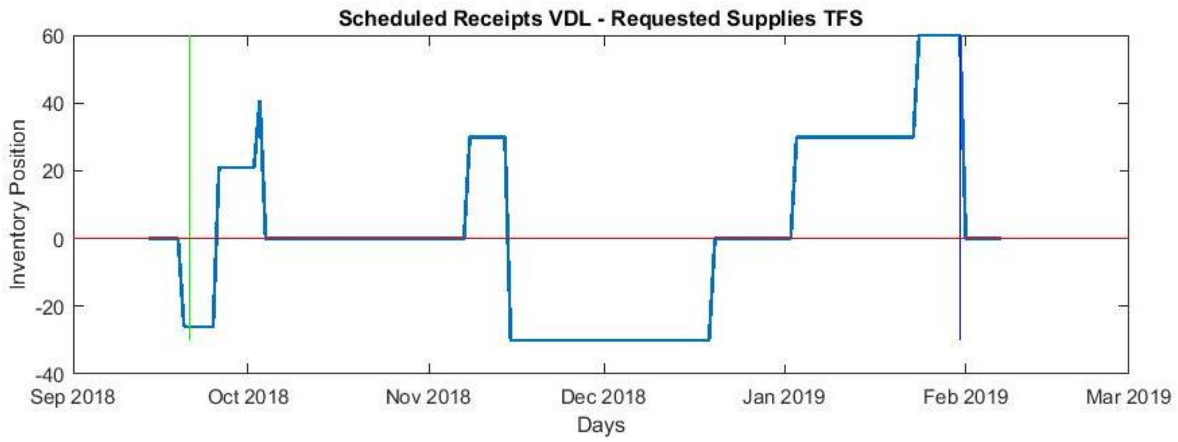
t	1--80	81--97	98--147
I_i^{TFS}	>=0	<0	>=0

Figure 11(b) shows that future material shortages are expected at TFS with the expected shipment dates of VDL ETG. Therefore, the comparison between the scheduled receipts of VDL ETG and consumption at TFS should indicate whether these shortages could be solved without escalating any orders. The net inventories that follow from this comparison are depicted in Figure 11(c). No material shortages are expected at TFS for item i when all finished products would immediately be shipped by VDL ETG, thus the planners should align the due dates of the demand with the due dates of the scheduled receipts.

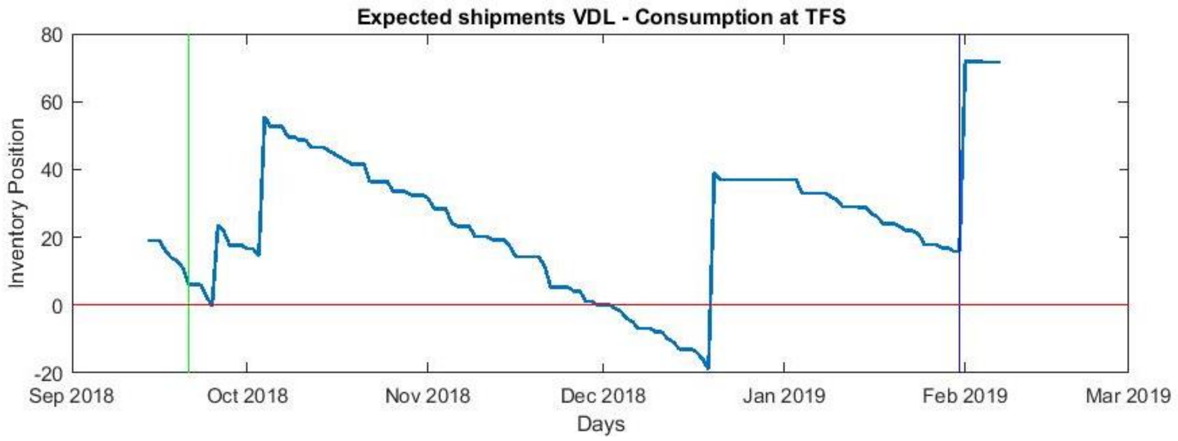
The decision stage of the CP process is finalized with a joint plan of aligned due dates for supply and demand. Figure 11(a) shows a backlog at VDL ETG in September, while Figure 11(b) shows that TFS will not have any material shortages with the expected shipment date. Thus, the planners could decide to align the requested delivery date of the first demand order with the WIP at VDL ETG. However, the inventory position of TFS moves completely towards zero. To avoid risks as transportation delays or unexpected demand TFS may request VDL ETG to advance their production due date. In this example, it is assumed that TFS agrees to postpone the requested delivery date to September 26th.

Figure 11(b) indicates that the demand order of 60 pieces at November 15th cannot be shipped before December 20th and this delayed shipment will result in material shortages at TFS. To solve the problem, planners should decide to align demand and supply and split the demand order into two separate orders. The first 30 pieces can be delivered at November 15th, while the other 30 pieces can be delivered at December 20th.

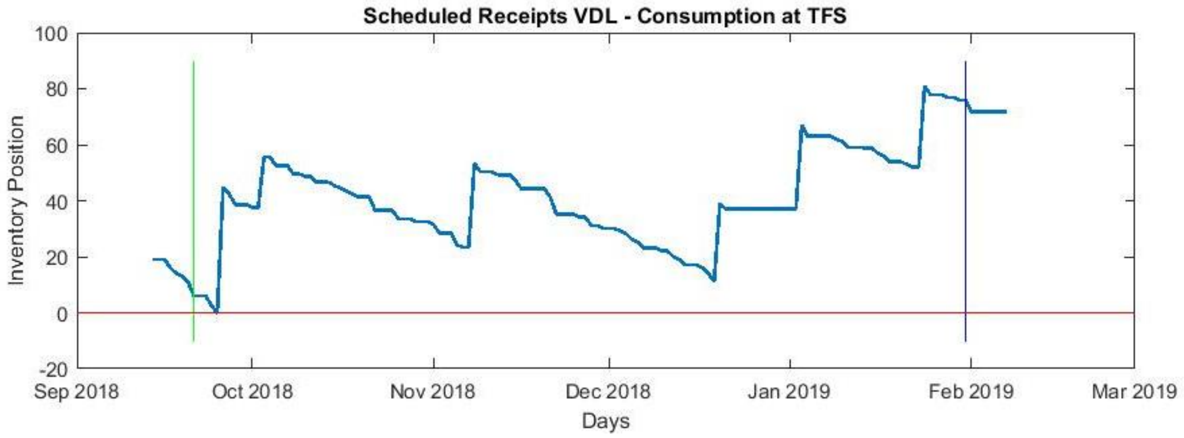
The finalized joint plan is given in Appendix B. Subsequently, the tool is used a second time to check whether the aligned due dates, which are in bold in Appendix B, have the desired effect. Figure 12(a) and Figure 12(b) show that the joint order release plan neither results in backlogs at VDL ETG nor at TFS. Therefore, it can be concluded that for this item i no escalations are needed and the third stage can be skipped. In order to actually increase the supply chain performance, it is required that both organizations deploy the decisions that are made during the CP process meeting and adhere to these decisions.



