MASTER

A framework for supply chain planning in make-to-forecast environments

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A Framework for Supply Chain Planning in Make-to-forecast Environments

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Subject headings: make-to-forecast; logistics; production strategy; supply chain management; supply chain planning; hierarchical planning; sales and operations planning; supply chain operations planning; supply chain responsiveness; supply chain integration; nervousness; planning stability; material coordination; capacity planning; inventory control; customer order decoupling point; tactical buffer management; manufacturing flexibility
“Education is an admirable thing, but it is well to remember from time to time that nothing that is worth knowing can be taught.”

Oscar Wilde
Abstract
A Framework for Supply Chain Planning in Make-to-forecast Environments
by M.D. (Marten) Kraaij

For high-tech supply chains, increased competitive pressures are demanding faster delivery of more customized products without increased costs. This requirement for responsiveness leads to a challenging Make-to-forecast business environment, where resource and pipeline alignment is of the highest strategical value. If these challenges are not addressed adequately, planning nervousness might be a consequence.

In this master thesis, we develop a framework for supply chain planning and control in a Make-to-forecast environment, that serves to improve responsiveness and stability. This framework is applied to the real-life supply chain of FEI Company, a high-tech microscope manufacturer. We identify gaps between the ideal and the currently used planning methodology.

To address these gaps, we developed an innovative approach for constraint-based aggregate and operational planning, that supports the development of control mechanisms and the placement of buffers against uncertainty.
Management summary

In this report, we present the results of a master thesis on the subject of supply chain planning (SCP) for OEMs in the high-tech industry. It is the result of research and a case study within FEI Company, a manufacturer of high-end microscopy technology. The project has been initiated by FEI’s Global Supply Chain team, and was carried out in collaboration with Eindhoven University of Technology (TU/e).

Problem Description

Increased competitive pressures in the global economy are demanding faster delivery of more customized products without increased cost. This challenge requires marketing and operation to develop innovative responses for achieving these historically antithetical competitive objectives: quick delivery and a highly-customized product.

High-tech supply chains that deliver customer-specific goods are characterized by their long manufacturing lead times; high product variety; low production volumes; and complex bill of material structures with expensive components. Rapid technological developments and volatile markets lead to a high risk of obsolescence and sudden demand ramp-ups.

As a result, end-product manufacturers such as FEI adopt a Make-to-forecast production strategy (Meredith & Akinc, 2007): they start building end-products without a definitive customer order and configuration specifications. Somewhere along the production process, the order is matched to a unit in the Work-in-process (WIP).

For FEI, a consequence of this strategy is that they experience a lack of planning stability, i.e. a discontinuity in maintaining former ordering decisions, also known as planning nervousness. We identify this as a symptom of a mismatch between external requirements for flexibility and internal determinants for flexibility, such as defined in the framework for supply chain responsiveness (SCR) of Reichhart and Holweg (2007).

Our research focuses on planning and control (the SCR determinants demand anticipation and inventory (Reichhart & Holweg, 2007)), and from that perspective, we identify the lack of an integrated strategy for decoupling uncertainties and a lack of control and consideration how to protect decoupling points from the effects of variation. As a solution, our main objective is to develop a framework for SCP and we answer the main research question:

*How to use a framework for supply chain planning and control, buffers against uncertainty and control mechanisms, in a Make-to-forecast environment, under the objective of improving responsiveness and stability?*

First, this question is answered through a definition of the concepts responsiveness and stability in Chapter 1.

New framework for SCP

Second, this question is answered by providing an adapted framework for SCP in a Make-to-forecast environment in Chapter 2. The foundation for this framework is in the case study at FEI and it consistent with other theories in the field of SCP, such as the SCP matrix (Fleischmann, Meyr, & Wagner, 2008) and the Eindhoven framework (Bertrand, Wortmann, & Wijngaard, 1998; De Kok & Fransoo, 2003). We present the outline of this framework in Figure 0.1. Furthermore, we modeled SCP with three operational planning concepts (OPC), where we identify
decision functions and their time-phasing on strategic level (Figure 2.4), aggregate / S&OP level (Figure 2.5), and on a level between tactical and operational planning, consisting of order acceptance, supply chain operations planning (SCOP) and production unit control (Figure 2.6).

Third, we contribute to answering the main research question by taking into account the objectives of responsiveness and stability in this framework. We do this by using the framework for SCR of Reichhart and Holweg (2007) and reflecting on the decision functions through which internal flexibility determinants are constituted.

From theory to practice: the case study

Fourth, we applied this framework at FEI Company, by comparing the ideal situation to the current situation in Chapter 3. This comparison lead to the identification of five important gaps, that can be categorized in the demand anticipation and inventory determinant of the SCR framework:

- Supplier agreements are mainly cost price focused, and only to a lesser extent enabling flexibility.
- The current forecasting process does not actually result in an estimation of company-wide future sales volumes, but is rather an expression of hopes and objectives. This creates e.g. unnecessary escalated orders to the supply chain, and longer manufacturing lead times. We recommend to discuss this issue on a high level within the organization to improve demand management.
- The order acceptance process is an ambiguous process. There is no firm customer lead time nor are there milestones in the Sales process. As a result, capacity management, configuration management and workload control are not addressed sufficiently.
- Parameter setting is not defined as an integrated process, and not executed in a structural manner.
Current aggregate planning and master production scheduling (MPS) practices do not provide a good basis for capacity management and material feasibility analysis in an early stage.

Closing the first three gaps can only be reached through a change in business strategy, i.e. through initiatives on executive level. We recommend further investigation and collaboration between responsible departments on these issues.

Approach for constraint-based planning

As a fifth contribution to answering the main research question, we (partially) address the last three gaps (partially with our methodology for constraint-based planning, such as described in Chapter 4. This approach supports the development of control mechanisms and placement of buffers against uncertainty. The basis for this methodology is a categorization of material and a description of the material flow in an MTF environment (Figure 2.1). This serves as a basis for different material coordination policies.

Our approach (Figure 0.2) entails the description of a planning process with aggregate planning, capacity management and forecasting to suppliers in a monthly cycle. This process is supported on a lower hierarchical level, in a weekly cycle. To support calculation of material feasible order releases, we propose to use material availability planning (MAP) (De Kok et al., 2005), as an alternative to most commonly used MRP-I logic. We tailored the MAP algorithm to low-volume MTF manufacturing environments. Additionally, we provide a basic discussion on parameter setting and associated buffering practices.

This approach could result in more responsiveness and more stability in planning. We support this hypothesis qualitatively, but applications and quantitative methods are needed to provide more empirical evidence.
Conclusions and recommendations

An extensive reflection on this research can be found in Chapter 5. The research and case study are a first conceptual step towards integrated planning and material coordination in MTF environments, specifically for high-tech OEMs and FEI, but the framework and planning approach is to a large extent generalizable.

We provide an ideal framework and planning methodology, and the implementation of these concepts is the actual recommendation, both for FEI as well as for other firms in a similar business environments.

Concrete recommendations for improving responsiveness at FEI specific include setting firm internal lead times, implementing constraint-based planning, starting a follow-up study for better demand anticipation and forecasting, and including flexibility requirements in supplier selection processes.
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<td>AM</td>
<td>Agile Manufacturing</td>
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<td>APS</td>
<td>Advanced Planning Systems</td>
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<td>ASP</td>
<td>Approved Shipment Plan</td>
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<td>ATO</td>
<td>Assemble-to-order</td>
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<td>ATP</td>
<td>Available-to-Promise</td>
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<td>BOM</td>
<td>Bill-of-Material</td>
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<td>BTO</td>
<td>Build-to-order</td>
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<td>CODP</td>
<td>Customer Order Decoupling Point</td>
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<td>CRM</td>
<td>Customer Relationship Management system</td>
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<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<td>ETO</td>
<td>Engineer-to-order</td>
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<td>FEI</td>
<td>Field Electron and Ion</td>
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<td>HP</td>
<td>Hierarchical Planning</td>
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<td>JIT</td>
<td>Just In Time</td>
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<td>KPI</td>
<td>Key Performance Indicator</td>
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<td>LP</td>
<td>Linear Programming</td>
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<td>LT</td>
<td>Lead Time</td>
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<td>Material Availability Planning</td>
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<td>MOQ</td>
<td>Minimum Order Quantity</td>
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<td>MPS</td>
<td>Master Production Schedule(s)ing</td>
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<td>MRP</td>
<td>Material Requirements Planning</td>
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<td>MRP-I</td>
<td>Material Requirements Planning logic</td>
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<td>MRP-II</td>
<td>Manufacturing Resource Planning</td>
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<td>Make-to-forecast</td>
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<td>MTS</td>
<td>Make-to-stock</td>
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<tr>
<td>MTO</td>
<td>Make-to-order</td>
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<td>NPI</td>
<td>New Product Introduction</td>
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<td>NSR</td>
<td>Non Standard Request</td>
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<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>OPC</td>
<td>Operational Planning Concept</td>
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<td>PBOM</td>
<td>Percentage BOM</td>
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<td>ROE</td>
<td>Return On Equity</td>
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<td>S&amp;OP</td>
<td>Sales &amp; Operations Planning</td>
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<td>SCOP</td>
<td>Supply Chain Operations Planning</td>
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<td>SCP</td>
<td>Supply Chain Planning</td>
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<td>SCR</td>
<td>Supply Chain Responsiveness</td>
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<td>SEM</td>
<td>Scanning Electron Microscopy</td>
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<tr>
<td>TCO</td>
<td>Total Cost of Ownership</td>
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<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
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<tr>
<td>VMI</td>
<td>Vendor Managed Inventory</td>
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<td>WIP</td>
<td>Work-in-Process</td>
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Chapter 1

Introduction

Increased competitive pressures in the global economy are demanding faster delivery of more customized products without increased costs. This challenge requires marketing and operations to work together to develop innovative responses for achieving these historically antithetical competitive objectives: quick delivery and a highly-customized product.

High-tech supply chains deliver customer-specific capital goods, assembled through a multitude of steps, executed by a multitude of different companies. Production volumes are low; product variety is high; bill of material structures are complex and include expensive components. Rapid technological developments lead to a high risk of obsolescence and sudden demand ramp-ups. Moreover, the end-product manufacturer operates in volatile market conditions, since in many cases customer bases are prone to cyclical demand and/or partly dependent on government spending priorities. In the past decades, time has become a factor in competitiveness as customers are increasingly reluctant to accept long lead times for products.

These complications lead to a challenging business environment, where resource and pipeline alignment within the supply chain is of the highest strategical value. This main challenge can be described as supply chain responsiveness (SCR): "[...] the speed with which a system can adjust its output [...] in response to an external stimulus" (Reichhart & Holweg, 2007). This concept rests at the core of various operations strategies such as lean thinking (Womack & Jones, 1996), Agile Manufacturing (AM) (Naylor, Naim, & Berry, 1999), and more recently Build-to-order (BTO) (Gunasekaran & Ngai, 2005; Mansouri, Gallear, & Askarianazad, 2012), demand-driven supply chain (Mendes, 2011; Smith & Smith, 2013), and Make-to-forecast (MTF) (Meredith & Akinc, 2007; Akinc & Meredith, 2015).

The objective of this study is to extend scientific knowledge and to develop solution concepts for high-tech OEMs to become more responsive and improve planning stability. Specifically, we aim to create a better understanding of the relation between responsiveness and supply chain planning; the effects of buffers against uncertainty; the effects of control mechanisms; and guidance on the optimal location of decoupling points for companies operating in the high-tech industry. To create an improved understanding of concepts such as responsiveness, flexibility, and stability in a SCP context, we describe a new conceptual framework for Supply Chain Planning (SCP) (Fleischmann & Meyr, 2003) in this industry.

The study is the result of a master thesis project at Eindhoven University of Technology, in collaboration with FEI Company, a designer and manufacturer of high-end microscopy systems. We start the remainder of this Chapter with a discussion on the research methodology (Section 1.1). We continue with an introduction to FEI and the problem context in Section 1.2. In relation to the problem context, we introduce some concepts from literature (Section 1.3). Then, we define the scope of the research (Section 1.4) and subsequently we formulate research questions in Section 1.5.
1.1 Research Methodology

One can make a distinction between explanatory sciences, like the natural sciences and most social science on the one hand, and design sciences, like medicine and engineering, on the other hand. Our research study fits within the latter paradigm. Van Aken (2005) described the mission of a design science: "to develop knowledge that the professionals of the discipline in question can use to design solutions for their field problems." Research in this paradigm is of a more pragmatic nature; it can be seen as a quest for understanding and improving human performance. The objective is to develop prescriptive knowledge in the form of technological rules or solution concepts.

We structure our research according to the associated reflective cycle for design-based problem solving in organizations (Van Aken, Berends, & Van der Bij, 2007; Heusinkveld & Reijers, 2009), see Figure 1.1.

The reflective cycle commences by concentrating on a specific domain of problem situations. We select the problem of improving responsiveness and stability in a make-to-forecast environment (see Sections 1.2.3 and 1.5). The selected case is the complex supply chain of FEI. In the selected case, the problem is addressed by enacting reality on the basis of the regulative cycle (Van Strien, 1997). According to Heusinkveld and Reijers (2009), the regulative cycle serves to understand a unique situation through the attempt to change it. Key elements of this process are problem formulation, problem diagnosis, design, and implementation of the design, after which the effects are evaluated in the light of the initial problem formulation. An iterative search process, not necessarily in a set order, continues until a satisfactory solution crystallizes. The output of the regulative cycle is a theory of practice that is applicable only in the individual case (Van Strien, 1997). In the scientific process of reflecting, we may generalize such a theory. Van Aken (2004) posited that through testing a technological rule by following the reflective cycle, one can gain insight into indications and contra-indications for successful applications, i.e. design knowledge. If we observe a research field, the reflective cycle is considered an iterative process. This project however, will comprise one instance only.

![Figure 1.1: The reflective cycle (Heusinkveld & Reijers, 2009)](image)
Chapter 1. Introduction

Practically, our research methods include:

- **Desk research**, including the use of academic literature, company documents, and company databases, to retrieve insights and support generation of new design knowledge.

- **Interviews** to discuss current problems and important issues to consider. Furthermore, to investigate new concepts and solution directions regarding material requirements variability. Lastly, to validate quantitative results as gathered from FEI’s databases.

- **Modeling** required to support the design phase of the project. This concerns development of mathematical models and quantitative concepts to understand the existing processes.

1.2 Problem context

1.2.1 Company background

FEI Company\(^1\) is an American publicly traded Original Equipment Manufacturer (OEM) in the high-tech secor. FEI designs, manufactures and supports electron, ion and light microscopy technology in its headquarters, located in Hillsboro, Oregon, and two other large sites in Eindhoven (Acht), The Netherlands, and Brno, Czech Republic. FEI was founded in 1971; the current company however, was formed by the 1997 merger with Philips Electron Optics. As such, the company can trace its roots in the electron microscopy to early commercial instruments produced by Philips in the 1940s.

It is FEI’s mission to enable customers to find meaningful answers to questions that accelerate breakthrough discoveries, increase productivity, and ultimately change the world. Their customers include world-renowned research institutes and universities, the life sciences industry, and semiconductor manufacturers. FEI has over 3,000 employees and sales and service operations in more than 50 countries around the globe. As of 2015, yearly revenues amount to $930 million (FEI Company, 2015).

This research focuses on the supply chain of the Eindhoven factory, where only Transmission Electron Microscopes (TEMs) are produced — FEI’s most complex systems. Each TEM is customer-specific; FEI produces around 2 of such systems yearly.\(^2\) In the remainder of this document, we refer to FEI Eindhoven (Acht) with FEI.

1.2.2 Challenges in the supply chain

The following distinguishing characteristics impact the high-tech industry, and FEI in particular.

Product complexity and diversity

FEI produces four different TEM models, but within these models many variants are possible. Variants are distinguished by options, which are in many cases not just add-ons or simple extensions of a model, but functionality that is integrated in a system. Some functionality requirements of an order are Non-standard Requests (NSRs): unique additions and adjustments. Microscopes are built on nanometer \(10^{-9}\) meter precision, and are highly sensitive to vibrations. The complexity is illustrated by the production process. It requires about two months to build an exemplary TEM, but an additional four to ten months to calibrate and test it. Changes in

\(^1\)As of September 19, 2016, Thermo Fisher Scientific Inc. has completed its acquisition of FEI Company. Thermo Fisher is the world leader in serving life science research customers, with revenues of $17 billion and more than 50,000 employees in 50 countries. Their mission is to enable our customers to make the world healthier, cleaner and safer. At the time this research was conducted, FEI were an autonomous firm. For this reason, there is no further mention of Thermo Fisher throughout this report.