(a) Net inventories VDL ETG

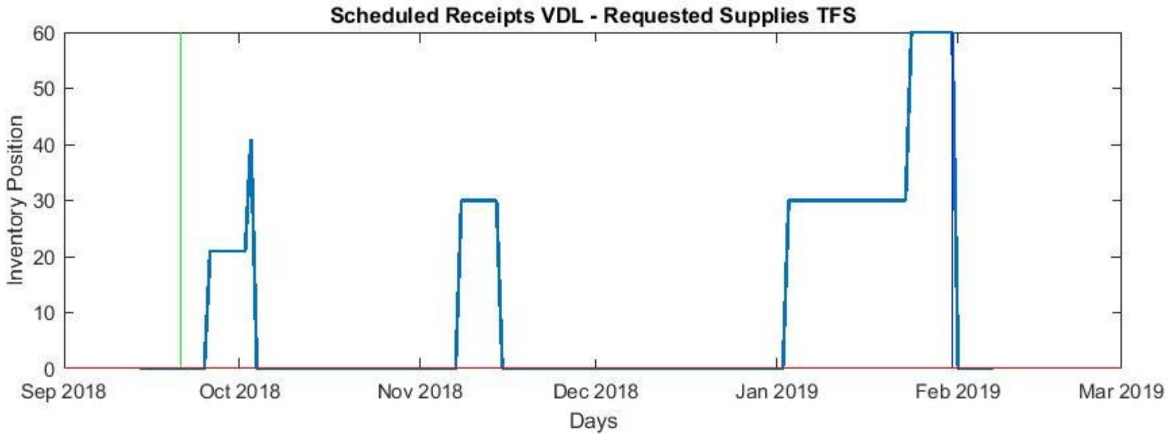


(b) Net inventories TFS based on expected shipments

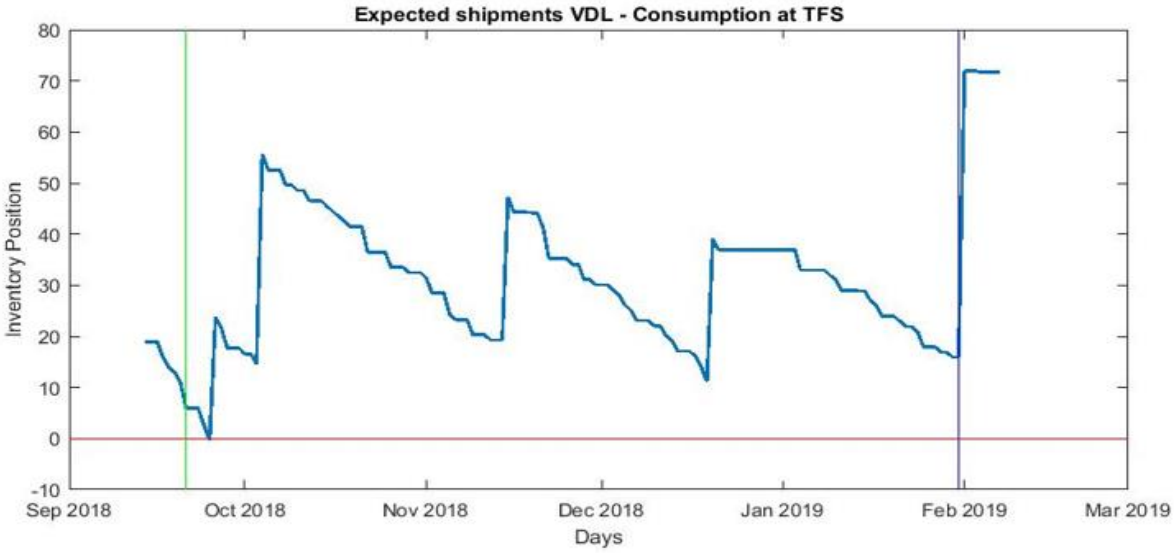


(c) Net inventories TFS based on scheduled receipts

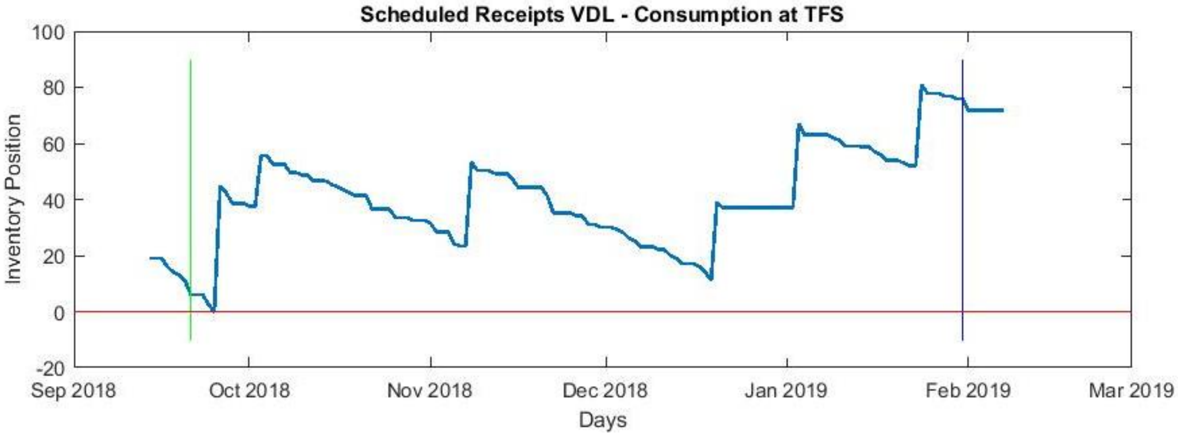
Figure 11: Expected net inventories of VDL ETG and TFS with original input data



(a) Net inventories VDL ETG



(b) Net inventories TFS based on expected shipments



(c) Net inventories TFS based on scheduled receipts

Figure 12: Expected net inventories of VDL ETG and TFS with the joint order release plan

6 Simulation

This chapter describes a simulation model that highlights how the CP model would have performed, had it been used in the past. It involves a counterfactual analysis and looks for changes in the outcome that are directly attributable to the settings of the decision variables. It is explained in section 2.4.2 that the simulation does not allow any alignment of supply and demand, and entirely focusses on the accurateness of order release decisions. These release decisions are exclusively made in the first CP model. The simulation indicates how several configurations of this first CP model, which are all defined in section 6.1, would have performed in the past. The setup of the simulation is described in the second sub-section. Finally, the results and consequent conclusions about the simulation are provided in section 6.3 and 6.4 respectively.

6.1 Configurations used in the Simulation

Several configurations are defined based on the three decision variables included in the CP model. The first decision variable is the review cycle length. This cycle length implies how often the status of the system is reviewed. The planning procedure is currently performed each month, hence the default value of the cycle length is also a month. Section 2.4.2 states that it is recommended to perform shortly cycles like a week, so the alternative value for the cycle length is a week.

The safety stock percentage is the second decision variable in the CP model. The default percentage should be set at zero based on the current commitment agreements between VDL ETG and TFS (section 5.2). Nonetheless, section 2.1.1 highlights the truncated horizon effect and the contradiction between the long-term forecasts and the StrAP. Both these findings may cause an inaccurate forecast which is lower than the actual demand. Adding a safety stock percentage could compensate for this inaccuracy (section 4.2). It is unreasonable to set uncommonly high safety stock percentages, because the MRP of TFS already incorporates safety lead time to cover demand uncertainty (section 1.2.2). Consequently, it is chosen to set the alternative safety stock percentages at 10, 20 and 30.

The third decision variable relates to the move rate policy. It is mentioned in section 4.1 that TFS and VDL ETG consider switching to the move rate policy formulated in section 4.2.4. It can be decided to either apply, or not apply this alternative decision rule. Applying the move rate policy results in two secondary decision variables. Firstly, the number of periods which is used to calculate the expected move rate (M). Secondly, the positive number of periods which is used to set the inventory threshold (Z). It is decided to calculate the expected move rate based on the demand for 6 months ahead, so M is set at 188. The height of inventory threshold affects how often the expected move rate will be released and it is chosen to define four different threshold levels. The threshold levels correspond to an average expected demand of 15, 30, 60 and 120 days.

The first configuration in the simulation implements the basic model with zero safety stock, no move rate policy and a cycle length of a month. In section 1.2.2 is mentioned that the MRP of TFS already incorporates safety lead time to cover demand uncertainty. As a result, it can be concluded that adding a safety stock percentage or applying the move rate policy can be considered as hedging. Because both decision variables are expected to have a similar effect, it is highly unlikely that TFS would implement both a safety stock and the move rate policy. Consequently, exclusively one of them will be applied in each configuration. Given this decision and the defined settings per decision variable, a list of 16 configurations is created and provided in Table 4.