\(^2\)The exact number is redacted for confidentiality reasons. The remainder of this thesis includes additional redaction of numbers and/or chart axis for data concerning production volumes or margins.
configuration during lead time require additional assembly and testing operations. Not only are the end-systems complex — many components are as well. That implies relatively long component lead times of up to 6 months, and serious yield risks.

Volatile market conditions

The industries in which FEI sells products are cyclical, which may cause results of operations to fluctuate. Furthermore, changes in product demands from customers may increase volatility. Economic outlooks have a large effect on the demand for high-end microscopy systems. Customers make a capital-intensive investment for multiple years — a strategically important decision. Science customers are in many cases subject to government budgets and subsidies, changes and fluctuations in government spending priorities and procurement practices could adversely affect the revenue (FEI Company, 2015). A request for budget may be followed by a long process before approval, due to bureaucracy. When, if and for what exactly approval will be reached is uncertain. This results in demand uncertainty (timing) and variability (quantity) for FEI. It adversely impacts FEI's ability to forecast demand and revenues.

Rapid technological developments

Technology developments are imminent for FEI. Customers experience rapid technological changes, with which FEI must keep pace (FEI Company, 2015). To compete successfully, FEI must succeed in their R&D efforts, develop new products and production processes, and improve their existing products and processes ahead of competitors. As a result, typically, one generation of a microscope is used for one year. Phasing-in and -out system types or generations and corresponding components is an ongoing process. Compare the short product life cycle to the internal lead time of nine months, and the total lead time (including purchase parts) that might be up to one and a half years. This asymmetry results in a high risk of obsolescence and it is a source of supply chain nervousness.

1.2.3 Problem statement

The problem statement and motivation for this research project is as follows:

FEI experiences experiences a lack of planning stability, i.e. a discontinuity in maintaining former ordering decisions, also known as planning nervousness (Vollmann, Berry, & Whybark, 1997; De Kok & Inderfurth, 1997).

We organized interactive interviews with several stakeholders within and around the Logistics department to support this problem statement. As a result, we constituted a cause and effect diagram, which was validated through an iterative process of interviews with stakeholders and some general quantitative analyses. The diagram is depicted in Appendix A. It reveals several causes and effects for FEI specific. Our research approach is to address the problem of planning nervousness for high-tech OEMs in general. Therefore, we first look at academic literature on some concepts that relate to this problem statement.

1.3 Concepts in the literature

1.3.1 Responsiveness, flexibility and stability

Roh, Hong, and Min (2014) studied the concept of supply chain responsiveness (SCR); they proposed that firms must become more customer-centric, information-intensive and flexible in order to become responsive to demand oscillation. The main objectives of SCR are therefore: i) to improve agility by utilizing point-of-sales information; ii) to increase flexibility by streamlining
and centralizing supply chain planning; and iii) to reduce risk by removing potential bottlenecks and disruptions in the supply chain.

Gunasekaran, Lai, and Cheng (2008) emphasized supply chain integration as an SCR enabler; they defined the responsive supply chain as "a network of firms that [...] can react quickly and cost effectively to changing market requirements."

Reichhart and Holweg (2007) provided an extensive discussion of SCR and introduce a conceptual framework (see Figure 1.2). They defined SCR as "the speed with which a system can adjust its output within the available range of four external flexibility types: product, mix, volume and delivery, in response to an external stimulus, e.g. a customer order." External flexibility can be linked to achieving a competitive advantage; it is the flexibility that a customer might be interested in. On the other hand, internal flexibility is the ability of any system to adapt to internal or external influences, thereby acting or responding to achieve external flexibility. If a system requires a high level of external flexibility, internal flexibility should enable this. Reichhart and Holweg (2007) distinguished factors that require SCR (demonstrated SCR, equivalent to external flexibility) and determinants that enable to be responsive (potential SCR, equivalent to internal flexibility). In this light, being flexible as a firm is a requirement to be responsive.

![Figure 1.2: Supply chain responsiveness: a conceptual framework (Reichhart & Holweg, 2007)](image-url)
1.3.2 The value of stability

The importance of stability in a planning context might not be as trivial as e.g. the customer service level or inventory costs. In literature, we find five different negative effects of planning nervousness.

- Rescheduling activities is labor intensive. In many cases these consequences can however, "not be valued in terms of cost or lost profits, since relevant replanning expenses depend on time-varying availability of planning capacity." (De Kok & Inderfurth, 1997, p. 12)

- The impairment of performance in short-term production control due to quickly altering production decisions (De Kok & Inderfurth, 1997). Indirectly, this can lead to a loss of goodwill towards the planning system. Again, these consequences are invaluable.

- Errors and mistakes in planning and communication. This effect is amplified in MRP-based planning, since MRP does not allow for identification of root-causes for action messages (Kraaij, 2016).

- Nervousness is propagated throughout a supply chain (De Kok & Inderfurth, 1997). The phenomenon of variability amplification upstream the supply chain is generally known as the bullwhip effect (Lee, Padmanabhan, & Whang, 1997). The bullwhip effect could result in excessive inventory, poor product forecasts, insufficient or excessive capacities, poor customer service, uncertain product planning and high costs for corrections throughout a supply chain (Lee et al., 1997). De Kok (2012) showed that the bullwhip returns, i.e. not only upstream links in the supply chain, but also downstream links suffer from the bullwhip effect.

- Nervousness can compromise the ability to effectively integrate manufacturer-vendor processes leading to higher total system costs (Sahin, Robinson, & Gao, 2008). For example, establishing an effective order commitment policy is a key method for improving channel integration and creating order visibility throughout the supply chain. The success of these policies hinges on a stable replenishment schedule to the vendor (Sahin et al., 2008).

1.3.3 Make-to-forecast

Traditionally, production strategies can be mapped as a responsiveness/customization trade-off. Actually, that translates into a trade-off between customer and manufacturing lead times. Akinc and Meredith (2015) presented a conceptual model to illustrate this as in Figure 1.3. The specific business environment at FEI and similar companies in high-tech supply chains require an unconventional production strategy. This "Make-to-forecast" (MTF) strategy is used, especially for large engineered equipment, to better meet today’s competitive pressures for faster delivery of more customized products without increasing costs (Meredith & Akinc, 2007). Firms like FEI must anticipate customer specifications as best they can and start building as if they are using a Make-to-stock (MTS) strategy. This is the forecast part. As orders arrive, they are matched to the existing units somewhere in the production pipeline, considering (among other things) the costs of modification. From that point on, the units are finished off in the manner of a Make-to-order (MTO) strategy. As such, Akinc and Meredith (2015) observe that the Customer Order Decoupling Point (CODP) (Hoekstra & Romme, 1992) is "floating" with each customer order. For such a case, the ETO, MTO, ATO and MTS production strategies do not apply, as well as a multi-dimensional CODP variant (as introduced by Wikner and Rudberg (2005)), since these strategies define a fixed CODP and require an unambiguous BOM.

The MTF strategy is useful in industries where the product is differentiated early and lengthy manufacturing lead times exceed customers’ desired delivery times (Akinc & Meredith, 2015). Then, modification could be faster than starting production when customer order specifications are known. It is important to note the consequences of MTF: rework, a return flow of modules
and/or components, and an immediate need for modules and components at the moment of order matching. In this research, we aim to address these challenges for material coordination.

1.4 Scope

We use the SCR framework (Figure 1.2) to define our scope. This research is written from an operations planning and control perspective, and focuses on improvements in the flexibility induced by internal determinants of SCR.

We discuss how external requirements and internal determinants for SCR as defined by Reichhart and Holweg (2007) are constituted in high-tech supply chains in general, and for FEI specific. Since we focus on planning on a tactical level, the external requirements are mostly described as a given situation.

Concerning internal determinants, this research provides a discussion on how a high-tech OEM can influence these. Regarding operational determinants, our discussion on product architecture and manufacturing flexibility will be concise, since these determinants are constituted on a strategic level, and within real organizations only to a small extent influenced by departments involved in supply chain planning. The remaining two operational factors are demand anticipation and inventory. These determinants are strongly intertwined and both fit within the context of Supply Chain Operations Planning (SCOP), Parameter Setting and Aggregate Planning, as discussed in the planning hierarchy framework of De Kok and Fransoo (2003). These determinants will be the main focus of this research.

Determinants of supply chain integration cover collaborations between different supply chain partners. Our discussion on the advantages of these collaborations will be of a more qualitative nature.

Our research is of a conceptual nature, in the sense that we describe processes and methodologies; we do not provide detailed (quantitative) analysis of models that support decision making.
1.5 Research questions

We propose that a lack of planning stability can be a symptom of a mismatch between demonstrated and potential SCR, based on the FEI case and the cause-effect diagram in Appendix A. This means that planning nervousness is a symptom of an immature strategy to achieve control on internal responsiveness determinants.

The objective of this study is to extend scientific knowledge and to develop solution concepts for high-tech OEMs to become more responsive. Concerning planning and control within FEI, we identify the lack of an integrated strategy for decoupling uncertainties and a lack of control and consideration on how to protect decoupling and control points from the effects of variation. This fits within the demand anticipation and inventory determinants for responsiveness (Reichhart & Holweg, 2007), and is in line with contemporary challenges for the industry (Smith & Smith, 2013). As a solution, we develop a framework for supply chain planning, in order to structure the use of flexibility and buffers and create better understanding on trade-offs between responsiveness and costs of logistics. This is summarized in the main research question for this project:

How to use a framework for supply chain planning and control, buffers against uncertainty and control mechanisms, in a Make-to-forecast environment, under the objective of improving responsiveness and stability?

In order to answer this question, reach the objectives, and structure the project, we use supportive detailed questions:

1. What is planning nervousness and how does it relate to responsiveness and flexibility?
2. What kind of framework for supply chain planning should be used to improve responsiveness and stability?
3. How can we use decoupling points and buffers against uncertainty, such as safety lead time and safety stocks, to improve internal flexibility?
4. How can we address the specific complexities in material coordination in a Make-to-forecast environment?
5. Which methods can be used for supply chain integration, to improve internal flexibility?

Additionally, we use the situation at FEI and perform a case study to propose a redesign and to identify innovative technological rules. For that purpose, we have defined the following questions.

6. In relation to responsiveness, what are the key features of the currently employed framework and mechanisms for supply chain planning and control at FEI?
7. How can FEI improve its supply chain planning processes and mechanisms to improve planning stability and to become more responsive?

1.6 Thesis structure

The remainder of this thesis is structured as follows. In Chapter 2, we define an ideal framework for SCP that serves as a basis for improving responsiveness. This framework is based on literature. We describe a case study on improving responsiveness at FEI in Chapter 3, compare the ideal situation with the situation at FEI, and as a result define three gaps in in FEI’s processes. In Chapter 4, we discuss a part of the framework (SCOP) in more detail and describe a new methodology for material coordination. Finally, in Chapter 5 we reflect on this work by answering the research questions defined in Chapter 1, by discussing limitations of this research, and by presenting recommendations for FEI as well as future directions for academic research.
Chapter 2

Supply chain planning framework

A responsive supply chain can be defined as "a network of firms that is capable of creating wealth to its stakeholders in a competitive environment by reacting quickly and cost effectively to changing market requirements" (Gunasekaran et al., 2008). Responsiveness is similar to Agile Manufacturing (AM), with the difference that AM only focuses on speed and flexibility, and not on cost (Gunasekaran et al., 2008). This definition is in accordance with the routemap to the responsive business of Christopher (2016, p. 132). He identified four contributing factors to responsiveness: agile supply; organizational agility; being demand driven; and strategic supply chain decoupling.

In this Chapter, we introduce a framework for Supply Chain Planning (SCP), that could serve to achieve such a responsive supply chain, and provide a basis to influence contributing factors. It includes decision functions and serves as a basis for a strategy on planning and control. We present a hierarchical structure of decision functions and guidance on their execution. We relate our framework to the SCR framework (Reichhart & Holweg, 2007, see Figure 1.2); we start by defining external requirements for SCR in Section 2.1. In subsequent Sections, we introduce the basis of supply chain planning, until we present our high-level framework in Section 2.5, and more detailed decision functions in the subsequent Sections. We address some internal determinants for SCR throughout these Sections, and some separately in Section 2.12 and Section 2.13.

2.1 External requirements for SCR

We commence with a definition of the external requirements for SCR, since these define the functional requirements of an SCP framework for a responsive supply chain.

2.1.1 Demand uncertainty and variability

Reichhart and Holweg (2007) identified unpredictable demand as the main reason for being responsive. Under conditions of reliable information about demand, there would hardly be a need to be responsive. Davis (1993) identified three different sources of uncertainty: supply, demand, and manufacturing; and argues that of these, demand uncertainty is the most severe type. Davis (1993) did not distinguish between uncertainty and variability, while Reichhart and Holweg (2007) did: "demand can be stable by not deviating from the previous schedule or forecast, and can be level (i.e. not variable), whereby day-to-day changes are kept small within predefined boundaries." We should clarify this: uncertainty refers to the timing and quantity of demand ("when do customers request orders?"); variability to the specifications of demand ("what configuration does the customer require?").

2.1.2 Product variety

Holweg and Pil (2004) differentiated between three dimensions of product variety: i) external variety refers to the number of configuration options available to customers; ii) dynamic variety refers to the speed with which customers are given access to new products; and iii) internal
variety refers to the complexity of the manufacturing process and the variety of components. Reichhart and Holweg (2007) referred to internal variety with product architecture as part of the internal determinants for responsiveness.

The management of (external and dynamic) product variety has implications on the firm’s wider performance. The need for managing product variety results from the competitive performance of variety, and it’s potential financial impact for product development and manufacturing operations (Reichhart & Holweg, 2007). The product variety that a company wants to offer to its customers should determine the supply chain strategy (Fisher, 1997).

Demand uncertainty is amplified by product variety, since total demand is disaggregated over more products (Fisher, Hammond, Obermeyer, & Raman, 1994). If customers are not willing to accept longer lead times, product variety increases the need for responsiveness, as the range of external mix flexibility increases. In the past, this problem has led firms to rethink the level of variety that their customers really require (Fisher et al., 1994).

Additionally, we should note that we discuss product variety as an external requirement. However, high product variety makes the use of a finished goods buffer stock more costly. In that way, it directly inhibits supply chains from being responsive (Holweg & Pil, 2004).

2.1.3 Lead time compression

This requirement refers to the desired customer lead time. If the competitive environment requires time-based competition, the need for responsiveness increases, since the supply chain is given less time to respond to new orders and order changes (Reichhart & Holweg, 2007).

Additionally, there is an indirect effect of lead time compression (i.e. shorter customer lead times). In general, forecasts are less reliable on a longer time horizon. The forecasting horizon becomes longer if the customer lead time decreases in relation to the production lead time (Mather, 1992). Therefore, lead time compression results in increasing demand uncertainty.

2.2 Internal determinants for SCR

Reichhart and Holweg (2007) grouped the internal determinants into two broad categories. The first category includes operational factors that focus on individual nodes of the supply chain. Our discussion of these factors stems from operations management and SCP literature. The second category encompasses factors that deal with the integration of supply chain partners. Traditionally, literature on responsiveness has focused on these last factors (Reichhart & Holweg, 2007). The operational determinants are a consequence of decisions made within a planning hierarchy, and we discuss how these determinants are affected through the design of our SCP framework. Both product architecture and manufacturing flexibility are influenced on a strategic planning level.

Starting in the 1990s (Fisher et al., 1994), firms started to realize that market volatility can be coped with if the appropriate SCP processes are in place. Before that, demand was often seen as a given; solely an exogenous factor that the business must respond to, not proactively but only reactively. Reichhart and Holweg (2007) used the term demand anticipation to refer to S&OP and SCOP processes; we introduce a more detailed description of these concepts in this Chapter.

Since the inventory determinant and the supply chain integration determinants do not fit within one area of SCP, we discuss these separately.