Table 4: List of configurations applied in the simulation

Configuration	**Review Cycle Length**	**Safety Stock %**	**Move Rate** **If Yes - (Z)**
1 – 9	Month - Week	0	No
2 – 10	Month - Week	0.1	No
3 – 11	Month - Week	0.2	No
4 – 12	Month - Week	0.3	No
5 – 13	Month - Week	0	Yes - (15)
6 – 14	Month - Week	0	Yes - (30)
7 – 15	Month – Week	0	Yes - (60)
8 – 16	Month - Week	0	Yes - (120)

6.2 Simulation Setup

Due to the complex environment and time restrictions of this research, several assumptions have been made in this simulation model. Here is the list of assumptions:

- Forecast documents were available before the first day of the new month, indicating that all order release decisions for the complete month are based on this forecast.
- The initial net inventory is set at zero, meaning that no backlog or stock exists for any of the VDL ETG items.
- The initial WIP is exactly set to the first lead time demand for each item. This WIP is applied to avoid backlogs or excess stock that are independent of the order release decisions made in the simulation.
- Production lead times are deterministic, meaning that items are produced exactly according to their defined lead times and delays never occur. Deterministic production lead times also indicate that an escalation is not allowed.
- Order release decisions are based on the requested date in the delivery data, which corresponds to the initial demand date triggered by the ERP system.
- When sufficient inventory is available, orders will be delivered exactly on the requested date and never earlier. Otherwise, an order will be delivered as soon as the total quantity of the order is available.
- No yield issues are present, so all released orders are completed without loss of production.
- The order release quantities during a week are clustered per item and will be produced in one batch. A fixed cost is applied per batch and not per separate order release decision, while each order release decisions retains its original due date.

The simulation applies the CP model of section 4.2 with a planning horizon of $T_i = LT_i + R$. Section 4.2 states that the exogenous input to determine the initial state of the system consists of demand, scheduled receipts and the start net inventory at VDL ETG. As can be seen in the assumptions, the initial scheduled receipts are equal to the first lead time demand and the net inventory is set at zero. The example in section 4.2 shows that demand currently consists of purchase- and forecast orders. Equation $A.2'$ is updated to comply with this characteristic:

$$S_i(t) = \left\lceil (1+\rho_i) * \sum_{s=0}^{LT_i} PU_i(t+s) + FC_i(t+s) \right\rceil \qquad i \in M \qquad t \geq 1 \qquad A.2''$$

In section 2.1.1 is stated that capacity limitations are a relevant issue at VDL ETG. Therefore, it would be unrealistic to assume infinite capacity at VDL ETG in this simulation. It is preferred to include resource constraint $B.3.4$, but due to time restrictions of this project and limited accurate information about the available capacity it is chosen to apply an extended version of resource constraint $B.3.1$. The original constraint implicates that each item has a maximum order release quantity per period. The extended version models the capacity over a planned lead time of multiple periods. It is mentioned in the assumptions that the order release decisions during a week are clustered and produced in one batch, indicating that capacity is modeled over a planned lead time of 7 periods t (days).

$$\sum_{s=t-F_k}^{t} c_i * WO_i(s) \leq C_k * (F_k + 1) \qquad k = 1, \dots, K \qquad t \geq 1 \qquad B.3.1'$$

The simulation applies the constraint with $F_k = 6$, which implies a maximum cumulative number of items that can be released per week. Applying this constraint avoids strongly volatile production patterns. No accurate information is available about the maximum weekly order release quantities per item, hence it is chosen to define the maximum number of items as 3 times the average weekly demand over the simulation period. Given that C_k and c_i are independent of t (section 4.2.2), calculation of the fixed maximum per week is straightforward. If the cumulative order release quantity for the relevant week is less than this maximum amount, the total order release quantity will be released. If the order release quantity exceeds the upper limit, VDL ETG exactly releases orders till the maximum cumulative number is reached.

The first cycle of the simulation starts at February 2016 and the last month is May 2018. The CP model determines the order release quantities for the complete review cycle. New scheduled receipts and net inventories are simulated via the state-updating procedure. Historic delivery- and forecast data are used throughout the simulation as input for the demand. The VDL ETG items that are present in all forecast documents over the complete time horizon are simulated. The list consists of 21 items and can be seen in Appendix C.

An inventory cost model is defined to calculate the total capital investment over the simulation period. The total capital investment consists of holding costs, backorder costs and fixed costs. Due to the time constraints of this research, it is chosen that each cost parameter is defined as a percentage of the purchasing price of an item, consistent for all items. Holding costs, observed in industry, range from 5 to 45% per annum of the purchasing or cost price of the product (Durlinger and Paul, 2012). This gives approximately an average of 25%, which is also a common number for the holding costs in the literature and therefore used in this simulation. In consultation with the stakeholders it is decided to define the annual backorder cost penalty at 5 times the holding cost percentage. The significant higher penalty for backorders indicates that some level of inventory is preferred to material unavailability. Lastly, the fixed cost per production batch is roughly estimated in consultation with VDL ETG and set at 10% of the purchasing price of a single item.

Subsequently, the different configurations are compared in an efficient frontier type of graph, whereby the total capital investment is plotted on the horizontal axis, and the aggregate service level on the vertical axis. The aggregate service level is calculated based on order deliveries, independent of the quantity per order. Furthermore, the legend of the graph provides the production stability rate of each configuration. This stability rate is equal to the percentage deviation of weekly order release quantities over the complete simulation period. Each configuration simulates a dot in the graph and indicates at what expense a higher service level could be achieved. For example, the move rate policy may show more stability and a higher service, but may also imply much higher inventory cost.

Besides this chart, several performance indicators are measured per item per configuration: the RLIP, the average number of days that an ordered is delivered too late, the average net inventory and the percentage deviation of weekly order release quantities. Furthermore, some graphs are drawn to visualize the performance of the different configurations per item. The graphs depict (1) the cumulative demand relative to the scheduled receipts and (2) the order release quantities per month.

6.2.1 Planning Cycle Example

One planning cycle is elaborated to indicate what output is generated per planning cycle. This example applies the first configuration. The lead time of this item is 14 weeks, corresponding to 98 days, which means that an order release at $t = 1$ corresponds to a scheduled receipt at $t = 99$. This particular planning cycle results in two order release decisions: $WO_i(1) = 5$ and $WO_i(4) = 7$. Furthermore, the expected net inventories of this item are depicted in Figure 13.

When the net inventory after lead time (red line) is below zero, in this case minus 5, this automatically results in an order release decision at $t = 1$ to catch up on backlogs. This configuration aims to have a net inventory of zero after lead time, so releases exactly 5 items. The order release quantity would be higher with a positive safety stock percentage. The order release of 5 items at May 1^{st} results in a scheduled receipt at August 8^{th}. The second order release decision in this example is based on the forecast, which initiates a release at May 4th and results in a scheduled receipt at August 11th. Furthermore, between June and August a backlog will be present which is mostly equal to 5. It is already mentioned in the introduction of this chapter that demand and supply are not aligned within lead time. The net inventory at the start of this cycle is obviously zero and the expected net inventory at the end of the cycle can be derived from the green line and equals minus 1.

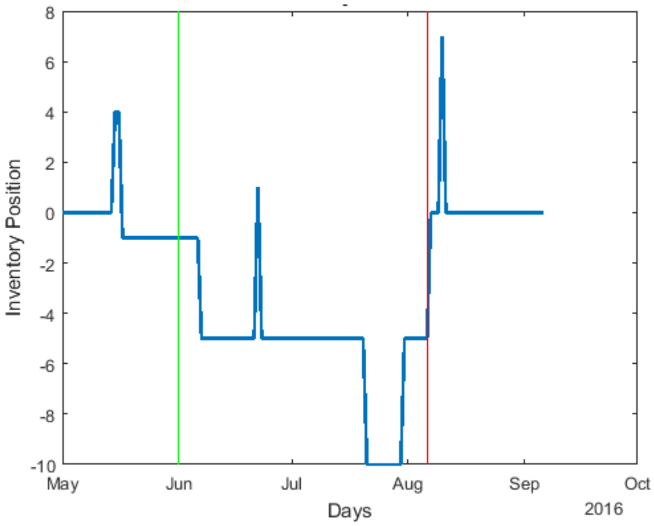


Figure 13: Planning cycle example at May 2016 with configuration 1

6.3 Simulation Results

The results of the performance indicators per item per configuration are provided in Appendix D. The efficient frontier type of graph is depicted here:

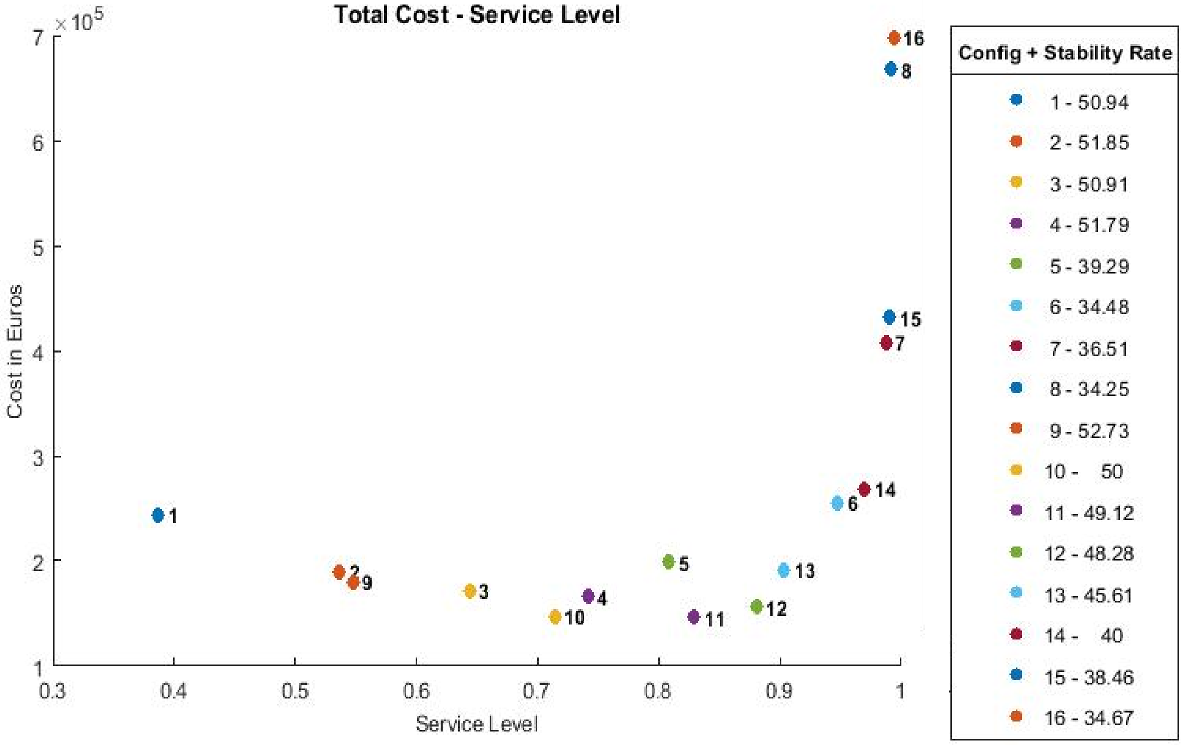


Figure 14: Aggregate Service Level relative to the Total Capital Investment

The aggregate service level of the first configuration is only 39%, which implies that circa 6 out of 10 simulated deliveries are late, which is defined as more than 5 days after the requested date. It can be concluded that when VLD ETG applies the basic CP model with a monthly review cycle length, the delivery performance is by no means close to the desired 100% that is pursued in a proper SCOP.

From classical inventory models, it is known that there is a no linear relationship between safety stock and service level. Increasing the safety stock percentage demonstrates diminishing returns, i.e. concavity, with a limit at its utmost of 100%. These statements are not fully confirmed by Figure 14 in which it can be seen that safety stock percentages till 30% structurally improve the aggregate service level with at least 10%. In addition, the total capital investment even decreases for these safety stock percentages, which can be explained by a severe decrease in backorder costs without significantly increasing the holding costs. The increased percentages do not show any diminishing returns, because of the low initial service level and its consequential high backorder costs. It is expected that the increase in service diminishes when further increasing the safety stock percentages. Subsequently, the total costs are expected to increase significantly for service levels above 90% as average inventory levels and corresponding holding costs increase exponentially.

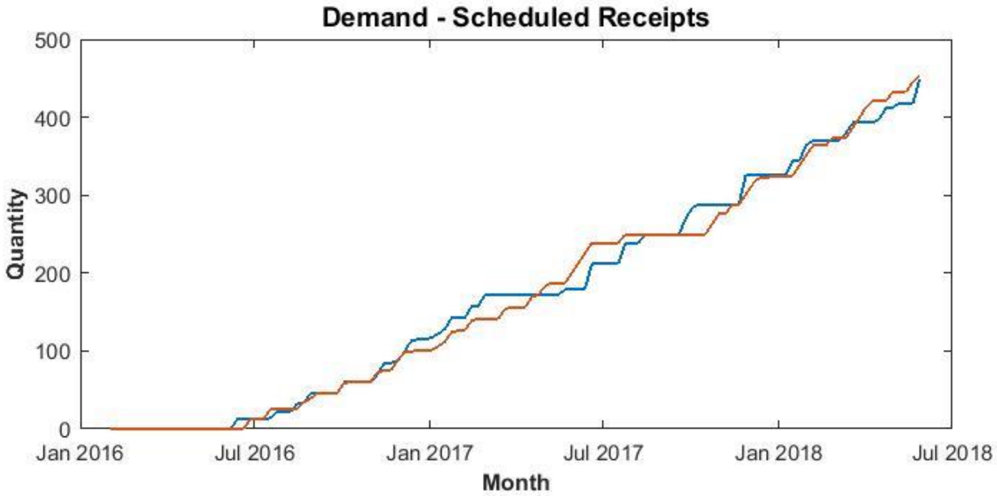
The positive effect on the aggregate service level is considerably larger for configurations with a move rate policy than for configurations with a safety stock percentage. Configurations applying the move rate policy with a threshold level of a 15-day average demand (Config 5/13) already outperform the configurations with a safety stock of even 30% (Config 4/12). The move rate policy demonstrates diminishing returns and total capital investment increases exponentially for Z values from 30 days, which can be attributed to the increased holding costs for service levels above 90%.

It can be seen in Table 4 that configurations 9 to 16 are differentiated from configurations 1 to 8 based on the review cycle length. The first 8 configurations have a monthly cycle, while the subsequent 8 configurations apply weekly cycles. Figure 14 shows that the ratios and relationships between weekly configurations are similar to the monthly configurations, thus including a safety stock percentage or applying the move rate policy has similar effects on total costs and service levels independent of the cycle length. Nevertheless, a configuration with a weekly cycle mostly outperforms the identical configuration with a monthly cycle length, confirming the statement to perform the CP process in short cycles like a week. Configuration 1 to 6 score a higher service level with a similar or even lower total capital investment than configuration 9 to 14 respectively. The performance of the other 2 coupled configurations are comparable, because the aggregate service level is already close to its limit, hence the range to improve becomes negligible.

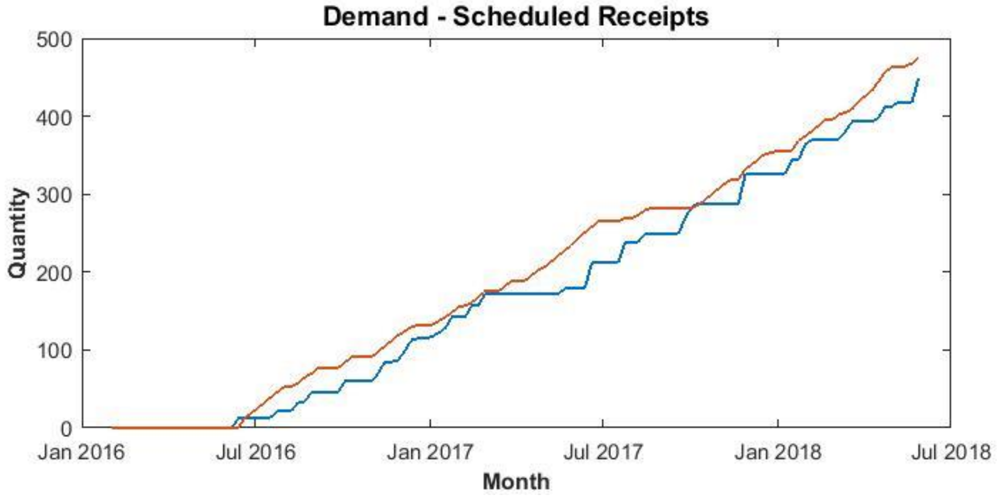
The legend in Figure 14 shows the production stability rate per configuration. The lower this rate, equal to the percentage deviation of weekly order release quantities, the more stable production is. Introducing a safety stock has a minor or negligible effect on the deviation percentage. Introducing the move rate policy results in significant lower deviation percentages. Section 6.1 mentions that the height of inventory threshold affects how often the expected move rate can be released. Move rate quantities are released more often with a higher threshold, which should result in a more stable production rate. This is confirmed by the stability rates in Figure 14.