2.3 Material flow in an ATO/MTF production strategy

Let us define a conceptual view on the material flow in the manufacturing process for an ATO production strategy (Figure 2.1), which is identical for a Make-to-forecast (MTF) strategy.
Separate modules are assembled; generic systems are assembled from modules and other materials; final systems are assembled from generic systems, extra modules and other materials. Some of the material is separately controlled with a KANBAN/2-bin system. An ATO strategy might not include the concept of a generic system when the final product is assembled from a collection of modules. In an ATO strategy, modules are always used in the same phase (start-up or configuration), whereas in an MTF strategy, materials might be used at a different phase for each system.

A backward material flow from configuration to upstream stock points is unique for the MTF production strategy. This flow includes both modules and other materials that are redundant as a result of the order matching process.

2.4 The customer order decoupling point

The development of a design for operations planning and control continues with defining the CODP (Hoekstra & Romme, 1992). The position of the CODP defines the supply chain strategy used (e.g. ETO, MTO, ATO, MTF, MTS).\(^1\) De Kok and Fransoo (2003) defined it as "the point that indicates how deeply the customer order penetrates into the supply chain; the distinction between the order-driven and forecast-driven parts of the supply chain." A consequence is that it is the boundary between push and pull (Mendes, 2011, p. 12), and that it separates physically efficient and market responsive processes (Fisher, 1997). According to Christopher (2016, p. 113), supply chains that deliver products with unpredictable demand and long lead times should employ a hybrid strategy. This strategy encompasses the definition of a CODP to divide the supply chain into a lean and an agile part (Figure 2.2).

Traditional literature (Hoekstra & Romme, 1992; Ashayeri & Selen, 2005) opts that i) to exclude uncertainty, it is best to put the CODP as far upstream as possible; ii) the position is pushed downstream by the customer service level requirements, i.e. if the requested lead time as a consequence of the competitive environment is shorter; iii) the product variety, i.e. to what extent products are universal or specific, is a factor of influence. Note that these three

\(^1\)Consider that the position of the CODP does not have to be the same for each product that a supply chain delivers.
guidelines for the CODP position fit exactly within the four forms of external flexibility as defined by Reichhart and Holweg (2007, further explanation in Section 2.1). Van Wanrooij (2012, p. 12) specified the influence of product variety, and introduces a controllability requirement for the CODP position. She argues that the CODP should be controllable, which is the case if the Coefficient of Variance (CV) for demand at the stock point is lower than 133%.

2.4.1 The difference between ATO and MTF

We observe that in a MTF production strategy (Akinc & Meredith, 2015), the CODP refers to the Work-in-process (WIP). When orders arrive, they are matched to existing units, which are all at a different stage in the production pipeline. Therefore, the CODP is at a different point in time for each order and the customer lead time is different for each order. Orders are never delivered off-the-shelf since systems are highly customer-specific and expensive.

The previous illustrates a difference between MTF and ATO. In an ATO system, the customer lead time is constant. Incoming orders are matched to existing units, that are all at the same stage of the production pipeline and finished in a planned lead time. The trade-off between early and late configuration is not different for each single customer order. With an ATO strategy, there is no rework as a consequence of order matching.

An ATO strategy should be preferred over MTF, since it enables the focus on efficiency in the push-part of the supply chain and the focus on responsiveness and agility in the pull-part of the supply chain. It provides a foundation for strategies on material coordination and buffering against uncertainty. For MTF models, these strategies are yet to be developed — Akinc and Meredith (2015) and Meredith and Akinc (2007) did not address material coordination in their papers; the developed models implicitly assume a capacity-constrained supply chain and ignore material constraints. This is contradictory to the situation in high-tech supply chains, where material constraints can be as important as capacity constraints.

However, an MTF strategy should be used in case there are no options for a controllable CODP, as a result of short and varying customer lead times, long manufacturing lead times, and large product variety.

2.5 Hierarchical planning

Along a supply chain, many decisions have to be made continuously, from rather simple operational decisions (e.g. the sequencing of jobs on a specific machine) to complex strategical decisions (e.g. increasing capacity by building a new plant). The generic term we use for the decisions on supply chain design, mid-term coordination and short-term scheduling is Supply Chain Planning (SCP). The idea could rise to address all planning tasks simultaneously with one comprehensive planning model. For reasons of mathematical complexity, this is not an option.

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2This number is based on a weakly supported theory of Hopp and Spearman (2008).
but Fleischmann and Meyr (2003) state four additional reasons in their handbook: i) the longer a planning horizon, the higher the uncertainty; ii) various lengths in planning horizons imply different frequencies of planning; iii) planning tasks on different levels need a different degree of aggregation in terms of time, place, products and resources; and iv) decisions are of different importance.

Hax and Meal (1975) defined the concept of Hierarchical Planning (HP) to describe the coordination of planning modules such that the right degree of integration can be achieved. The Supply Chain Planning matrix (Fleischmann et al., 2008, p. 87) is a paradigm in the research area and a widely accepted HP framework. This matrix is the basis of our planning framework. Whereas it explicitly separates decisions between the functional areas, Feng, D’Amours, and Beauregard (2008) argued for more integration on the mid-term level with a Sales & Operations Planning (S&OP) process, which was originally created by Ling and Goddard (1988).

Another hierarchical model was published by Bertrand et al. (1998), and described by De Kok and Fransoo (2003). Bertrand et al. (1998) also integrated decisions on the mid-term level, and introduced the term aggregate planning. In their model, Supply Chain Operations Planning (SCOP) has a central role. It is the theoretical objective of SCOP 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 & Fransoo, 2003). The idea of SCOP is that underlying PU’s, which represent the short-term level, operate as a black box, with a certain planned lead time that is required to transform inputs into outputs (De Kok & Fransoo, 2003). If we compare this framework with the SCP matrix, we observe that SCOP is not the same as medium-term planning, since it does not concern many aggregate planning decisions. SCOP is also not the same as short-term planning: De Kok and Fransoo (2003) argued that in most industries, SCOP deals with a horizon up to several months with weekly time buckets, whereas Fleischmann and Meyr (2003) argued that the planning horizon of short-term planning is restricted to a few weeks. Additionally, De Kok and Fransoo (2003) introduced parameter setting and order acceptance as separate functions.

To describe planning in the high-tech industry, we introduce a framework in Figure 2.3, which is a synthesis of the SCP matrix (Fleischmann et al., 2008, p. 87) and the SCOP hierarchy (De Kok & Fransoo, 2003).

2.6 Cross-functional coordination and integration

2.6.1 Information flows

The modules in hierarchical planning need to be connected by information flows (Fleischmann et al., 2008). Information flows can be divided into horizontal and vertical flows. Horizontal flows generally go upstream in the form of e.g. customer orders, sales forecasts, internal work orders and purchase orders. Information exchange in both directions and not only between neighbored modules can improve the supply chain performance, e.g. prevent the bullwhip effect.

Downward vertical flows coordinate subordinate plans and concern future events. These usually come in the form of constraints and decisions. Typical information entities are aggregate quantities, target levels, projected values, capacity allocations and due dates.

Upward flows provide the upper level with more detailed data on the attainment of sent-down decisions and constraints and the performance of the supply chain. These flows are feedback on vertical information flows that occurred previous in time. Examples include actual costs, utilization of equipment, lead times etc. This information can be used to anticipate consequences of high-level decisions for the lower-level processes.

Footnotes:
3 Originally in Dutch: aggregaatbeheersing or aggregaatproductieplanning.
4 This term is introduced by De Kok and Fransoo (2003), originally Bertrand et al. (1998) used the Dutch words materiaalcoördinatie (material coordination) and bezettingsplanning (capacity planning).
2.6.2 Time-phased decision functions

A hierarchical framework only shows the decision functions in their respective hierarchical level but lacks in time aspects. An operational planning concept (OPC) can be used to represent these time aspects: the sequence of decision functions and the frequency of decision making. It consists of a set of hierarchically ordered decision functions that eventually lead to i) timing and quantity of material and resource releases (SCOP) and ii) timing of the transformation processes employed to convert material into sub assemblies and end products (PU control). Generally, these decisions come in the form of theoretical outputs such as constraints, agreements and parameter settings; or more practical outputs such as work orders, procurement orders and purchase orders. An OPC is most effective when tailored to a specific business environment. In the following Sections, we introduce an idealized OPC that is specifically relevant for high-tech OEMs. Examples for different industries can be found in master theses (e.g. Broft, 2014; Kreuwels, 2014; Tjiptowidjojo, 2006).

Distribution is included in the hierarchical framework, but we exclude it from our further discussions, and assume that distribution does not constraint other SCP activities.

2.7 Strategic planning

Refer to Figure 2.4 for the strategic planning OPC. The decision about the product program a firm wants to offer is directly linked with long-term sales planning and financial planning (Fleischmann et al., 2008). Mostly, this process is performed on a high aggregation level (e.g. product families, sales regions). Following Fleischmann et al. (2008), one should consider customer lead times and respective decoupling points at this stage.

Long-term changes in product programs or sales figures as well as continuous improvement of available production technologies require to review the existing production capacities and
plant locations. Decisions on plant locations should be based on e.g. the implications for the distribution structure and the availability of knowledge workers. Resource planning is the process of establishing, measuring and adjusting limits or levels of long-range capacity, in terms of labor and manufacturing resources (APICS, 2016d). It imposes a manufacturing capacity constraint on lower hierarchy levels. Designing the manufacturing system entails organizing a single plant, i.e. designing the layout and resulting material flows. The design of the production system is also dependent of the design for manufacturing, i.e. the process that defines the product architecture (how products are made).

Furthermore, the design for manufacturing implies a materials program: the process that defines the materials that should be sourced currently and in the future. Supplier selection is a comprehensive approach for locating and sourcing key material suppliers. One should consider price, quality and availability at this stage, but also the constraints that different material coordination agreements impose on lower hierarchy levels (see Section 2.12). Further reduction of procurement costs is often achieved by strategic cooperation with suppliers of important components. Co operations can be implemented with models such as Vendor Managed Inventory (VMI) and Just-in-time (JIT) supply (Fleischmann et al., 2008).

We use the term strategic parameters to denote the collection of constraints that are set at a strategic level through all decision functions. Examples are revenue forecasts; budgets; manufacturing capacity in a plant; the flexibility of manufacturing equipment; the contracts and agreements with suppliers; and the customer lead time.

At this strategic level, product architecture and manufacturing flexibility are determinants for the responsiveness of a supply chain. For this reason, we address these concepts separately.

2.7.1 Product architecture

Product architecture constitutes internal product variety and manufacturability. Product design inhibits responsiveness, since it imposes constraints for the manufacturing process. Adjusting the product architecture can, be used as a way to employ decoupling points to offer a wide variety of products to end customers, while reducing inventory holding costs (Reichhart & Holweg, 2007).

Pérez Pérez, Serrano Bedia, and López Fernández (2016) identified two forms of flexibility to achieve through product architecture: i) Modification, the ability to implement minor design changes in a given product; and ii) Routing, the capability to use alternative sequences or routes to make a product.

Responsiveness can be increased through e.g. postponement of product differentiation activities (Lee & Tang, 1997) and modular design (Baldwin & Clark, 1997). In many cases, this requires cooperation with supply chain partners on product development (Petersen, Handfield, & Ragatz, 2005). The philosophy of postponement would ideally start in the development phase, so that products are designed with late configuration in mind. The longer products can
remain generic, the more flexibility there will be (Christopher, 2016, p. 128). Modular design possibly enables postponement, since a modular system is composed of units that can be built separately, and integrated as a whole in a later stage. Other advantages of modular design are that it spurs innovation (Baldwin & Clark, 1997) and that it reduces complexity for SCP.

### 2.7.2 Manufacturing flexibility

By definition, SCR requires the manufacturing system to be responsive. With the concept of manufacturing flexibility, we refer to flexibility in the process stage of the transformation process (Sawhney, 2006), that is not related to product architecture. Pérez Pérez et al. (2016) identified several relevant internal manufacturing flexibility types:

- **Expansion.** The ability to easily add capability and capacity.
- **Labor.** i) The range of tasks that a person can perform; and ii) the ability to vary the workforce.
- **Material.** i) The ability of the material handling system to move material effectively through the manufacturing system; and ii) the ability to make parts with alternative compositions.
- **Machine.** The ability of a machine to perform different operations.
- **Program.** The ability of a system to run virtually unattended.
- **Process.** The capability to produce a given set of parts types using different ways (process, material, or sequences).
- **Input-quality.** The ability to accommodate a range of input (mostly component) variations, and conform to a range of tolerances.

The latter five types (material, machine, program, process, and input-quality) all refer to a type of flexibility that is enabled through advanced manufacturing technology. Roh et al. (2014) presented an empirical study to confirm that this is a contributing factor to responsiveness.

In the context of manufacturing flexibility, Reichhart and Holweg (2007) mainly focused on the value of lead time reduction, through measures such as logistics lead times; faster information processing; and more direct manufacturing flexibility such as shortened machine changeover times. We see a similar focus on process lead time reduction within the AM paradigm (Mason-Jones & Towill, 1999). A broad range of research shows the necessity for lead time reduction as a pre-requisite for agility and responsiveness (Naylor et al., 1999; De Treville, Shapiro, & Hameri, 2004; Christopher, 2016).

### 2.8 Sales and Operations Planning

Refer to Figure 2.5 for the aggregate planning OPC. Sales and Operations Planning (S&OP) is a monthly-based tactical planning process, with the objective to balance demand and all supply capabilities of production, distribution, procurement and finance (Feng et al., 2008). It is designed to conjoin a number of the processes that we discuss in this section.

*Mid-term sales planning* considers the potential sales for product groups in specific regions or markets. The result of this process is "a time-phased statement of expected customer orders anticipated to be received" (APICS, 2016e): a forecast. The experienced level of demand uncertainty is mainly dependent on the quality of this forecast (Fleischmann et al., 2008). In a regular S&OP process, the final approved shipment plan (ASP) is a result of some process where

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5Throughout literature there is ambiguity on definitions of (types of) flexibility. As an example, Sawhney (2006) used the term process flexibility for the combination of manufacturing flexibility and product architecture in our definition.

6Pérez Pérez et al. (2016) and Reichhart and Holweg (2007) do not agree on the distinction between internal and external flexibility and the scope of manufacturing flexibility. Some of the manufacturing flexibility types Pérez Pérez et al. (2016, Table 6) identified are irrelevant for this part of our discussion. On the contrary, we adopt the input-quality type from Sawhney (2006).
manufacturing and marketing/sales agree on the plan (Mendes, 2011). For this reason, the feasibility of an initial sales plan for production and supply should be analyzed. The ASP is input for SCOP as well as the following aggregate processes.

Aggregate production planning is a process to develop tactical plans based on setting the overall level of manufacturing output and other activities to best satisfy the current planned levels of sales, while meeting general business objectives and performance indicators (APICS, 2016c). Capacity planning is part of this activity, and entails the amount of capacity needed on aggregate level.

Aggregate personnel planning has to calculate personnel capacity required for manufacturing. It requires specific know how of personnel groups, availability and labor contracts (Fleischmann et al., 2008).

Aggregate material requirements planning entails material coordination on a longer term. This process might include creating forecasts to suppliers over aggregated time buckets; detailed material coordination in small time buckets is part of SCOP (see Section 2.10). It can also include negotiating e.g. price, quality or delivery conditions of materials for the next planning horizon. Note that these decisions are constrained by supplier agreements made on a strategic level.

In the following Sections, we will elaborate upon the execution of S&OP and the parameter setting function, since these are both relevant processes in relation to responsiveness.

### 2.8.1 Execution of S&OP

Christopher (2016) provided six guidelines for successful S&OP:

1. **Generate aggregate demand forecast.** The aggregation level should be as detailed as possible, while allowing for a reasonable level of accuracy to be achieved. We argue for an aggregation level at the same position as the CODP (see Section 2.4). In that case, a similar controllability requirement holds, that would enable sufficient forecast accuracy.

2. **Modify the forecast with demand intelligence.** It is necessary to utilize specific intelligence on current market conditions and events, such as competitive products; substitutes; price changes; new product introductions; and end-of-life products.

3. **Create a consensus forecast.** A cross-functional approach through regular meetings is at the heart of S&OP.
4. Create a ‘rough-cut’ capacity plan. A firm should ensure that there is enough capacity and resources available. If not, demand should be managed (e.g. negotiate delivery lead times) or additional capacity has to be found.

5. Execute at SKU levels against demand. If possible, S&OP can be more detailed (i.e. can include product mix requirements) as one gets closer to the point of demand.

6. Measure performance. The performance indicator for the S&OP process should be how high the percentage of order achievement is, compared to the number of days of inventory and the amount of capacity needed to achieve that level.

Mendes (2011, p. 54) introduced a set of operational steps in the S&OP process, and discussed these in more detail. These include data gathering, forecasting, demand planning, analysis, and executive meetings. The ideas of both authors coincide with our ideal OPC (Figure 2.5), which consist of a mid-term sales planning or forecasting part, an aggregate planning part, which is equivalent to Christopher’s “rough-cut capacity plan” and Mendes’ “analysis” and an approval of the plan by marketing and operations executives.

Regarding execution of the S&OP process, Lapide (2004) adopted a more people-centered focus, and discussed 12 success factors of S&OP; the factors include cross-functional participation and empowered participants.

2.8.2 Parameter setting

Explicit tactical parameter setting is described by De Kok and Fransoo (2003) as a necessary function. These should not be set in the same time frequency as SCOP, but on a higher level. Optimal parameter setting in stochastic environments is not trivial: models for realistic situations are not mathematically tractable (De Kok, 2015).

The parameter setting function is key to the implementation and modeling of internal determinants. Parameters are set to create a predictable supply chain environment, for instance with the goal to achieve a certain degree of on-time delivery or fill rate, or to induce buffers that determine flexibility. Since they interact with each other, setting them should be an integral process that accounts for inter-dependencies.

Parameter setting relates to the CODP concept and can be used to decouple uncertainty: before the CODP, one is mainly subject to demand quantity uncertainty; after the CODP, one is mainly subject to timing uncertainty (De Kok, 2015). One could argue that demand quantity uncertainty for modules might still be present after the CODP, if customers demand for configuration changes. For the purpose of buffering against uncertainty we propose to address this problem separately. That means: aim to minimize these changes, or to defer the consequences of these changes to the customer. In case that is not a feasible business strategy, we propose that a company should create separate buffers for the purpose of configuration changes. The previous discussion reduces the problem of buffer placement and parameter setting into a number of decisions:

- Hedging or overstatement of demand in the S&OP phase. This is recognized as a valid buffer against demand uncertainty in literature (e.g. Tempelmeier, 2011, p. 302), and it can be categorized as a proxy for quantity buffers (safety stock) before and at the CODP.

- The use of quantity buffers before the CODP, in the form of slack materials and slack resources, to account for yield uncertainty and demand quantity uncertainty. This includes safety stock for components, generic systems and modules.

- The use of time buffers in the timing of order releases to subsequent phases in the final assembly process, to account for manufacturing process uncertainty (Atan, De Kok, Dellaert, Van Boxel, & Janssen, 2016). These buffers are set through planned lead times that include safety, in order to achieve a certain service level.
Chapter 2. Supply chain planning framework

- The use of specific buffers in time or quantity to address configuration changes. Again, safety stock and/or safety lead time.

- The use of target parameters, e.g. service levels for the supply chain as a whole as well as for separate PU’s, and utilization rate targets for resources, i.e. workload parameters.

As a consequence, there are two prerequisites for parameter setting.

First, the decision for early or late product differentiation activities. Configuration decisions before the CODP lead to rework and obsolescence risks. Postponing configuration decisions until after the CODP leads to increased flexibility, but decreased responsiveness (i.e. longer delivery lead time). Note that this is highly dependent of product architecture.

Second, categorization of materials. Different materials should be coordinated according to different control policies. For purchase parts, a practical tool that is used in industry is the ABC-XYZ classification (e.g. Silver, Pyke, & Peterson, 1998). In Chapter 4, we introduce a methodology that can also be used for internally produced parts.

2.9 Order acceptance and demand fulfillment

Refer to Figure 2.6 for the combined OPC of order acceptance, SCOP and PU control. In SCP, the demand fulfillment function deals with the arriving customer orders; it decides on acceptance of orders; and it sets delivery dates that are promised to customers (Fleischmann & Meyr, 2003, p. 504), in line with the defined customer lead time. Order acceptance is equivalent to short-term sales planning, and is introduced to control the total amount of work accepted by the supply chain. In general, the order acceptance function is used to avoid that due date realization of currently accepted orders is endangered (Bertrand et al., 1998). Fast generation of reliable order promises gets more complex as e.g. products are configured during the ordering process; the average product life cycles get shorter; and demand variations increase and get less predictable (Kilger & Meyr, 2008).

Available-to-Promise (ATP) (Kilger & Meyr, 2008) is an often-used practical methodology for material-constrained supply chains. The ATP is executed for MPS items; the ATP quantity represents the current inventory and future supply availability minus the cumulative customer orders (APICS, 2016a). In such a process the configured BOM is exploded and component availability can be checked for all ATP-relevant items upon customer order entry. It is important to note that the latest availability date of all components determines the earliest possible delivery date for the complete order. ATP enables synchronizing procurement and production of all requirements to the set delivery date. It is not supported in MRP-based planning systems, but only possible through advanced planning systems (APS) (Kraaij, 2016).

For a high-tech OEM, customer lead time is an ambiguous concept. The ordering process is quite complicated, and therefore a firm should realize that the uncertainty and variability of demand can be influenced through order acceptance. When a strict lead time cannot be imposed to customers, other methods can be used, such as milestones: strict moments in time when final decisions on functional requirements should be made by the customer. Furthermore, the process could include negotiations on the lead time, whenever configuration changes are required: an increase in demand variability is "traded" for an increase in lead time. The other way around, a firm could offer a shorter lead time in exchange for a less complex configuration. With such a process, it is necessary that order acceptance and MPS are integrated or at least an iterative process to enable feasible order matching.

2.10 Supply chain operations planning

This Section comprises a discussion of SCOP; the OPC is presented in Figure 2.6.
2.10.1 Master production schedule

A Master Production Schedule (MPS) is "an anticipated build schedule of end products or product options that reflects the desired aggregate output of manufacturing" (Tallon, 1989). An effective MPS provides the basis for making customer delivery promises, utilizing plant capacity effectively and attaining strategic objectives as reflected in the shipment plan (Vollmann et al., 1997, Ch. 6). The MPS activity has to deal with fluctuations of demand and has to calculate a frame for necessary amounts of overtime (Fleischmann et al., 2008). As the plan is based on product families, it does not consider single production processes. The decision function here is to balance the cost of capacity against the cost and risk of inventories. In general, a supply chain can be predominantly capacity-constrained (e.g. in the consumer goods industry); then, MPS should integrate production planning of critical resources. On the other hand, a supply chain can be predominantly material-constrained (e.g. in the computer industry); then, MPS should integrate procurement of critical materials. However, some companies (e.g. in the high-tech industry) experience a supply chain that is material-constrained as well as capacity-constrained.\(^\text{7}\)

Within an ATO/MTF environment, a complexity is introduced into the MPS function by great variety in end-product features and short delivery lead times (Berry, Tallon, & Boe, 1992). This can be accommodated by using a two-level MPS system, where the MPS function is performed at a lower level in the product structure. It results in a reduction of the number of MPS items (relative to the vast amount of possible configurations) and an increase in operational flexibility and order promising visibility (Tallon, 1989; Vollmann et al., 1997, Ch. 14). This method can be employed by using a percentage BOM (PBOM) (Berry et al., 1992). We illustrate the mechanism in Figure 2.7. The shipment plan is translated into an MPS by taking into account inventories and WIP. This MPS states the total number of units to be produced per product family. This schedule is multiplied by a forecast percentage for each optional configuration module; the result are module requirements, but we can also see this as a derived MPS on a lower level. The next step is to explode the detailed requirements for lower-level components, i.e. material requirements planning (MRP).

PBOMs result in low customer service levels and inventory performance in the case of high demand uncertainty, since this technique is unable to respond effectively to variations in the product mix (Tallon, 1989). For this reason, we argue that high-tech OEMs should use a more sophisticated concept: product option modules and super bills (Berry et al., 1992). However, Tallon (1989) argued that percentage bills might be used when the number of optional features is too high to be forecast as individual items, or when the features occur deep in the product structure. All together, this leads to the proposed MPS approach as depicted in Figure 2.7. This includes decoupling some modules, which are not necessarily assembled in separate production lines. Requirements for these modules are not calculated through PBOMs but independently planned. Furthermore, one should define control policies (e.g. KANBAN, basestock) and parameter settings (e.g. safety stock, safety lead time) for these modules separately. It also includes the definition of a common parts set per product family (Berry et al., 1992), to make these parts less vulnerable to product-mix forecast errors. The remaining modules and components can be planned with a PBOM.

2.10.2 Material requirements planning

With the MPS as a basis, MRP serves to explode the detailed requirements for lower-level components. Paradoxically, this is not necessarily done with the traditional MRP-I planning logic (Orlicky, 1975), although this logic is widely used in discrete manufacturing industries and supported in most ERP systems. Alternatives for MRP-I are e.g. (synchronized) base stock policies (De Kok & Visschers, 1999; De Kok & Fransoo, 2003; De Kok et al., 2005), stochastic

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\(^\text{7}\)The material constraints in high-tech are trivial. Hard capacity constraints that appear are due to a scarcity of well-educated engineers, as well as the requirements for a controlled production environment (cleanrooms) that restrict short-term expansion.
Chapter 2. Supply chain planning framework

**Figure 2.6:** Operational OPC: order acceptance, SCOP and PU control

**Figure 2.7:** Two-level MPS approach: basic (left) and more detailed (right)
inventory systems (e.g., Silver et al., 1998), and Advanced Planning Systems (APS) (Stadtler & Kilger, 2008). Please refer to Kraaij (2016) for a literature study on planning models and systems and to e.g. Boulaksil, Fransoo, and Van Halm (2009) for a review on approaches to the SCOP problem and MRP. We propose a methodology that is based on SBS policies in Section 4.5.2.

2.10.3 Personnel planning

Furthermore, we include personnel planning as a decision function. While aggregate personnel planning provides a rough overview of the necessary working time, personnel planning on SCOP level has to calculate the personnel capacity for individual production operations on a weekly basis (Fleischmann et al., 2008).

2.10.4 Integrated SCOP

If material constraints (on component level) and capacity constraints are explicit, one can generate an MPS and subsequent order release decisions as a direct consequence of a sales plan. An ideal, well-designed SCOP process can enable a more or less trivial calculation of feasible order release decisions once planning parameters are set (De Kok et al., 2005). However, integrating both constraint types into MPS requires organizational maturity and alignment of business functions. We make an attempt by proposing a methodology in Chapter 4.

2.11 Production unit control

As SCOP deals with order and resource releases, Production Units (PU’s) make decisions on the lowest operational level: on a daily or even more detailed basis. PU control functions are responsible for controlling lead time in a particular unit of the supply chain (De Kok & Fransoo, 2003; Bertrand et al., 1998). The focus of PU control is on due date reliability: the control functions should be set such that the planned lead time is achieved with a certain probability, i.e. the service level that is defined at S&OP level.

For production, decisions include lot-sizing and machine scheduling to determine the size of batches and sequence of production activities. Shop Floor Control includes i) assigning priority of each shop order; ii) maintaining working-process quantity information; iii) conveying shop order status information to the office; iv) providing actual output data for capacity control purposes; v) providing quantity by location by shop order for WIP inventory and accounting purposes; and vi) providing measurement of efficiency, utilization, and productivity of workforce and machines (APICS, 2016f).

For procurement, these activities only include purchase order management, i.e. translating material ordering decisions into purchase orders and adapting, monitoring, receiving, and acceptance of those orders (APICS, 2016b).

2.12 Inventory as an SCR determinant

In the context of responsiveness, the inventory determinant for SCR (see Figure 1.2) does refer to two things: i) buffers in stocks at different positions in the supply chain; and ii) methods for material coordination that can improve or limit the flexibility and responsiveness.

2.12.1 Inventory buffers

Inventory buffers are set through the parameter setting function, such as explained in Section 2.8.2. The tendency to become lean and operate with less stock across industries (Womack & Jones, 1996) does not mean that inventory buffers are unnecessary and inefficient; we explain this in Section 2.4. Buffer stocks (e.g. through safety stock, safety lead time, demand hedging)
can increase flexibility and responsiveness (Reichhart & Holweg, 2007; De Kok, 2015), but only if inventory is present at the right place. The highest value of buffer stock should be formed at the CODP; if buffer stock is close to the final product, it leads to increased flexibility.

### 2.12.2 Material coordination

We discuss several aspects of mechanisms for material coordination that have an effect on flexibility.

*Long component lead times* decrease the flexibility of ordering. A decision made at a moment in time, has a delayed effect after the lead time.

*Minimum Order Quantities (MOQs)* require companies to order at least a certain amount of material. MOQs might be appealing, since in many cases they can result in lower component prices. However, a disadvantage is the detrimental effect on flexibility.

*Order periods* are used to pile requirements over a future period into one purchase order. This lotsizing procedure defines the time intervals on which purchase orders are released, and imply inflexibility. Vollmann et al. (1997, p. 462) identified this as the main cause of nervousness amplification in MRP systems.

*Forecast methods* (e.g. using move rates) can imply commitment to a supplier. These methods can limit flexibility, if the agreements include an upper or lower bound on the order value or quantity. However, forecast commitments might be used in agreements with suppliers to decrease lead times, MOQs and order periods. Therefore, flexibility can also improve by committing forecast.

In many cases, the above methods are defined as constraints on the strategic level. Therefore, to improve responsiveness, a firm should consider the effects of these mechanisms on a high level: they should be included within functional requirements that are used for decision making regarding supplier selection, cooperations and contracting. *Key performance indicators (KPIs)* for decision makers should not only be cost-focused but also flexibility-focused.

The line of research that focuses on *total cost of ownership (TCO)* (Ellram & Siferd, 1993; Ferrin & Plank, 2002) can support a better understanding of the costs of material coordination mechanisms. TCO implies that all costs associated with acquisition, use, and maintenance of an item be considered in evaluating that item, and not just the purchase price (Ellram & Siferd, 1993). Inflexibility is one of the cost drivers that are discussed in literature, along e.g. quality-related factors. See Ferrin and Plank (2002) for an extensive list. More recent research on the topic addresses challenges in practical implementation of TCO, e.g. calculation complexities and costing procedures (Visani, Barbieri, Di Lascio, Raffoni, & Vigo, 2016).

### 2.13 Supply chain integration as an SCR determinant

At its boundaries a firm interacts with suppliers and customers. Traditionally, firms are competing with each other. In the present world however, it is rather supply chains competing with each other (e.g. Christopher, 2016). For that reason, supply chain integration has become an important factor contributing to achieving competitive advantages. Reichhart and Holweg (2007) discuss various practices for integration in four different forms. The four determinants are strongly intertwined, and it might not be possible to improve one without addressing the other(s).

#### 2.13.1 Information integration

The detrimental effect of a lack of demand visibility in the upstream supply chain nodes is called the bullwhip effect (Lee et al., 1997). Towill (1997) explained how demand uncertainty is created to a great extent by downstream supply chain partners, through e.g. reorder levels.
The result is that upstream partners are required to "play the guessing game", i.e. to anticipate decisions of the downstream partner.

Suggestions for improvement largely aim at creating transparency or visibility of demand and capacity information without any time delays, by the use of innovative information systems (Reichhart & Holweg, 2007). Over the past decade, enabling technologies have evolved, and the availability of adequate information systems to support information sharing is no longer an issue. The main challenge today is that a firm should also be willing to share this information, which will not be possible when supply chain partners regard each other as "the enemy", and e.g. compete with each other (Sahin & Robinson, 2005). As a matter of fact, the first step toward a friendly relationship is that both partners see the benefits of information integration.

An implementation of an approach for information integration with the aim to reduce the bullwhip effect, was published by De Kok et al. (2005). They introduce a process called **Collaborative Planning**, that involves both the buyer and the supplier. The process is supported with software to create feasible plans, based on synchronized base stock (SBS) planning logic.

### 2.13.2 Coordination and resource sharing

This refers to "how processes, value-adding steps, and related decisions are coordinated and potentially rearranged across firm boundaries and how resources are shared to add value to products at interfaces in supply chains" (Reichhart & Holweg, 2007).

For instance, Sahin et al. (2008) argued that approaching MPS function while considering a single firm’s characteristics only, is a major fallacy. Optimizing the manufacturer’s MPS policy without considering the impact on a vendor has an adverse effect on responsiveness and stability. Control concepts and parameters should be aligned between supply chain partners.