All above statements can be substantiated by the results in Appendix D. For example, the RLIP of the first configuration is above 60% for only 1 of the 21 items. Furthermore, the RLIP structurally improves by including the safety stock percentages or applying the move rate policies. The effect of the configurations on the average number of days late and the average net inventory is interrelated with the effect on the RLIP. Logically, the average number of days late decreases considerably when the RLIP significantly increases. On the other hand, the average net inventory and therefore holding cost will increase as the RLIP increases. Especially configurations with a high safety stock percentage or a move rate policy with a high threshold result in substantial average inventory levels. Finally, it can also be seen that introducing a safety stock has a negligible effect on the deviation percentage of most items, while introducing the move rate policy results in significant lower deviation percentages.

One random item is now considered to show the graphs of (1) the cumulative demand relative to the scheduled receipts and (2) the weekly order release quantities. These graphs are compared for configuration 1 and 14. For item 11 it can be seen that the RLIP for the first configuration is only 53%, while the configuration 14 results in a 98% delivery performance. Figure 15(b) shows that the cumulative receipts for configuration 14 are consistently above the demand, while the demand of the first configuration often exceeds the receipts in Figure 15(a). Additionally, the percentage deviation of configuration 14 is even 70% less than the deviation of the first configuration. This is confirmed by Figure 16(a) which shows strongly volatile release quantities for the first configuration, namely either zero or the maximum number allowed 13, while Figure 16(b) shows that configuration 14 mostly releases a move rate quantity of 7 items.

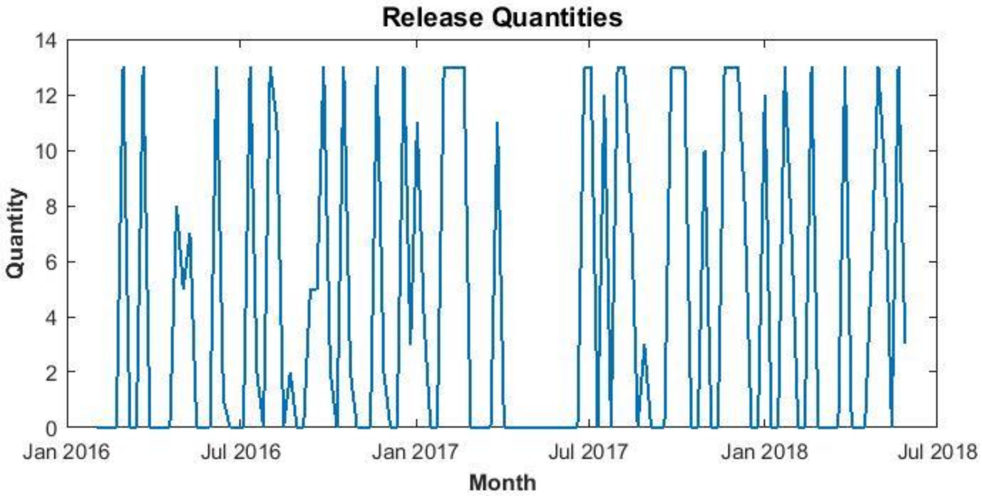


(a) Configuration 1

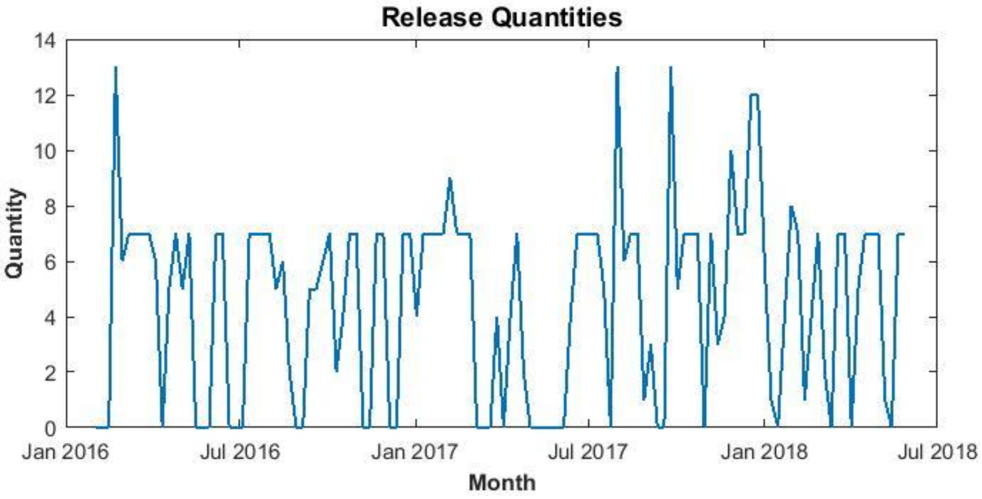


(b) Configuration 14

Figure 15: Cumulative demand (blue) relative to the scheduled receipts (red)



(a) Configuration 1



(b) Configuration 14

Figure 16: Weekly Order Release Quantities

6.4 Conclusions from the Simulation

The simulation shows that the order release quantities of the first configuration, which corresponds to the current commitment agreements, would have been inaccurate and structurally too low in the past. The simulation shows that both a safety stock percentage and the move rate policy would have increased the aggregate service level, although applying the move rate policy would have been more effective. Based on the simulation, it is recommended to apply a move rate policy with a threshold value Z not larger than 30 days, otherwise the total capital investment increases exponentially. In addition, the move rate policy results in significantly lower percentage deviations. This corresponds to a more stable production rate, which is favorable for VDL ETG. Furthermore, the configurations with a weekly cycle consistently generate better results than configurations with a monthly cycle length.

Purely based on the results of this simulation it is most logical to apply a CP model with a weekly cycle length and to include the move rate policy. Nevertheless, it is not recommended to blindly apply these settings because they would have performed best in the past. The move rate policy will have the desired effect when the demand trends from the past continue in the future. However, when forecasts unexpectedly become higher than the actual demand, the move rate policy results in excess stock and consequent holding costs. Applying the move rate policy with a relatively low threshold value could partly prevent such scenarios. Instead of applying a move rate policy to positively hedge the forecast, it is advised to investigate why the forecasts were structurally too low. Finding the cause could help to improve the forecast. Consequently, the order release decisions become more accurate and less alignment of demand and supply is required within the lead time.

7 Reflection

This research project modeled and analyzed a CP process for a high-tech supply chain in a MTF environment. This CP process improves the SCOP and eventually increases material availability at TFS. Section 7.1 provides an answer to the research questions formulated in section 2.4. Specific recommendations for TFS and VDL ETG are provided in section 7.2. Lastly, section 7.3 elaborates on limitations of the current work and proposes directions for future research.

7.1 Research Questions

- **Sub-Q1:** Which planning approach(es) can be used for the CP model to create a feasible order release plan and identify bottlenecks at an early stage?

The literature study in Chapter 3 indicated that a modified base stock policy, or specifically the SBS policy is most suitable to perform the SCOP in an environment such as the supply chain of TFS and VDL ETG. The CP model in the Philips case of De Kok et al. (2005), which was comparable to the current research, is based on the SBS policy and is therefore used as a basis for the CP model in this research. One of the characteristics of the SBS policy is that child items are pre-allocated to final items in an early stage. In this specific case study, the VDL ETG items that are consumed in modules cannot be pre-allocated, because the production planning of these modules is decoupled from the final systems. Consequently, the initial CP model and its planning approach are adapted to deal with this pre-allocation issue.