As another example, one can think of re-order level alignment. A recent development is **Vendor Managed Inventory (VMI)**, also termed **consignment stock**. In the VMI model, the OEM defines the minimum and maximum inventory levels of the components, and the suppliers are responsible to keep the inventory between those target levels. There are two main ways in which VMI can impact responsiveness (Kaipia, Korhonen, & Hartiala, 2006): i) eliminating one layer of decision-making; and ii) eliminating information delays in the process. According to Disney and Towill (2002), two of the bullwhip causes defined by Lee et al. (1997): gaming and batching, can be mitigated by adopting VMI. Kaipia et al. (2006) discussed the impact of VMI on stability, and considerations that should be made when implementing this concept.

Tempelmeier (2011, p. 232) adopts a more critical perspective. He notices that practitioners attribute advantages to VMI: shorter reaction times to demand variations; lower inventory or higher service levels; and improved opportunities for optimization of supplier’s logistical processes. However, he finds that "the observed improvements assigned to VMI are mainly due to the in-depth consideration of the hitherto neglected area of inventory management." He argues that VMI is suboptimal and that central inventory control and improved information can also be used to achieve near-optimal allocation of buffers (e.g. safety stock) in the supply network, by use of echelon policies (cf. Clark & Scarf, 1960; De Kok & Fransoo, 2003).

### 2.13.3 Organizational integration

Close organizational integration can positively influence manufacturing and supply chain performance as well as responsiveness (Reichhart & Holweg, 2007). One should consider integration both during operational execution and in the NPI phase. An example for integration is the cross-supplier collaboration in the Japanese automobile industry. A more relevant example for the high-tech industry would be employing engineers of suppliers at customer sites to improve communication and enable faster problem solving. Other methods include

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8The fundamentals of this process are equivalent to fundamentals of the methodology we propose in Chapter 4.
joint design teams, process and quality teams, joint performance measurement and problem solving (Bagchi & Skjoett-Larsen, 2002).

### 2.13.4 Spatial integration and logistics

Trivially, the benefit in spatial integration comes from logistical proximity. This reduces transportation lead times and increases responsiveness (Reichhart & Holweg, 2007). Spatial integration benefits can be explicitly incorporated as a requirement in sourcing decisions.

### 2.14 Summary

For practical application, the most important result of this Chapter is the identification of decisions made in SCP and the level of the hierarchy where these are made. The execution of these decision functions partially determines the responsiveness of the supply chain. As a summary of this Chapter, we represent the decisions made with a cross-functional flowchart in Figure 2.8, which is a high-level overview of the OPC concepts presented in this Chapter. Furthermore, we present the decision functions that are most relevant for responsiveness in Table 2.1. The tabular form enables an overview and a more elaborate representation simultaneously.

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**Figure 2.8: High-level ideal cross-functional flowchart for SCP**
### Table 2.1: Trigger events, inputs, controls and outputs of most relevant decision functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supplier selection and cooperations</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger event</strong></td>
<td>New material introduction &amp; predetermined review moment</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Required materials; Projected demand</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Feedback from SCOP/PUC: supplier evaluation, flexibility requirements.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>Unambiguous supplier agreements regarding price, flexibility in quantity and time, delivery terms.</td>
</tr>
<tr>
<td><strong>Tactical parameter setting</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger event</strong></td>
<td>New material introduction &amp; predetermined review moment.</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Material or process characteristics, e.g. yield, demand</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Strategic parameters, e.g. supplier agreements, manufacturing constraints (capacity, flexibility), customer lead time.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>Agreed-upon definition of and commitment to all defined parameters in Section 2.8.2.</td>
</tr>
<tr>
<td><strong>Aggregate production planning</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger event</strong></td>
<td>Predetermined moment, monthly recurring.</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Mid-term sales planning.</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Strategic parameters, such as manufacturing capacity; Tactical parameters, such as production lead times.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>A statement of production starts, and finishes, as well as production hours required, in monthly time buckets.</td>
</tr>
<tr>
<td><strong>Aggregate material requirements planning</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger event</strong></td>
<td>Predetermined moment, monthly recurring.</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Mid-term sales planning; Aggregate production planning.</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Tactical parameters, specifically: supply lead times, lead time offset, safety stock.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>Projected monthly requirements based on: production starts, ship dates, and requirements for decoupled modules.</td>
</tr>
<tr>
<td><strong>Order acceptance</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger event</strong></td>
<td>Customer request for quotation.</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Customer orders.</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Approved S&amp;OP plan, tactical parameters.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>A weekly statement of accepted and prioritized customer orders with a feasible lead time and due date, given the required configuration.</td>
</tr>
<tr>
<td><strong>Master production scheduling</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Trigger event</strong></td>
<td>Predetermined moment, monthly recurring &amp; arrival of new accepted order.</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Approved S&amp;OP plan; Individual orders; Historical demand.</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Tactical parameters and aggregate plans.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>A statement of projected start and end dates for all designated MPS items, in weekly time buckets as well as an overview of matched orders to units in production.</td>
</tr>
</tbody>
</table>
Chapter 3
Case study

In this Chapter, we discuss the FEI case. We describe the firm’s supply chain by using the SCR framework of Reichhart and Holweg (2007). To create a better understanding of the underlying causes and implications of external requirements and internal determinants for SCR, we provide a short discussion on the architecture of a microscope in Section 3.1. In Section 3.2, we discuss the demonstrated SCR: the external flexibility requirements. After that, we discuss the most important currently employed internal flexibility determinants in Section 3.3. We compare the ideal design of Chapter 2 to the current demand anticipation mechanisms and identify gaps in Section 3.4. We conclude that a better approach for planning could close gaps in parameter setting, order acceptance, aggregate planning and MPS.

3.1 Transmission Electron Microscopy

Microscopy is one of the few methodologies applied to nearly every field of science and technology in use today. A microscope can be as simple as a hand held light microscopy device or as complex as a multi-million dollar research tool. The TEM’s that FEI produces are of the last category. These systems enable scientists to explore synergistic relationships of structure and properties of materials. A TEM creates an electron beam that passes through a thin slice of specimen (see Figure 3.1). This produces a two dimensional view. If required, a variety of techniques and software can be used to create a 3D view. The range of a TEM enables to create images of a single atom.

For SCP, it is important to understand the different parts of a TEM, although technical details might seem a little irrelevant. The following discussion is based on the architecture of the Titan High Base family, but is similar for other TEM types. From a configuration perspective, families are different in that they imply different variants of the modules, or that some optional modules might not be available to a certain family.

Figure 3.2 is a model of a TEM. The microscope itself (within the cube) is column-shaped, built on a base and, with the exception of a Titan LB, covered with an enclosure. An electron beam is accelerated from the top with a Field Emission Gun (FEG), through the condensor system to the objective. The specimen holder is located within the objective, and fits within the compustage. The compustage facilitates stabilization and computer-controlled movement of the holder across five axes. After the electrons pass through the objective, the imaging system converts the created image and projects a focused image in the projection chamber. The most important other optional modules include a CCD camera to view the image on a monitor; a side-view camera to make pictures of the image; an energy filter to enhance contrast and remove the effects of chromatic aberration; an EDX detector for imaging and investigating specimen properties; a STEM package and optional BF/DF detector to include Scanning Electron Microscopy (SEM) techniques; a probe and/or image corrector to correct aberrations and avoid blurred images.

To make a system operative, various other modules are needed: an optics, TEM and Power cabinet to control modules and power supply with precision; a HT tank to generate high tension, the filament current and the emission current; a vacuum pump system to provide a necessary

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1 This Section is completely based on internal FEI documents (Alberto, 2014a, 2014b).
Figure 3.1: The working principle of a TEM and an example (Alberto, 2014a)

Figure 3.2: Modular structure of a TEM
vacuum in some parts of the system; a table with a user interface to control the microscope and view images.

On another note, we can distinguish materials by the phase of production in which they are needed. The main column is assembled at start-up. To make the system operative, one needs to connect the cabinets and the HT generator, mount the FEG, and attach the sample holder (and autoloader, only for Krios). Various other modules are add-ons: the camera’s, the energy filter, the EDX detector and other options. Some material is not needed during assembly and testing of the microscope, therefore only needed just before shipment. This includes e.g. parts that are used during dismantling, shipment and installation, but also the enclosure and the user interface.

3.2 External requirements

3.2.1 Demand uncertainty within FEI

The FEI customer base is a source of demand uncertainty. To procure a microscopy system, customers are dependent of approval by many stakeholders. In many cases, they require government funding or budgets. Bureaucracy leads to a long and uncertain process for approval. Orders can be canceled or requested delivery dates adapted due to e.g. compliance and customs regulations or microscope environment requirements (e.g. a vibration-free room). These characteristics lead to forecast errors on the product family level.

Forecasts are created monthly on S&OP level and result in an Approved Shipment Plan (ASP). To quantify the changes in the ASP, we define the forecast demand during lead time in quarter $t$ as $FLT(t)$, and similarly the actual shipments during lead time $DLT(t)$ as such:

$$FLT(t) = \sum_{x=0}^{L-1} F_{t,m}(t + x)$$

$$DLT(t) = \sum_{x=0}^{L-1} D_{t}(t + x)$$

In this formulation, $L$ represents the lead time of a system in quarters. $m \in 1, 2, 3, 4$ represents the counter of the forecast for the respective quarter.²

See Figure 3.3, for the resulting graph for all systems produced in Acht. Additional graphs for product families Krios, Metrios, and Titan are published in Appendix B. We note that shipments and forecasts on the aggregate level are quite synchronously: the CV of the forecast difference over 2014-2015 is 44%.³ The aggregate variance of lead time demand is very stable as well, with a CV of 15%. This is largely due to demand management: as a consequence of capacity constraints and the customization, there cannot be a large variation in factory output. Although there is more variability on the product family level — between 27% for Titan HB and 65% for Krios — we note that this is well within the 133% boundary of controllability that Van Wanrooij (2012) defined (see Section 2.4).

Additionally, note that FEI currently employs a demand hedging strategy (see Section 2.8.2): there is a continuous overestimation of demand.

3.2.2 Demand variability within FEI

As a consequence of e.g. the complex nature of microscopy systems and the rapid technological developments, customers do not exactly know exactly what kind of system they require — they

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²In general, forecasting is recurring monthly, thus three times per quarter, but in some cases this is twice or four times.

³We omit 2013 data here, since the S&OP process was not in a mature phase until 2014.
approach FEI with a research problem, and ask for a microscopy solution. This becomes clear during the Sales process. Required specifications are highly variable; both before and after an order is official. In Appendix C, we sketch an idea about product configuration. It includes the configuration of the most important dimensions of four system system types. Figure 3.4 shows the amount of configuration changes on main system production orders within 180 days and over 180 days before the production due date; it is relevant that FEI shipped a total of TEMs in 2015.

However, in addition to the main system configuration, customers request several special options, e.g. specialized software, an additional monitor, or a unique energy filter. These are called *accessories* when they exist in FEI’s portfolio. In case they do not — i.e. the customer requests a non-generic and unique part, module, or variant — they are called *Non-Standard Requests (NSRs)*. An order has on average seven accepted NSRs.

### 3.2.3 Product variety within FEI

A TEM can be configured to a large extent. Currently, FEI’s strategy is to offer everything that a customer wishes, if it is possible. If the desired option does not exist, it is a NSR. If an NSR is potentially interesting for other customers as well, FEI starts a project to make it part of the regular configuration options. In conclusion, external variety is high.
Microscopy technology becomes increasingly advanced to enable researchers to make innovative discoveries. Since FEI aims to offer state-of-the-art technology, a new generation of each TEM type is released with a frequency of around once per year. Similar frequencies hold for individual modules. We conclude that dynamic variety is very high as well.

### 3.2.4 Lead time compression within FEI

There is no perfect and unambiguous way to measure the requested lead time. As illustrated in Section 3.2.1, the occurrence of a customer order is a process. First, the customer inquires about the possible technologies that FEI delivers. Then, a long negotiation process leads to an ultimate order. Officially, a *reservation approval* functions as the moment that FEI starts to configure a system to customer requirements. We measured the requested due date on this date, and the realized ship date. We define the requested and actual lead time as the difference between these dates and the reservation approval date. The result of this analysis is shown in Figure 3.5. Note that 46% of the orders is requested and 31% delivered within a quarter.

![Histogram of the requested and realized customer lead time](image)

**Figure 3.5:** Histogram of the requested and realized customer lead time

We define the realized manufacturing lead time as given in Table 3.1 as the difference between months from the month that the first material is added up and until the minimum of the shipment month and the month that the last material is added. The planned lead time is an estimated value per family, but it should be noted that the exact configuration can imply a large difference in lead time. e.g. a Titan HB with an image and probe corrector, as well as a couple of NSRs will require more than 12 months. The average value is in all cases larger than the planned manufacturing lead time. In the cases when the manufacturing lead time is longer, there are months where no material value is added. This is a logical consequence of the production strategy that FEI uses: there might be a period between start-up assembly and final configuration without production activities.

In conclusion, we notice that the manufacturing lead time is much larger than the customer lead time. This leads to the necessity of production strategies that include forecasting demand and defining a CODP, and it requires FEI’s supply chain to be responsive.

### 3.3 Internal determinants

The above characteristics of external determinants for responsiveness FEI’s supply chain resulted in the adoption, or rather evolution, of each of the internal determinants of responsiveness. Both the determinants manufacturing flexibility and product architecture are outside of the 4

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4This data is not consequently and correctly saved in FEI’s database. Therefore, we measure limited available data for systems of three product families shipped in 2015 and 2016. For the requested ship date, we take the earliest date of different fields in CRM that are used for this purpose.
Table 3.1: Added material value over the lead time per product family

<table>
<thead>
<tr>
<th>Family</th>
<th>Shipments</th>
<th>LT (months)</th>
<th>Planned LT (months)</th>
<th>Mat. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krios</td>
<td></td>
<td>10.0</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Metrios</td>
<td></td>
<td>9.2</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Titan HB</td>
<td></td>
<td>13.7</td>
<td>12.0</td>
<td></td>
</tr>
</tbody>
</table>

scope of the redesign part of this project, since strategic decision functions are outside of the responsibility of a planning department. Furthermore, we do not consider currently used methods for supply chain integration. As a result, we only discuss the demand anticipation and inventory determinants.

3.3.1 Demand anticipation within FEI: the SCP process

To create a better understanding of demand anticipation within FEI, we first identify interactions on a departmental level in Figure F.2, Appendix F.

Demand anticipation is constituted through the way of working regarding planning and logistics. This way of working is FEI’s SCP process, which we modeled with a cross-functional flowchart (swimming lane diagram) in Appendix F, to show the time-phased decision functions. We identify functional responsibilities. Every responsibility is represented in a decision function. In the same Appendix F, we model the separate decision functions by using an IDEF0 methodology. The core of this method is to model decision functions, with respective inputs, outputs, control factors and mechanisms (see Figure F.1).

In this OPC concept, and in accordance with the hierarchical planning framework (Section 2.5), we identify planning on three levels: Strategic, S&OP, and Operational. Operational decisions include SCOP (Nodes J and K), Order acceptance (Nodes G and H), and PU control (Nodes N (production) and M (procurement)).

3.3.2 Inventory within FEI

Inventory management and operational excellence have not been FEI’s strategy focus, for two reasons: i) cashing in accomplished revenues faster is an easier way to increase working capital; and ii) responsiveness and flexibility is of such importance that high material availability is required. As a result, the inventory turn rate has been between 1 and 2 over the last years. Furthermore, around 25% of the material has been on stock for more than a year. As a consequence of the long lead times, the WIP represents the largest part of the inventory. Since finished goods are highly customer-specific, the finished goods inventory is low. Please refer to Figure 3.6 for the distribution of the inventory value by type and the development of inventory over time.

3.4 Gaps between the current and ideal SCP process

We discuss five main gaps we have identified between the ideal situation of Chapter 2 and the current situation of Appendix F. A gap means that there is a discrepancy between the (execution of) the ideal OPC (see Chapter 2) and the currently used OPC.

3.4.1 Gap 1: Supplier agreements

At FEI, the business strategy encompasses a focus on direct costs of materials in supplier selection. As discussed in Sections 2.12 and 2.13, such a focus does not contribute to responsiveness. It would be better to include flexibility requirements in the supplier selection process. Furthermore, supply chain integration through information sharing and resource coordination is
a direct determinant of responsiveness; a sole focus on cost price does inhibit suppliers from working closely together.

3.4.2 Gap 2: Forecasting in S&OP

We have characterized the forecast error in Section 3.2.1. However, we identify that the current forecasting process does not actually result in an estimation of company-wide future sales volumes, but rather an expression of hopes and objectives. Since FEI is a public company, executives have the obligation to publish revenue forecasts. It is beneficial for the stability of the stock price to conform the actual revenue to this forecast, and to publish a stable revenue forecast. These goals are important drivers for the forecasting process. Furthermore, we repeat that FEI’s products are the most important revenue drivers and sold in very small volumes. We illustrate the resulting forecast behavior with an example.

In December 2015, FEI estimates that 3 $6 million Titan High Base systems, with a 12 month production lead time can be sold in Q4 2016. By January 2016, they have market signals that 2 of the 3 might move to Q1 2017. However, this would impact the revenue forecast stability, so they do not communicate this through S&OP. By April 2016, Sales actually managed to get a provisional agreement of 3 customers for shipment of the Titan’s in Q4 2016. However, by June 2016, two of these customers shift their demand to the next budget year, i.e. Q1 2017. By now, the forecast level is actually changed to inform production, but to retain the revenue forecast, Sales is pulling 2 other different family systems from Q1 2017 to Q4 2016. In September 2016 however, sales realizes that the pull-in strategy has not succeeded, and the 2 systems will actually be sold in Q1 2017.

The forecasting behavior creates i) unnecessary escalated orders to the supply chain for some materials of the pulled-in family; and ii) two Titan HBs that occupy factory capacity for a quarter longer. Of course, we cannot prevent this situation wholly, since it is a consequence of the volatile market. However, this volatility is not reflected in the ASP. More accurate forecasts, i.e. not redacted to conform to revenue forecast, could result in better risk and buffer management in the supply chain.

3.4.3 Gap 3: Order acceptance

In the ideal situation, order acceptance is an unambiguous process that serves to control the workload in the supply chain. In the current situation, workload control does not function properly.
Order acceptance is divided between Sales, which approves any order within the product variety boundaries; and order desk, which translates these accepted orders to for logistics understandable assignments that serve as input for the MPS planning process. Therefore, the information flows that should enable workload control are distorted and delayed. This, and additionally the business environment (high margins make lost sales extremely costly) and the complex manufacturing process (which requires difficult capacity planning), resulted in a situation where Sales has a dominant role in order acceptance.

To characterize workload control in more detail, it is important to distinguish between acceptance on family level and acceptance on configuration level.

On family level, we identify some sort of capacity management. Capacity is reserved through the S&OP process, and consumed by actual customer orders. If there is a scarcity of systems in the pipeline, i.e. in case of a sudden demand ramp-up, the customer order lead times promised become longer. Apparently, this is something FEI can do to customers. On the other hand, when there is an apparent excess, the sales organization will try to push the market for more orders. Of course, scarcity and abundance are prevented through S&OP and forecasting, but with a delay.

On configuration level, we do not identify management of any kind. FEI’s strategy is to allow as much customization as possible; which is manageable. More importantly however, the customer orders are only definitive in a late stage. Changes in customers wishes do have an effect on the lead time and manufacturing and supply chain capacity, but this is not recognized in the order acceptance process. A deadline on order configuration (or more, for different configuration decisions), even when it is only short before delivery would create opportunities for much more responsiveness and stability (Section 2.9). From a strategic business perspective, we assume that this is to some extent possible, since for most systems, FEI’s competitive advantage is largely its product differentiation and only to a lesser extent its operational excellence.

3.4.4 Gap 4: Parameter setting

In the ideal situation, parameter setting would be included on an aggregate level, as a structurally recurring and defined process (Section 2.8.2). We include parameter setting on a strategic level in the cross-functional flowchart, since the current process is largely immature and undefined, and mainly a result of constraints rather than a decision function in itself. One could also argue that parameter setting is not defined at all, or that it is done at any other hierarchical level. But some parameters, although not always explicitly defined, are actually recurring as control factors in subordinate decision functions. To create an understanding of the current situation, we illustrate the process for a few specific parameters.

- The extent to which hedging (demand overstatement) is applied is defined and checked on a strategic Sales executive level.
- Purchase lead time parameters are largely dependent on contracts that are defined at a high level in the organization (Global Sourcing).
- Production lead time parameters are constrained by decisions that are made on the design for manufacturing. Active and structural safety time planning for production activities, based on analysis is not done. It is rather on an ad-hoc basis incorporated in the MPS planning at MPS item level, i.e. only the lead times of full systems is planned with some safety time. The current information systems allow for an analysis of historic production times on a more detailed level and subsequently for more advanced lead time planning.
- Safety stocks are not actively reviewed and controlled, but adapted on an ad-hoc basis, based on tacit knowledge.
- Workload control parameters are not explicitly set, except for the number of systems in production; this is a consequence of the limited number of test positions that is available.
3.4.5 Gap 5: Aggregate planning and the MPS

In the ideal situation, there are aggregate production, personnel and material requirements planning processes in place as part of S&OP to provide for a granular planning of required capacity; as well as to provide feedback on the material- and capacity-feasibility of the mid-term sales planning (i.e. the ship request). At FEI, personnel planning is currently in place, but after the S&OP cycle (not during). Aggregate production planning does coincide with the MPS, which is updated after each S&OP cycle. Aggregate production planning during S&OP is done by creating a projected MPS. Since FEI produces low volumes in long lead times, this is manageable as long as it only employs systems as MPS items and does not decouple generic systems; currently the ASP as a result of S&OP is almost equivalent to an aggregate production plan. When FEI would incorporate other modules as MPS items and creates generic systems, the MPS function should include decoupled modules. As a consequence of the CODP definition, the aggregate production plan would differ from the MPS, so the aggregate production planning process would change as well. Aggregate material requirements planning is currently done in the form of forecast, but on an incorrect hierarchical level. Forecasts of material requirements are currently made in monthly buckets based on redacted material requirements, i.e. procurement orders created through MRP. Actually, it is better to provide suppliers with forecast on actual usage of materials in time buckets, as we show in our discussion on information integration in Section 2.13. In the ideal situation, we propose to do this during each S&OP cycle, just as aggregate production planning, such that possible material shortages can already be recognized during the S&OP process (see Chapter 4).

3.5 Conclusion

In this Chapter, we characterized FEI’s business environment by discussing the product they make, and the external requirements for responsiveness. By comparing FEI’s current SCP process with the ideal process, we have identified a number of gaps. In the remainder of this thesis, we do not address the gap within forecasting on S&OP level and the gap in supplier agreements, since both are a result of company culture and strategy on executive level, not something we can improve through a planning process redesign. We do (partially) address the other gaps in Chapter 4, where we present a control concept that aims to accomplish integration of feasibility checks into aggregate planning.
Chapter 4

Design of implementation

This Chapter describes our attempt to change the current situation for a specific case, which is the purpose of the regulative cycle (see Section 1.1).

Currently, FEI employs a strategy that is similar to the MTF strategy (Meredith & Akinc, 2007). Production is started based on forecast, and configuration decisions are made according to an estimate; there is no firm CODP, i.e. lead times are different for each order. In Section 3.4, we have revealed a number of gaps in FEI’s approach. The specific MTF strategy of Meredith and Akinc (2007) lacks guiding on material coordination, whereas this is highly relevant in the high-tech industry. Transformation to an ATO/BTO strategy is not possible, since there is an absolute necessity for early configuration decisions that require possible rework in a later stage.

Therefore, we describe an alternative approach for (parts of) order acceptance, SCOP and S&OP in Make-to-forecast environments, with the objective of dealing with short delivery times and a high degree of customization. This approach is tailored to include material coordination. As such, the goal of this Chapter is to use this approach to provide a method i) to create a feasible (not optimal) set of order release decisions; and ii) to support determining appropriate, close-to-optimal buffers in inventory and time for different phases of production. Both of these goals contribute to improved responsiveness and stability.

4.1 Manufacturing and the CODP at FEI

In this Section, we describe an alternative view on the planning of manufacturing operations for FEI, depicted in Figure 4.1.

![Figure 4.1: Alternative view on FEI manufacturing operations](image)

Production is started based on forecast. These forecasts are in quarterly time buckets, and created monthly on product family level. The product families defined serve as MPS items. A family should be defined when at start of production, a set of production choices should be made that cannot be changed afterwards.\(^1\) Forecast-based production operations can be generic

\(^1\)In practice, this means that the current S&OP families are not sufficient. e.g. Titan Krios should be split into a corrected and an uncorrected Krios family.
for a certain family type (flow 1); on the other hand, they can be configuration decisions on a more detailed level than family, but still forecast based (flow 2 and 3). These are configuration decisions that can be modified in a later stage. After all, if they could not, they would be generic to a product family.

When a customer order is accepted (at the point of order entry and match), it is matched to a unit made in production according to some matching rule. This unit can be more or less configured. At this point, some modifications could be required immediately, as a result of early configuration decisions. After this point, we assume no more configuration uncertainty.

As a consequence of managing business risk however, there are some transformation processes that will not be performed in any case without a customer order (flow 4); these transformation processes have a certain lead time. The actual customer order can be earlier in time; but this is only beneficial, since it decreases uncertainty about order configurations. From a control perspective however (see Section 2.8.2), we should define the CODP to distinguish the order-driven and forecast-driven part of the supply chain. Therefore, we set it at the start of this order-driven transformation lead time, although a definitive order and subsequent manufacturing decisions may appear earlier in time. For this reason, we distinguish between flow 2 and 3.

### 4.2 The idea of constrained-based planning

In order to improve stability, we aim to adopt the hierarchical planning structure truly. Practically, this means that a feasible aggregate plan, in monthly time buckets, is created, by checking the ASP and/or an accepted order against material and capacity constraints (De Kok & Fransoo, 2003). As a consequence of constraints, the MPS and subsequently MRP can be generated — this is in contradiction with a traditional MRP-I approach where the MPS is decided-upon. The MRP-I approach starts planning from the highest BOM level and does not consider demand during cumulative lead time. The constraint-based approach starts planning from the lowest BOM level and considers demand during cumulative lead time. As such, it prevents creating infeasible planned orders (planned orders in the past) that trigger actions on an operational level (e.g. MRP-I rescheduling messages). Backlog information is provided at MPS item level, and may trigger quick corrective actions before material problems are passed to lower items. More accurate ATP information based on a feasible MPS may lead to a better insight of production capabilities at order acceptance and in case of order changes. Bottlenecks can be identified in an early stage.

Such a necessary complexity of integrated order acceptance, MPS and MRP distinguishes an MTF strategy from ATO or BTO. The latter strategies do not comprise an order matching process that results in imminent due date and/or material requirements rescheduling.

Refer to Figure 4.2 for an illustration of the material availability planning (MAP) concept in comparison to the currently-used (MRP-II based) concept. In the following Sections, we will discuss this approach in more detail, and we start by categorizing material to enable differentiation of control mechanisms.

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2We do not discuss such rules; Meredith and Akinc (2007) discuss three different heuristics based on unit priorities, costs of modification and costs of lost flexibility, that could all be applied in FEI’s case.

3Contrarily to the situation described by Meredith and Akinc (2007), these modifications cannot be postponed to after all other operations, due to technical reasons.

4For FEI specific, this point may thus not refer to the point of order acceptance in the current process, but to a point later in time, when there are no reasonable indications for imminent customer-driven configuration changes or cancellations.
4.3 Categorization of material

The categorization of material is necessary for implementing two-level MPS as in Figure 2.7. We introduce the concept of a module, which we define as a certain part of the microscope, that can be built from a collection of materials, either by FEI itself (the module is a subassembly) or by a supplier (the module is a purchase part). We can divide material at FEI into two categories: material that is used in a module; and material that is used in multiple modules (see Figure 2.1). The last category includes mainly "screws and bolts". The material coordination for multi-module items is done best using KANBAN or statistical inventory control. For the first category, we can classify the modules according to three characteristics.

First, as a consequence of product architecture, the material is either family-specific or used in multiple product families. This characteristic is useful to illustrate that stability can be improved through decoupling. If material is used in multiple or all product families, the CoV of it’s demand during lead time is lower on the aggregate level than on the product family level. By decoupling the modules, one can leverage this commonality through the lower safety stock requirements. A "common parts set" should be used to coordinate material used in every microscope. Demand for these items is relatively stable, since the aggregate number of systems produced per quarter is quite stable.

Second, the material has a single variant (the same component is always used), or has multiple variants (which can be: is optionally included).

Third, the material is required in the forecast part of the manufacturing process, or the make-to-order part. This can be a consequence of product design: if material can be added in a later stage, with limited consequences on testing and alignment. It is also a supply chain decision: FEI can decide to build a certain module only when a customer order is given. This has consequences for the customer lead time.

The second and third characteristic divide the remaining module material into four different categories:

- **Forecast & generic.** Family-generic material that is essential for the core functioning of the product and thus required at the beginning of the manufacturing process.

- **Order & generic.** Family-generic material that is not essential for the core functioning of the final product, and that is not required during testing and alignment. Otherwise, it would be forecast.
Chapter 4. Design of implementation

- **Order & multiple variants.** This category will include more items than the previous, since it is more appealing (or necessary) to control material order-based when there are more variants, simply because the variability is higher.

- **Forecast & multiple variants.** Material that is required in an early stage of manufacturing, e.g. since it is essential for testing and alignment, or because assembly based on order leads to an undesirable long lead time. However, these materials are optional or exchangeable and might be changed as a result of the actual order.

For the exemplary Titan High Base product family, we apply the categorization of material and respective percentages of material value in Table 4.1.

| TABLE 4.1: Titan High Base material value per module and category\(^5\) |
|--------------------------|----------------|----------------|----------------|
| Forecast generic         | Order generic  | Forecast variants | Order variants |
| 31.32%                   | 22.48%         | 40.50%           |
| Corrector (8.98%)        | Enclosure (2.42%) | Accelerator (10.15%) | Energy filter (32.01%) |
| Cabinets (5.50%)         | Ship & Install (2.61%) | STEM Package (1.77%) | CCD/SV Camera (6.46%) |
| Projection (3.58%)       | User interface (0.66%) | Sample holder (0.96%) | Options/NSRs (2.03%) |
| C1/C2/C3 (2.40%)         |                | HT Generator (2.96%)         |
| Compustage (2.14%)       |                | Super-X (6.64%)   |
| Objective (2.08%)        |                |                   |
| Base (1.30%)             |                |                   |
| Vacuum system (0.96%)    |                |                   |
| Generic/other (4.38%)    |                |                   |

4.4 Operational material control

Following our earlier discussion in Section 2.8.2, we conclude that material coordination and parameter setting should be different before, at and after the CODP. Therefore, we categorize material according to where it is used. In this Section, we will focus on the practical control of material and parameter setting. Material coordination serves the core purpose of SCOP, i.e. the generation of order release decisions. We consider a value network structure with \(M\) items, that can be described in discrete time, by means of the variables in Table D.1. Our notation is largely derived from De Kok et al. (2005), but not exactly the same.

The goal of our discussion is to provide a methodology to determine the order released for item \(i\) in week \(t\), \(R_i(t)\), as a consequence of the S&OP forecast \(X_z(t)\), the item lead time \(L_i\) and the cumulative echelon safety stock \(SS_i\) in a rolling horizon, under capacity constraints, for each category of material and not only for the current period, but also for future time periods. This forward-looking approach provides insight into potential future item shortages and overages. For this algorithm, we consider the safety stock, and the lead time exogenous parameters: these are determined on a different hierarchical level. As a consequence, we assume no lead time uncertainty. Of course, this assumption is violated on a detailed planning level. On a SCOP level however, this assumption is valid if planned lead times are determined such that these are met with a sufficiently high probability (cf. De Kok & Fransoo, 2003). We summarize the questions to be answered in the following Sections:

1. Which items to include in the set of end-items, i.e. items with independent demand \(N\).
2. How to determine the demand forecast \(D_i(t), i \in N\) for future time periods, and for each category of material, as a result of \(X_z(t)\).
3. How to determine \(L_i\) and \(SS_i\) for each item \(i \in M\).