Sub-Q2: What decision variables and (material/ resource) constraints need to be included in the model?

The first stage of the CP model includes a calculation method for the order release quantity. Besides, it adopts a state-updating procedure that defines new scheduled receipts and presents the expected net inventories of items at VDL ETG over the planning horizon. The second stage of the CP model applies a similar state-updating procedure. It presents the expected net inventories of items at TFS based on the expected shipment dates and the scheduled receipts of VDL ETG. The framework with material- and resource constraints of Wiers and De Kok (2018) is used to ensure feasible order releases. This framework is a basic model for supply chain planning and the constraints are defined in such a way that they hold for any SCOP concept. The primary decision variables in the CP model correspond to (i) the review cycle length, (ii) the safety stock percentage and (iii) whether to apply the move rate policy. Applying the move rate policy results in two secondary decision variables: (i) the number of periods which is used to calculate the expected move rate and (ii) the positive number of periods which is used to set the inventory threshold.

- **Sub-Q3:** What data needs to be collected and how should it be gathered and/or prepared to run the model?

This data can be found in section 4.2 and 4.3. The exogenous input for the first stage of the CP model consists of the demand, scheduled receipts and the start net inventory of VDL ETG. The second stage uses the output of the first stage and required additional data about the planned consumption of items at TFS. In section 5.1 is described that each organization is responsible to collect the required live data directly from their ERP systems. All data needs to be checked for correctness and consistency. How to observe the status of the system and gather the relevant information is also explained in section 5.1.

- **Sub-Q4:** How should the output of the CP model be used to improve the SCOP and eventually increase material availability?

The 4-stage CP process (see section 5.1) should be executed in a tightly managed weekly cycle. The example CP process in section 5.2 illustrates how the CP model can be used and what kind of decisions should be made during a CP meeting. The example CP process shows how the CP model highlights future shortages at VDL ETG and indicates whether these backlogs will have an actual impact on the production planning of TFS. The output of the CP model is used to jointly finalize an order release plan and agree on all due dates. The rapid CP model enables an interactive planning environment which allows planners to check whether the finalized plan has its desired outcome. Concluding, the CP model enables rapid informed decision making based on facts and therefore supports speedy problem solving.

Sub-Q5: Which configuration(s) of the CP model would have performed best based on historic data, and what can be concluded from these findings?

The simulation in Chapter 6 indicates which configuration(s) of the CP model would have performed best, had the model been used in the past. The results of the simulation in section 6.3 reveal a remarkably low delivery performance for the most basic configuration, while specifically this is the configuration that corresponds to the current commitment agreements. This finding implies that, excluding alignment of supply and demand, the CP process will probably not have its desired impact on the supply chain performance. Based on the simulation, it is expected that the configuration with a weekly cycle length and a move rate policy with a threshold of 15 or 30 days would result in the greatest supply chain performance. However, this would only be true if the demand trends remain constant. Therefore, it is recommended to identify the cause of the inaccurate forecast and improve the forecast method instead of relying on patterns in the past.

- **Main-Q:** How can a MTF SCOP be improved by a CP model in order to create material feasible order releases, avoid material-coordination issues, and ultimately resolve material unavailability?

This research answers the main research question by: i) defining a planning model for the forecast-driven part of a supply chain which generates a feasible order release plan and indicates future shortages; ii) providing an adapted and extended CP model to ensure a proper SCOP in a MTF business environment, based on a case study at TFS and VDL ETG (Chapter 4); iii) defining a CP process that applies the CP model to improve the SCOP and either avoid or resolve material-coordination issues (Chapter 5); iv) running a simulation to analyze the counter-factual impact of the CP model on the supply chain performance and suggest improvement activities.

7.2 Recommendations

- **TFS**: Include planning KPIs to evaluate the supply chain performance. Section 1.2.4 explains that the KPIs that are currently used at TFS to evaluate the supply chain performance do not consider the quality of the planning. It would be valuable to consider planning KPIs as well, because the performance of the execution mainly depends on the quality of the planning. Therefore, it would be helpful to measure the forecast accuracy of TFS. Furthermore, it is recommended to measure the supplier delivery reliability of VDL ETG based on original forecasts instead of merely measuring the supplier delivery reliability of purchase orders.

- **TFS**: Start a follow-up study with the objective to improve the forecast accuracy. Both the cause-effect analysis and the simulation indicated inaccurate and structurally too low forecasts. Section 2.1.1 highlights two possible causes for this inaccuracy; disregarding the StrAP and the truncated horizon effect. However, the inaccuracy could also be caused by other internal or external elements such as unexpected demand due to yield issues.

- **TFS & VDL ETG**: Define flexibility agreements between TFS and VDL ETG. In section 2.1.1 is explained that currently no agreements are made whether VDL ETG should comply with increased or decreased forecasted amounts within the production lead time. Forecasts are always subject to some level of uncertainty, thus requirements may increase or decrease over time. Flexibility agreements would provide insight to what degree VDL ETG should be able to react to these changes on one hand. On the other hand, the agreements ensure compensation for the provided flexibility.

- **TFS**: Share a realistic long-term, equal to at least a few years, forecast to indicate what capacity will be required in the following years. The current forecasts are based on the ship plan which only considers the current month plus 6 quarters ahead (section 1.2.1). Consequently, the long-term material requirements move towards zero. A declining demand trend causes VDL ETG to be reluctant to invest in new resources. Meanwhile, the StrAP of TFS indicates an increase in the long-term demand. To properly inform VDL ETG of these long-term demand trends, it is recommended to either incorporate the StrAP in the current forecast, or share a separate long-term forecast document.

- **VDL ETG**: Collect data about the available capacity of resources and the required capacity to process items at VDL ETG. It is mentioned in section 5.2 that this data is currently not available, hence it is impossible to include the preferred resource constraint $B.3.4$ into the CP model. Collecting this data and including this constraint will result in less or no unjustified rejections in the order release plan and therefore improve the CP model.

- **TFS & VDL ETG**: Consider applying the full CP model of the Philips case for items that are directly linked to the production of final systems. These items can be pre-allocated, so it would be possible to consider the complete value network including the sales items of TFS.

- **TFS & VDL ETG**: Continue with the move rate policy and consider applying the policy in the CP model. This alternative method was defined to increase stability of production and possibly improve delivery performance (section 4.1). The simulation confirmed both objectives, thus it could be beneficial to further exploit this policy.

7.3 Limitations and Directions for Future Research

- This research is based on a single case study and only considers one customer-supplier relationship within the supply chain. For future research, it is interesting to determine whether this CP process can be applied to other links in the supply chain and eventually to a larger part or even the complete the supply chain.

- Since the CP model in this research does not show the impact of material shortages on subsequent parent items, it could be useful to (i) find a method to alternate the SBS-policy to deal with decoupled sub-assembly production processes or (ii) define an alternative model or procedure that considers the complete value network.

- This research is completely focused on the design phase of the problem-solving cycle. This work provides a detailed CP process for which it would be useful to present an implementation plan. Furthermore, it would valuable to define KPIs to measure and evaluate the performance of the CP process.

- In section 2.1 is explained that the misalignment of supply and demand results in general supply chain nervousness. The CP process of this project should increase the supply chain responsiveness and consequently reduce this nervousness. Besides collaborative planning, lead time reduction is one the largest enablers of responsiveness. As current cumulative lead times are extremely long, possibilities should be explored to reduce this lead time and subsequently reduce supply chain nervousness.

- The current CP model generates a feasible order release plan and indicates future shortages, but does not propose any solutions for these shortages. It could be valuable to extend the current model and/or create an algorithm that automatically proposes a solution for each shortage. An extended CP model could immediately show the new situation with the proposed solutions. Users of the model still decide whether the solution will be implemented, but less time will be required to perform the rescheduling activities.

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Appendix A

Truncated Horizon Example

The truncated horizon effect is shown for item *i*:

Table 5: Item specifications example item *i*

Production lead time [weeks]	**Forecast call-off lead time [weeks]**	**MPQ**	**MOQ**	**Type**
30	6	5	1	Forecasted

The order lead time is 30 weeks, so VDL ETG starts producing based on the forecasted quantities for 8 months ahead. In forecasts till November 2017 it seems that forecasted quantities decrease after approximately 7 months, while these quantities then increase within the lead time. This automatically results in material coordination issues. The truncated horizon effect is less obvious from November 2017, which is the point in time that TFS started extrapolating their ship plan.

Table 6: Forecasted quantities of item *i*

Forecast month	**Forecast Quantities**								
	+5 months	+6 months	+7 months	Average	+8 months	+9 months	+10 months	+11 months	Average
Aug-17	4	1	3	2,67	0	0	1	1	**0,5**
Sep-17	0	4	1	1,67	0	1	1	0	**0,5**
Oct-17	4	1	1	2,00	1	1	2	0	**1**
Nov-17	1	2	2	1,67	3	3	2	1	2,25
Dec-17	2	4	4	3,33	3	2	2	2	2,25
Jan-18	3	4	3	3,33	3	2	2	2	2,25

Appendix B

Input and Output Data for CP Process Example (Section 5.2)

Table 7: Input data for the CP process example

Demand		
Article Number	**Due Date**	**Qty**
4022 261 58211	2018-09-20	26
4022 261 58211	2018-10-04	41
4022 261 58211	2018-11-15	60
4022 261 58211	2019-02-01	60

Scheduled Receipts		
Article Number	**Due Date**	**Qty**
4022 261 58211	26-9-2018	47
4022 261 58211	3-10-2018	20
4022 261 58211	8-11-2018	30
4022 261 58211	20-12-2018	30
4022 261 58211	3-1-2019	30
4022 261 58211	24-1-2019	30

Consumption		
Article Number	**Due Date**	**Qty**
4022 261 58211	2018-09-14	1
4022 261 58211	2018-09-14	1
4022 261 58211	2018-09-17	1
--	--	--
4022 261 58211	2019-02-01	1
4022 261 58211	2019-02-04	0,1
4022 261 58211	2019-02-04	0,1

Stock Levels		
Article Number	**VDL ETG**	**TFS**
4022 261 58211	0	21

Table 8: Output data for the CP process example

Demand		
Article Number	**Due Date**	**Qty**
4022 261 58211	**2018-09-26**	**26**
4022 261 58211	2018-10-04	41
4022 261 58211	**2018-11-15**	**30**
4022 261 58211	**2018-12-20**	**30**
4022 261 58211	2019-02-01	60

Scheduled Receipts		
Article Number	**Due Date**	**Qty**
4022 261 58211	26-9-2018	47
4022 261 58211	3-10-2018	20
4022 261 58211	8-11-2018	30
4022 261 58211	20-12-2018	30
4022 261 58211	3-1-2019	30
4022 261 58211	24-1-2019	30

Consumption		
Article Number	**Due Date**	**Qty**
4022 261 58211	2018-09-14	1
4022 261 58211	2018-09-14	1
4022 261 58211	2018-09-17	1
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4022 261 58211	2019-02-01	1
4022 261 58211	2019-02-04	0,1
4022 261 58211	2019-02-04	0,1

Stock Levels		
Article Number	**VDL ETG**	**TFS**
4022 261 58211	0	21

Appendix C

List of Simulated Items

Table 9: List of Simulated Items

Reference	Article number	Rev.	Description	Order lead time [weeks]
1	1009101	CSP	Diaphr. support gun	12
2	1024581	B	Gun valve housing	14
3	1032625	A	Assy. vacuumpipe	12
4	1033018	L	Gun vacuum block (AISA kit)	16
5	1066740	B	Assy diaphr hold HT insu	14
6	1076884	A	Aperture support gun+C2	10
7	1088534	B	DISTR. FLANGE WELDED	24
8	4022 197 04262	-	SAM.TIP	11
9	4022 199 70301	-	SAM.HS-DOORVOER	16
10	4022 261 44932	-	Gun valve seating	12
11	4022 261 47171	-	Bellow assy gun apert.	17
12	4022 261 50653	-	Yoke plate	12
13	4022 261 50691	-	BEAM LINER TUBE ASSY.	24
14	4022 261 50741	-	ASSY. IMAGE LINER TUBE	20
15	4022 261 51191	-	CONN. ASSY	19
16	4022 261 58211	-	Screening cap lead conus	20
17	4022 261 58242	-	Diafragmasteun SED-EDX	13
18	4022 261 58401	-	Screening Vac upper	12
19	4022 261 58581	-	Screening Vac lower	12
20	4022 261 59292	-	Lorentz liner tube assy.	20
21	4022 264 15553	-	Diaphr.hold.PT long cryo	21

Appendix D

Simulation Results

Table 10: Simulation Results - RLIP

Configuration	Item Reference																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0.48	0.36	0.07	0.59	0.67	0.52	0.18	0.24	0.31	0.31	0.53	0.48	0.34	0.33	0.5	0.26	0.53	0.06	0	0.38	0.48
2	0.57	0.53	0.07	0.74	0.67	0.6	0.42	0.52	0.45	0.63	0.57	0.57	0.64	0.33	0.55	0.35	0.58	0.18	0.14	0.54	0.62
3	0.61	0.67	0.29	0.83	0.67	0.71	0.53	0.67	0.58	0.63	0.61	0.7	0.68	0.42	0.59	0.61	0.58	0.35	0.29	0.69	0.69
4	0.74	0.8	0.43	0.86	0.67	0.75	0.76	0.67	0.8	0.69	0.74	0.83	0.77	0.5	0.68	0.78	0.63	0.35	0.43	0.69	0.72
5	0.78	0.93	0.43	0.98	1	0.85	0.55	1	0.54	0.94	0.81	0.83	0.82	0.92	1	0.61	0.84	0.71	0.64	1	0.97
6	1	1	0.71	1	1	0.94	0.84	1	0.86	1	0.94	1	1	0.92	1	0.87	0.95	1	0.86	1	0.97
7	1	1	0.79	1	1	1	0.95	1	1	1	0.98	1	1	0.92	1	1	1	1	1	1	0.97
8	1	1	1	1	1	1	0.95	1	1	1	0.98	1	1	0.92	1	1	1	1	1	1	0.97
9	0.78	0.52	0.08	0.79	0.67	0.76	0.26	0.62	0.53	0.47	0.62	0.7	0.57	0.25	0.55	0.36	0.74	0.18	0	0.5	0.52
10	0.87	0.73	0.08	0.93	0.78	0.84	0.5	0.71	0.84	0.75	0.75	0.87	0.73	0.42	0.68	0.45	0.79	0.41	0.29	0.58	0.66
11	0.91	0.82	0.54	0.96	0.78	0.88	0.74	0.86	0.97	0.75	0.91	0.91	0.84	0.5	0.77	0.73	0.84	0.59	0.64	0.75	0.72
12	0.96	0.95	0.62	0.96	0.78	0.88	0.87	0.86	0.97	0.84	0.98	0.91	0.91	0.67	0.82	0.86	0.84	0.65	0.71	0.75	0.76
13	0.96	1	0.62	1	1	0.9	0.66	1	0.89	0.97	0.87	0.96	0.95	0.92	1	0.68	0.84	0.82	0.71	1	1
14	1	1	0.77	1	1	0.94	0.87	1	0.98	1	0.98	1	1	0.92	1	0.86	0.95	1	0.93	1	1
15	1	1	0.85	1	1	1	0.95	1	1	1	1	1	1	0.92	1	0.95	1	1	1	1	1
16	1	1	1	1	1	1	0.95	1	1	1	1	1	1	0.92	1	0.95	1	1	1	1	1