\(^5\)The figures represent the percentage of the total value of materials in shipped HB systems from 2014Q1-2016Q1.
4.4.1 Control per material category

The generic family system

This is the main system and consists of modules we defined as "Forecast generic", i.e. set $K$. We depict the simplified structure of such an assembly system in Figure 4.3. Some of these modules are actual sub assemblies (Module C, example: objective); that means they are assembled in a so-called “feederline” before adding these to the generic system. Other modules are merely a collection of purchase parts (Module B, example: vacuum system), but one requires all of these parts to start assembling the microscope. Some modules are just one purchased part (Module A/D/E, example: base). Most of the modules are required in the beginning of the manufacturing process, which we can separate in two phases (from a SCP perspective): column assembly (4 weeks), and connection & alignment (depending on the family 9 - 35 weeks). The end items ($i \in K$) in the example structure are 9 and 10 and represent two distinct generic systems; these items are the CODP items. If we forecast these items, we can subsequently calculate all order release decisions for underlying items of the generic system according to the algorithm in Appendix E. For FEI, it holds for these generic systems that the set of S&OP families where item $i$ is used $|Z_i| = 1$; therefore if we define $L_z^c$ as the customer lead time for an S&OP family, then $D_i(t) = \sum_{k \in Z_i} X_k(t + L_z^c)$.

Forecast variants

The BOM of an exemplary system before definitive configuration is ambiguous, since it differs with the forecasted variants. The demand for these modules is not dependent only from the end-item demand but also from the changes as a result of matching orders to units. We decouple these modules from the generic system, i.e. we define these modules as end-items in order to allow for analysis of the system. This approach means that we use the decomposition assumption (De Kok & Fransoo, 2003, p. 649) for the generic family end-items: “[for the decoupled modules], safety stock parameters are set at such high levels that every material order released can be satisfied from stock on hand without checking upstream availability.” The practical implication is that we should set the service level for these items high (e.g. 99%). For
material coordination, we can distinguish between two cases: \( i \) is either a purchase part, which means that the set of immediate predecessor items \( G_i = \emptyset \); or a sub assembly \( (G_i \neq \emptyset) \).

- If module \( i \) is a purchase part and demand is stationary (e.g. for the sample holder) then we can use single-echelon inventory control policies (Silver et al., 1998). For high-value, low-volume purchased modules, restrictions on the review period and the lot size do not exist, and therefore the base stock policy \( (R = 1, S) \) is optimal. To define this policy, we should set a service level and we require the demand distribution of \( D_i \) as well as it’s first and second moment (see Section 4.6.3). It is important to recognize that \( D_i \) is the sum of consumption for generic systems and consumption for customer orders minus the return flow when a module is replaced with another variant. That means that \( D_i \) is not strictly non-negative, and as such \( D_i \) cannot be modeled as a Poisson random variable.

- If module \( i \) is a purchase part and demand is not stationary, i.e. it shows a seasonal pattern, we cannot use base stock policies. This is the case for e.g. the HT generator: the variant mix is strongly dependent on the product family demand mix. In this case, we should determine the forecast \( D_i(t) \) and adopt the same methodology as for sub assemblies.

- If module \( i \) is a sub assembly (e.g. the accelerator), we should determine the forecast \( D_i(t) \). From \( D_i(t) \), order release decisions for underlying items follow through the algorithm in Section 4.5.2. The challenge here is that we cannot directly derive this forecast from \( X_i(t) \), such as for the generic system. For these items, one should determine a product mix estimate, and subsequently \( D_i(t) \). The sum of \( D_i(t) \) for all \( i \) that represent the same module should be equal to the total estimated starts of the succeeding generic systems. An exception is when modules are not be needed at the start of generic system production, but required somewhere later in the process; then, one needs to offset requirements relative to the estimated start by use of so-called operation steps. \( D_i(t) \) should not be adapted as a consequence of expected returns and requirements that are a result of order matching (deviations of the estimated mix); to provide flexibility here, we propose to use safety stock for \( i \) dependent on the variability of the product family mix.

**Generic parts on order**

These parts are in FEI’s case never sub assemblies, but solely purchase parts (although there might be phantomization in the BOM structure). Therefore, we have two options. On the one hand, we can use the forecast to implement a dynamic base stock policy, which is equivalent to an MRP-I policy for these items (Arts, 2015, Appendix F). For part \( i \), since the BOM is unambiguous, it holds that \( D_i(t) = \sum_{k \in \mathcal{Z}_i} X_k(t + L_{ik}) \). Then, we can determine a dynamic base stock level through Equation E.9. However, this method does not address the calculation of the optimal \( SS_i \); that would require distribution fitting. Therefore, we propose to implement the second option: to use single-echelon base stock policies instead; this requires distribution fitting and moment estimation to determine an optimal base stock level \( S_i \) as in Section 4.6.3.

**Variants on order**

These materials represent a large share of material value, but a limited amount of different items. Again, for FEI, these materials are only purchase parts \( (G_i = \emptyset) \). Because of the low volumes, it is possible to adopt an approach with manual matching of orders and materials required, and detailed risk management. This is necessary in any case for the NSRs, and for the Energy Filter, which are in many cases customer-specific modules. Cooperation with suppliers is key for all of these parts, in order to decrease risky and costly inventory buffers.

Alternatively, we can resort to single-echelon base stock policies for all variants of a module (e.g. for the CCD Camera: CETA and US1000). Since these materials are controlled order-based, negative demand such as with the forecast variants is not possible.
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4.5 The constraint-based planning approach

The manufacturing process has both capacity constraints as well as material constraints. FEI should plan accordingly in order to stabilize logistics. First, let us introduce the variables to determine the initial state of the system that require exogenous input: the total number of generic systems for S&OP family $z$ in production just before period one $V_z(0)$; scheduled receipts $SR_i(t)$ for all $i$ and $t = 1, \ldots, L_i - 1$; $D_i(t)$ for $t = 1, \ldots, \max_{i,j} L_i^*$. 

4.5.1 Capacity constraints for generic systems

We define three hard capacity constraints. First, the S&OP forecast per quarter must equal the total forecast demand in that quarter (Constraint 4.1). Second, the number of slots (i.e. spaces for system assembly and testing) in the factory is constrained to a certain level, which is defined per S&OP family (Constraint 4.2). Furthermore, warehouse capacity is limited and therefore number of start-ups in a week is restricted (Constraint 4.3). Define production lead time $L_{pz} = L_i^p$ for generic system $i$ associated with family $z$; $V_i(t)$ estimated starts of generic system $i$; $Y_z(\tau)$ forecast of demand for $z$ in quarter $\tau$; $KS_z$ the number of production slots in the factory for $z$; $KV$ the possible number of start-ups in a week. Then the constraints are:

\[
\sum_{t \in \tau} X_z(t) = Y_z(\tau) \quad \forall t, \tau \quad (4.1)
\]

\[
\sum_{\gamma < t} V_z(\gamma) - \sum_{\gamma < t} X_z(\gamma) \leq KS_z \quad \forall t, z \quad (4.2)
\]

\[
\sum_{i \in K} V_i(t) \leq KV, \quad \forall t \quad (4.3)
\]

As such, this is an integer Linear Programming (LP) problem, if we define an objective function, e.g. a holding cost based linear function. There might be alternative objective functions however; the capacity constraints are most important in the FEI case and a little excessive inventory is less important. With such an objective function, we verified the functioning of this approach using OpenSolver in MS Excel.

4.5.2 Planning material feasible order releases from forecast

The material constraint is the lead time required to create or procure an item. Furthermore, we cannot start a work order unless all predecessor materials are in stock. These constraints are incorporated in an algorithm for constraint-based MAP, published in Appendix E. This algorithm serves the purpose of calculating order release decisions, which is the core purpose of SCOP, and is adapted from De Kok et al. (2005). We corrected an error in the algorithm regarding the state-updating procedure and the definition of $I_i(t)$, which includes scheduled receipts in the period $t$. Furthermore, we adapted the allocation mechanism to allow zero safety stock for an item. A last adaptation was made to allow solely integer order releases, since this is relevant for a low-volume environment.

The planning logic enables backorders, but only for the end items. Constraint E.1 implies that the net stock of all non-end items is non-negative immediately after all orders have been released: only material feasible work orders are released.

We verified the functionality of the algorithm by implementing it in MS Excel with VBA code.
4.6 Parameter setting

4.6.1 Lead time setting

We consider the lead times to be exogenous to the SCOP problem cf. De Kok and Fransoo (2003). This means that the system should take care of controlled lead times such that these are more or less fixed and met with a high reliability. Consequently, lead times for purchase items are set at such levels that are in accordance with supplier contracts, possibly with some slack if supplier reliability is insufficient. Lead times for internal work orders should be based on analysis of historical data, in order to determine the mean and variance. Distribution fitting is required to set the lead time, such that the lead time is realized with a certain probability. For assembly systems such as FEI’s generic system, earlier research shows that any slack should be better positioned at the final assembly stage rather than at the early stages (Atan et al., 2016). The effect of lead time setting on SCR is an opportunity for further research.

4.6.2 Generic system BOM safety stocks

For the generic systems, FEI currently employs the demand hedging method: the S&OP family forecast is structurally overestimated (see Section 3.2.1). We propose to retain this methodology. It provides Sales and executives an opportunity to determine the buffer for demand uncertainty as a result of the strategic trade off between inventory risk and risk on lost sales. As a consequence, it is not necessary to use any additional safety stock on generic system level, since demand uncertainty is already taken into account, and supply uncertainty is taken into account through planned lead times.

For the underlying purchase parts, we identify two additional risks. Some items may have very long lead times (e.g. 192 calendar days for the image corrector). Demand hedging is then based on forecast of up to one and a half years. On this horizon, we expect forecasting accuracy to decline, mainly as a consequence of short life cycles. Safety stock might be appropriate to address this uncertainty.6

Alternatively, some items experience yield uncertainty. Then again, safety stock should be used. Inexpensive items are generally scrapped and replaced. In that case, calculation can be done through statistical analysis of historical data on yield. Expensive items are usually repaired in the high-tech industry. Then, calculating buffers is a complex problem which is outside the scope of this research.

4.6.3 Base stock levels for end-item modules

The following formulation is adopted from Shang and Song (2003). Consider a single-item, single-echelon inventory system in which the demand is stationary, and the replenishment lead time is constant. It is known that for this system, a base stock policy with base stock level $S_i$ is optimal. That is, monitor the inventory position continuously. Whenever the inventory position is below $S_i$, order up to $S_i$. Otherwise, do not order.7 Denote $D_i$ as the demand of item $i$ during lead time, and $F_i(\cdot)$ the cumulative distribution of $D_i$. Denote $S_i^*$ as the optimal base stock-level that minimizes inventory under the service level $\theta_i$; then it holds that:

$$F^{-1}(\theta) = \min\{x | F(x) \geq \theta\}, \quad 0 \leq \theta \leq 1 \quad (4.4)$$

$$S_i^* = F^{-1}_i(\theta_i) \quad (4.5)$$

---

6 Note that in this case, adequate life cycle management should be in place, since safety stocks should be decreased in the decline phase of the life cycle.

7 The policy does not allow for a batch size (MOQ) or review periods larger than one. Optimal single-echelon policies exist for these cases, but we do not discuss these here.
Chapter 4. Design of Implementation

This methodology does not work for modules, unless it is possible to determine $\theta$ properly and fit a distribution to the demand during lead time. That poses a problem in many cases, but we have provided alternatives for base stock policies in Section 4.4.

4.7 The detailed planning process

In this Section, we describe the practical planning process, that should be used to implement the described production strategy. In Figure 4.4, we present a cross-functional flowchart with explicitly defined decision variables as inputs, outputs and control. Variables not stated in this chart are merely calculated. Be aware that state variables defined at time $t < t$ are inputs for the decision functions to determine the variables at time $t \geq t$. For readability reasons, we did not include feedback arrows representing these relationships. Furthermore, be aware that the output variables of PU control are realized figures (not planned decisions in the future).

![Figure 4.4: Cross-functional flowchart, constraint-based planning approach](image)

4.7.1 Parameter setting (quarterly)

Review the lead times and safety stocks of all items quarterly, and adapt according to the basic methodology in Section 4.6. Parameter setting should also be done in case of new product introductions. Parameters can be copied or adapted from predecessors or comparable items, or induced through supplier contracts. Parameters for items at the end of the life cycle should be managed adequately in order to avoid obsolete stock.

4.7.2 Aggregate production planning (monthly)

First, translate the ship request $Y_z(\tau)$ (the result of S&OP), which is expressed in quarterly time buckets into $X_z(t)$, which is expressed in weekly time buckets. The manufacturing lead time implies a frozen period for $X_z(t)$ on the interval $[t, L_z^+ + L_z^− - 1]$.

As a consequence of $X_z(t)$, derive $D_i(t)$ for all generic systems ($i \in \mathcal{K}$) and for all forecasted multiple variant sub assemblies $\{i \in \mathcal{N} \setminus \mathcal{K} : G_i \neq \emptyset\}$ according to the method in Section 4.4.1. At this point, we assume that generic units are directly matched to an actual system order when
finished, such that the total lead time is equal to the sum of the production and the customer lead time. Set the production lead time for a generic system equal to the maximum cumulative lead time of all work orders, and derive an estimated start plan:

\[
L_p^i = \max_{j} (L^*_{ji} - L_j)
\]  
(4.6)

\[
V_i(t) = D_i(t + L_p^i)
\]  
(4.7)

At this stage, we incorporate capacity management. Use constraints 4.2 and 4.3 to create a feasible plan, optionally with integer LP. If (one or both) constraints are violated (there is no feasible solution), this should be resolved manually. There are several options: i) manually adapt \(X_z(t)\), i.e. advance or expedite forecast by weeks within the quarter; ii) decrease the production safety lead time and thus \(L_p^i\); or iii) adapt the ship request, i.e. advance or expedite forecast over quarters.

4.7.3 Aggregate material requirements planning (monthly)

We propose to implement aggregate MRP, i.e. sending out forecast to suppliers, in monthly time buckets.\(^8\) In general, forecast quality decreases in the far future. By aggregating on a monthly level, we aim to improve stability of the forecast. We can directly derive aggregate MRP quantities from the scheduled receipts \(\hat{SR}_i(t)\) for all purchase parts.

For purchase parts used in generic systems or forecast variants, i.e. \(\{i : \{j : j \in E_i\} \subset \mathcal{N} \land G_i = \emptyset\}\), \(E_i\) is the set of immediate successors of item \(i\) we can implement aggregate MRP through our definition of the estimated start plan \(V_i(t)\), and define

\[
\hat{SR}_i(t) = \sum_{j \in E_i} V_j(t - L_p^j + (L^*_{ij} - L_i))
\]  
(4.8)

At this level, we can check for material feasibility through comparing the previous schedule with the current schedule for each purchase part. Special attention should be given to adaptations within the lead time. For many materials (for many suppliers), lead times are not a hard constraint. In many cases, agreements might be in place that allow for increasing or decreasing orders with a certain amount. Finally, when expedition of material is not possible, one should resort to adapting the aggregate production planning or even the ship request. Another method to check for feasibility and possible shortages is comparing the scheduled receipts to the aggregate planning.

All end-item purchase parts \(\{i \in \mathcal{N} : G_i = \emptyset\}\) are controlled with a base stock policy. Aggregate MRP for these parts entails forecasting based on historical demand data. Since the expected demand for these items is dependent on the forecast of the S&OP families where the item is used, we adapt the average demand over the past year accordingly, and define

\[
\hat{SR}_i(t) = \sum_{k \in Z_i} X_k(t) \frac{\sum_{\gamma=1}^{52} SR_i(t - \gamma)}{\sum_{k \in Z_i} \left\{ \sum_{\gamma=1}^{52} X_k(t - \gamma) \right\}}
\]  
(4.9)

If all capacity and material constraints are met, we finalize the S&OP process and implement the ship request as an approved shipment plan.

\(^8\)From a SCOP perspective, this step might not seem necessary since we already use constraint-based planning for future time periods. However, this process is necessary according to many supplier agreements and to incorporate forecast commitments.

\(^9\)Remember, we assume that materials used in multiple modules are separately coordinated. This implies that materials in generic systems are never used outside generic systems and analogous for decoupled modules.
4.7.4 Order acceptance and master production scheduling (weekly)

The goal of the order acceptance process is to match an order to a generic system (unit) and to generate a due date, i.e. the output of this process for all items (including generic systems) is the adaptation of $D_i(t)$ and $X_z(t)$. As such, this function and MPS are strongly interdependent in an MTF environment. If the functions are split between departments, it is necessary that order acceptance and MPS is an iterative process.