Table 11: Simulation Results - Average number of days late

Configuration	**Item Reference**										
	1	2	3	4	5	6	7	8	9	10	11
1	14	20	26	11	12	11	33	19	23	19	14
2	10	14	25	5	10	9	19	12	14	9	8
3	9	9	23	3	10	7	13	9	9	9	5
4	6	5	17	2	9	6	6	8	4	8	2
5	5	1	17	0	0	4	14	0	10	1	5
6	0	0	10	0	0	2	4	0	3	0	1
7	0	0	4	0	0	0	1	0	0	0	0
8	0	0	0	0	0	0	1	0	0	0	0
9	7	9	16	4	10	5	24	9	10	14	10
10	6	4	16	2	7	4	10	7	4	7	5
11	4	3	10	1	7	4	5	3	1	6	3
12	2	1	8	1	6	3	2	3	1	4	0
13	1	0	8	0	0	3	8	0	2	0	2
14	0	0	4	0	0	1	3	0	0	0	0
15	0	0	2	0	0	0	2	0	0	0	0
16	0	0	0	0	0	0	2	0	0	0	0

Configuration	**Item Reference**									
	12	13	14	15	16	17	18	19	20	21
1	16	25	21	15	21	19	39	29	25	23
2	9	15	15	12	15	16	34	23	17	17
3	7	10	13	8	10	13	31	19	11	13
4	6	6	9	7	7	11	28	17	9	9
5	6	4	2	0	10	6	10	9	0	0
6	0	0	2	0	3	1	0	2	0	0
7	0	0	2	0	0	0	0	0	0	0
8	0	0	2	0	0	0	0	0	0	0
9	9	15	18	10	17	13	25	23	24	19
10	4	8	11	7	12	10	18	19	12	14
11	2	3	10	4	8	8	15	15	6	10
12	2	2	6	3	4	7	11	12	4	7
13	2	1	2	0	8	5	3	7	0	0
14	0	0	2	0	2	0	0	1	0	0
15	0	0	2	0	0	0	0	0	0	0
16	0	0	2	0	0	0	0	0	0	0

Table 12 shows the average monthly demand per item to provide a benchmark for the average inventory levels.

Table 12: Average monthly demand per item during the simulation period

Item Reference	1	2	3	4	5	6	7	8	9	10	11
Monthly Demand	19,4	8,9	25	11,2	1,7	17,5	20,2	5,2	20,8	7,1	20,3
Item Reference	12	13	14	15	16	17	18	19	20	21	
Monthly Demand	16,2	8,9	5,7	7,3	19,6	8,6	7,7	9	2,2	3,9	

Table 13: Simulation Results - Average Inventory

Configuration	**Item Reference**										
	1	2	3	4	5	6	7	8	9	10	11
1	0.9	1.7	1.6	3.8	2	1.9	0.6	0.1	2.9	0.4	4.8
2	4.9	3.1	6.1	6	2.8	4.7	4	0.8	5.6	1.8	8.9
3	8	4.7	9.5	8.5	3.1	8	8.1	1.8	9.3	3.2	13.3
4	12	6.6	13.7	11.3	4	11.5	13.8	2.8	14.2	4.9	18.5
5	11.3	13.1	9.6	14.9	15.7	12.4	5.2	13.8	6.4	12.9	11.1
6	21.7	27.2	16.1	29.2	27.7	24.9	11.2	27.7	12.9	27.2	20.5
7	49.1	53.9	29.4	57	41.2	50.7	33.2	53.2	37.3	53.9	43.8
8	98.1	99.6	68.9	107.8	47.1	98.4	74.3	94.9	78.7	99.4	86.5
9	1.7	2.7	2.6	6.3	2.8	7	0.9	1.4	5.8	1.5	7.8
10	6.8	5	9.2	9.8	3.7	10.5	6	2.4	10.9	3.3	12.7
11	10.9	7.3	15	13.2	4	13.9	12.2	3.4	17.3	5.1	18.1
12	15.9	9.8	21.6	16.7	5	17.4	20.1	4.6	24.3	7.1	24.2
13	13.9	16.1	13.2	19.6	17.8	17.3	8.1	16.1	12	14.8	16.1
14	13.9	16.1	13.2	19.6	17.8	17.3	8.1	16.1	12	14.8	16.1
15	52.1	56.8	37.4	61.6	44.5	53.2	36.8	55.3	47.6	55.6	49.8
16	101.2	102.7	78	112.3	53.1	101.1	76.8	96.5	87.1	101.1	93.9

Configuration	**Item Reference**									
	12	13	14	15	16	17	18	19	20	21
1	2.4	1.4	0.5	2.6	3	0.3	0	0.1	1.8	1.7
2	5.5	3.6	2.1	4.9	7.8	1.8	1.6	2	2.9	3.1
3	9	5.8	3.8	6.9	12.6	3.3	3	4.1	3.9	4.3
4	12.6	9	5.7	9.4	18	5	4.6	5.8	5.1	5.4
5	12.5	10.8	11.5	14.8	11.3	11.7	9.8	11.3	15	13.8
6	22.6	24.8	23.2	28.8	19.7	24.9	23	24.4	27.1	27
7	48.2	51.5	43.8	54.2	40.6	51.1	50	51.4	43.2	50.1
8	95.7	95.5	74.6	97.6	82.7	97.9	97.1	99.4	52.8	89.6
9	4.9	2.7	0.5	4	5.9	0.8	0.2	0.2	1.9	3

10	9.1	5.9	2.3	6.9	11.3	2.6	2	2.3	3.1	4.4
11	13.7	9.5	4.2	9.5	16.7	4.5	3.8	4.5	4.3	5.9
12	18.3	13.6	6.1	12.6	22.6	6.6	5.9	6.3	5.8	7.4
13	17.5	14.7	12.3	17.8	14	13.2	12.1	12	15.7	16.1
14	29.3	29	23.9	32.1	22.3	26.5	25.9	25.5	27.6	30
15	56.3	55.3	44.6	58.6	43.9	52.8	52.9	52.5	43.5	55.1
16	106.3	100	77.1	103.7	85.6	99.6	100	100.3	53.1	95.1

Table 14: Percentage Deviation from Average Cycle Release Quantity

Configuration	**Item Reference**										
	1	2	3	4	5	6	7	8	9	10	11
1	147.5	125	152	170	233.3	135	120	160	122	125	140
2	147.5	125	128.33	170	175	137.5	120	160	124	125	140
3	145	130	128.33	170	175	137.5	120	170	124	130	142.5
4	145	130	130	116.67	200	140	120	170	126	130	114
5	112.5	110	108.33	140	160	112.5	94	170	84	115	97.5
6	82.5	110	90	96.67	133.3	102.5	70	170	66	115	85
7	75	115	60	96.67	112.5	80	62	90	56	120	60
8	58	80	38.33	103.33	69.2	58	58	90	41.67	83.33	58
9	147.5	125	125	165	233.3	137.5	120	160	122	130	140
10	147.5	125	126.67	170	175	140	120	170	122	130	114
11	147.5	125	128.33	170	175	140	120	170	124	130	114
12	147.5	125	130	113.33	200	140	120	170	126	135	116
13	122.5	120	111.67	145	160	115	96	170	84	120	112.5
14	92.5	120	90	96.67	150	102.5	72	170	62	125	70
15	60	125	60	100	112.5	82.5	60	90	56	125	60
16	58	83.33	37.14	103.33	69.2	60	54	90	41.67	86.67	58

Configuration	**Item Reference**									
	12	13	14	15	16	17	18	19	20	21
1	156.67	125	170	125	135	125	135	155	90	160
2	160	130	180	130	137.5	125	135	155	90	160
3	160	130	180	130	140	125	135	160	100	160
4	160	130	180	130	140	125	135	155	90	160
5	136.67	115	170	115	115	115	120	135	90	150
6	106.67	115	170	120	92.5	115	120	140	90	160
7	80	120	90	125	62	120	125	93.33	90	170
8	77.5	80	85	83.33	60	83.33	83.33	96.67	30	85
9	160	125	180	125	137.5	125	130	155	90	160
10	163.33	130	180	130	137.5	125	130	155	90	160
11	163.33	130	180	130	112	130	135	160	100	160
12	122.5	130	180	135	112	130	135	155	90	160

13	143.33	120	180	125	120	120	125	140	90	160
14	87.5	120	180	125	82	120	125	145	90	170
15	82.5	125	90	130	68	125	130	96.67	90	170
16	80	83.33	90	86.67	64	83.33	86.67	100	30	90