If a customer order is accepted, it is matched to a unit, based on some heuristic. This unit is not necessarily unmatched, but in many cases it will be, since matched order-units are highly customer-specific because of directly executed modifications.

There is a hard constraint, in that the number of orders in a quarter cannot exceed the sum of $X_z(t)$ in that quarter (on the SCOP hierarchy level, the ASP is a strict maximum). In case all orders are accepted (which is the case at FEI, due to the immense margins), this constraint is guaranteed through setting a lead time equal to or larger than $L_z$. In many cases, within-quarter changes will be made to $X_z(t)$ in the process.

For the forecast materials (before the CODP), MPS and aggregate production planning are similar for FEI, and we propose to do this monthly to ensure a relatively stable MPS. On a weekly basis, MPS comprises determining the product mix through starting up different variants of the generic systems. This mix should be determined according to historical data of shipped configurations, but adapted according to e.g. market trends and changes in the product portfolio.

A direct result of order acceptance and MPS (i.e. adapting $D_i(t)$ and $X_z(t)$) will be changes in material requirements, e.g. as a result of due date changes or configuration changes. As such, this process should be triggered again when critical material constraints surface through MAP.

4.7.5 Material availability planning (weekly)

This process exists of weekly execution of the algorithm in Section 4.5.2, and determining order releases for base stock-controlled items through $R_i(t) = (S_i - IP_i(t))^+$, after adaptation of $D_i(t)$ as a consequence of order acceptance. Any shortages in material are only represented through a negative inventory for end items, but it is easy to identify the shortage material, in order to try to solve the problem; either with the supplier or by expediting an internal work order. Definitive shortages in material should be solved by adapting $D_i(t)$, i.e. expediting forecast for generic systems. This can be reached by shortening the order lead time (if possible) or by adapting $X_z(t)$. A change within the quarter does not affect the ASP, while a change over quarters does.

4.8 Summary

In this Chapter, we described an innovative methodology for mid-level planning in a Make-to-forecast environment, based on the ideal OPC’s in Chapter 2 and aiming to address the gaps defined in Section 3.4. We commenced by describing the production strategy, and introduced a categorization of material. Then, we described the planning methodology, both from a perspective of these different categories, as well as from a practical perspective in a monthly and weekly cycle.
Chapter 5

Reflection

We conclude this research project with a reflection on our findings. We commence by answering the research questions formulated in Section 1.5 in Section 5.1. In Section 5.2, we summarize our contributions to academic literature. Furthermore, we provide recommendations for FEI specific in Section 5.4 and directions for further research in the SCP field in Section 5.5. Lastly, we reflect on the limitations of our research in Section 5.6.

5.1 Research questions

We formulated the research questions in order to address the problem statement: provide a first step towards improving planning stability.

Q1: What is planning nervousness and how does it relate to responsiveness and flexibility?

We answered this question in Section 1.3. The SCR framework (Reichhart & Holweg, 2007) can be used to characterize requirements and determinants for responsiveness. The collection of internal determinants defines the internal flexibility. If these determinants do not address external requirements well enough, planning nervousness might be an effect. We provide qualitative support for this theory through the FEI case study in Chapter 3.

Q2: What kind of framework for supply chain planning should be used to improve responsiveness and stability?

This question lies at the core of the main research question. We answered this question in Chapter 2, by defining a framework for SCP. We developed a hierarchical planning structure, and modeled the decision functions on each hierarchical level. Furthermore, for the most relevant decision functions, we explained the effects on responsiveness, and summarized this in Table 2.1.

Q3: How can we use decoupling points and buffers against uncertainty, such as safety lead time and safety stocks, to improve internal flexibility?

We provided the answer to this question for a general case in Sections 2.8.2 and 2.12. Parameter setting on S&OP level serves the purpose to create a predictable supply chain environment and induce buffers that determine flexibility. More specifically for the FEI case, we provided a methodology to categorize material, determine decoupling points, and set parameters in Chapter 4. This basic approach can be generalized for companies operating in a similar business environment. However, note that optimal parameter setting yields complicated multi-item multi-echelon multi-resource problems that are currently mathematically intractable.
Q4: How can we address the specific complexities in material coordination in a Make-to-Forecast environment?

The specific complexities are mainly due to possible configuration changes within the production lead time. We defined material categories in Chapter 4 and proposed a methodology for material coordination of the forecast variant materials in Section 4.4.1. This approach was tailored to the FEI case, but can be used for companies operating in a similar business environment.

Q5: Which methods can be used for supply chain integration, to improve internal flexibility?

We answered this question in Section 2.13 on a conceptual level. Information integration and coordination and resource sharing are key to compete as a supply chain. The planning approach presented in Chapter 4 might be used across companies, and the basis was initially even presented as such as part of a concept called collaborative planning (De Kok et al., 2005). However, information sharing barriers prohibit supply chains from taking such an approach since buyers and suppliers keep seeing each other as competitors.

Q6: In relation to responsiveness, what are the key features of the currently employed framework and mechanisms for supply chain planning and control at FEI?

This question is addressed in Chapter 3. We have described the external requirements for SCR for FEI and we have described the demand anticipation and inventory determinants by modeling the current SCP process at FEI. As a result, we described four important gaps between this process and the ideal design in Section 3.4.

Q7: How can FEI improve its supply chain planning processes and mechanisms to improve planning stability and to become more responsive?

Closing the gaps defined in Section 3.4 would improve responsiveness for FEI. We provide the basis of a new methodology for planning and control in Chapter 4. This methodology addresses parameter setting, order acceptance, aggregate planning, MPS and MRP. As such, it provides a solution for three of the gaps defined. The other gap is addressed in our recommendations for FEI (Section 5.4).

Main Question: How to use a framework for supply chain planning and control, buffers against uncertainty and control mechanisms, in a Make-to-Forecast environment, under the objective of improving responsiveness and stability?

This research answers the research question by: i) defining the concepts responsiveness and stability based on accumulated empirical evidence in literature in Chapter 1; ii) providing an adapted framework for SCP in a Make-to-Forecast business environment, based on a case study at FEI and consistent with other theories in the field of SCP in Chapter 2; iii) taking into account the objectives of responsiveness and stability in this framework; iv) applying this framework to a real world case in Chapter 3; v) providing a planning approach that supports the development of control mechanisms and the placement of buffers against uncertainty in Chapter 4.

5.2 Scientific contribution

This research project contributes to academia in a number of ways:

- We related the concepts of planning nervousness and responsiveness and provided empirical evidence for this relationship with our case study.
• We introduced a framework for SCP in a Make-to-forecast environment, and as such extended the literature on the conceptual ideas underlying this production strategy, that was introduced by Meredith and Akinc (2007).

• We have applied the framework of Reichhart and Holweg (2007) for a real case, and therefore extended the empirical evidence that this framework is adequate.

• We introduced an innovative planning approach in Chapter 4, that can be applied not only at FEI, but possibly at other high-tech OEM’s as well.

• We extended the constraint-based MRP algorithm of De Kok et al. (2005) for a case with integer inventory constraints and zero safety stock for a number of items in Appendix E.

• We described meaningful recommendations to improve responsiveness, especially for companies operating in a Make-to-forecast environment.

5.3 Generalizability

Other companies can benefit from the research done at FEI in a number of ways. Our framework in Chapter 2 is a generic discussion on SCP in MTF environments, and provides an insight to the main drivers of SCR. The methodology presented in Chapter 4 applies to FEI, but the main concepts can be extrapolated: the methods and formulas that we use — specifically the methodology for categorization of material and the description of integrated order acceptance and SCOP — are applicable to any company operating according to an MTF strategy, with an S&OP induced demand forecast.

5.4 Recommendations to FEI

• Set firm internal lead times that are realized with a high degree of certainty. This includes the minimum customer lead time. It can be as low as required, as long as it is firm and non-negotiable, such that safety stocks, safety lead times and hedging mechanisms can be set to achieve a fixed flexibility requirement.

• Implement constraint-based planning, such as in Chapter 4, in order to enable easy identification of bottlenecks in resource capacity and materials. Such a planning methodology fulfills the desired functionality for assessing feasibility of any shipment plan as it integrates order acceptance, MPS and MAP. As FEI will be able to identify bottlenecks, the logistics and sourcing teams will know what areas to focus on in order to improve responsiveness of the (internal) supply chain gradually.

• Include flexibility requirements better in strategic supplier selection in order to solve the first gap defined in Section 3.4. Enable responsiveness on a strategic level through contracts, especially for expensive items with volatile demand.

• Start a follow-up study on demand anticipation, with the objective to improve forecasting accuracy and close the second gap. We provided a short discussion on success factors for demand anticipation within the S&OP process. A follow-up project should be driven by the Business Units, Sales, and SSOC but with the Logistical Teams as a customer. Its goal should be more advanced anticipation methods and pro-active demand management, with the objective to reduce demand uncertainty and variability.

• Address the third gap in order acceptance, by starting an investigation into the possibilities for a strict minimum customer lead time or configuration milestones.
5.5 Directions for further research

There are several opportunities for further research, and follow-up projects within FEI:

- Lead time reduction is one of the largest enablers of responsiveness. Internal manufacturing lead time could be reduced through e.g. more advanced ways of testing equipment, mitigating quality issues or reducing yield. Supply lead time can be reduced through collaboration with suppliers such that they can reduce manufacturing lead times. Another way to reduce lead times is through advanced logistical contracts with terms that include e.g. implementing forecast commitment, move rates and consignment stock (VMI).

- Safety stock setting for items of different categories in a Make-to-forecast environment is a complex challenge. Simulation studies with real data could provide accurate trade-offs between costs and benefits of responsiveness through safety stock.

- Material control and parameter setting for items that can break down during production and require repairs, such as the accelerator. Our discussion in Chapter 4 lacks solutions for this problem.

- The ways supply chain integration could be used to improve SCR through material coordination. Research to date is mostly of a descriptive nature, and lacks applications in practice and case studies.

5.6 Limitations of this study

This research project has its limitations:

- Our approach is based on a single case study and does not involve research at other companies than FEI, except through referring to previous research in the field.

- Key enablers of responsiveness are supply chain integration and collaborations between firms. We address this issue only conceptually in Section 2.13, and did not empirically research the relations of FEI with its suppliers and the effect on responsiveness and stability in SCP.

- We did not present an action plan and contingency plan for FEI, nor did we conduct a force field analysis or stakeholder analysis. If FEI would implement the methodologies presented, one should consider organizational change theory.

- The main objective of the framework in Chapter 2 and the planning approach in Chapter 4 is to improve responsiveness. We validate this objective with qualitative indications, but we do not provide quantitative models, such as simulation, to reinforce our arguments.
References


References


References


Appendix A

Cause-effect diagram for planning nervousness

This Appendix includes the cause-effect diagram for planning nervousness at FEI. It was constituted as a result of interactive interviews with various stakeholders within and around FEI Logistics. We have grouped several sets of causes. This reveals similarities with the determinants and requirements of SCR in the framework of Reichhart and Holweg (2007).
Figure A.1: Cause-effect diagram for planning nervousness
Appendix B

Forecast and demand during lead time

This Appendix presents the forecast and demand during lead time (9 months) for four different product families.

**Figure B.1**: Forecast and actual demand during lead time for the Titan Krios family \((L = 3, CV = 65\%\))

**Figure B.2**: Forecast and actual demand during lead time for the Metrios family \((L = 2, CV = 54\%\))
Appendix B. Forecast and demand during lead time

**Figure B.3**: Forecast and actual demand during lead time for the Titan Low Base families ($L = 3$, $CV = 42\%$)

**Figure B.4**: Forecast and actual demand during lead time for the Titan High Base families ($L = 4$, $CV = 27\%$)
Appendix C

Configuration diversity

This Appendix presents the configuration diversity for a number of shipped systems in four product families.

<table>
<thead>
<tr>
<th>TABLE C.1: Configuration diversity for shipped systems 2014Q1-2016Q1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
</tr>
<tr>
<td>Alignment</td>
</tr>
<tr>
<td>60 kV</td>
</tr>
<tr>
<td>80 kV</td>
</tr>
<tr>
<td>120 kV</td>
</tr>
<tr>
<td>200 kV</td>
</tr>
<tr>
<td>300 kV</td>
</tr>
<tr>
<td>Total objective</td>
</tr>
<tr>
<td>CDC</td>
</tr>
<tr>
<td>CLC</td>
</tr>
<tr>
<td>SDC</td>
</tr>
<tr>
<td>SDX</td>
</tr>
<tr>
<td>SLC</td>
</tr>
<tr>
<td>SLX</td>
</tr>
<tr>
<td>Accelerator</td>
</tr>
<tr>
<td>X-FEG 200</td>
</tr>
<tr>
<td>X-FEG 300</td>
</tr>
<tr>
<td>X-FEG 300 Mono</td>
</tr>
<tr>
<td>HT Generator</td>
</tr>
<tr>
<td>Mono</td>
</tr>
<tr>
<td>Regular</td>
</tr>
<tr>
<td>Corrector</td>
</tr>
<tr>
<td>Double</td>
</tr>
<tr>
<td>Image</td>
</tr>
<tr>
<td>Probe</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>STEM</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>STEM w/ BF/DF</td>
</tr>
<tr>
<td>CCD Camera</td>
</tr>
<tr>
<td>CETA</td>
</tr>
<tr>
<td>US1000</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>Energy Filter</td>
</tr>
<tr>
<td>Enfinium</td>
</tr>
<tr>
<td>Quantum</td>
</tr>
<tr>
<td>None</td>
</tr>
</tbody>
</table>
Appendix D

Definition of variables

This Appendix includes an overview of variables used for the mathematical model of the constraint-based planning approach in Chapter 4 and the algorithm for constraint-based SCOP in Appendix D.

Unless otherwise defined, all state variables and parameters are defined within the set of all integers $\mathbb{Z}$. 
### Table D.1: Definition of variables

<table>
<thead>
<tr>
<th>Variant</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Indicators, sets and relationships</strong></td>
<td></td>
</tr>
<tr>
<td>$t \in \mathbb{N}$</td>
<td>time or period indicator (weeks)</td>
</tr>
<tr>
<td>$\tau \in \mathbb{N}$</td>
<td>time or period indicator (quarters)</td>
</tr>
<tr>
<td>$i$</td>
<td>item</td>
</tr>
<tr>
<td>$z$</td>
<td>S&amp;OP family</td>
</tr>
<tr>
<td>$Z$</td>
<td>set of all S&amp;OP families, i.e. aggregate items with quarterly forecast</td>
</tr>
<tr>
<td>$M$</td>
<td>set of all items (not families: $Z \cap M = \emptyset$)</td>
</tr>
<tr>
<td>$N$</td>
<td>set of all end items, i.e. items with independent demand, $N \subset M$</td>
</tr>
<tr>
<td>$K$</td>
<td>set of all generic system items, $K \subset N$</td>
</tr>
<tr>
<td>$C_i$</td>
<td>set of immediate successors (parents) of item $i$, $i \in M$</td>
</tr>
<tr>
<td>$G_i$</td>
<td>set of immediate predecessors (childs) of item $i$, $i \in M$</td>
</tr>
<tr>
<td>$E_i$</td>
<td>set of end items delivered by item $i$, $i \in M$</td>
</tr>
<tr>
<td>$Z_i$</td>
<td>set of S&amp;OP families where item $i$ is used, $i \in N$</td>
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<tr>
<td><strong>Parameters associated with each item</strong> $z \in Z$</td>
<td></td>
</tr>
<tr>
<td>$L_c^z$</td>
<td>customer lead time for S&amp;OP family $z$</td>
</tr>
<tr>
<td>$KS_z$</td>
<td>slot capacity for S&amp;OP family $z \in Z$</td>
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<tr>
<td><strong>Parameters associated with (a subset of) $i \in M$</strong></td>
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</tr>
<tr>
<td>$L^p_i$</td>
<td>production lead time for item ${i \in N : G_i = \emptyset}$</td>
</tr>
<tr>
<td>$KV$</td>
<td>warehouse capacity for weekly start-ups for every item $i \in K$</td>
</tr>
<tr>
<td>$a_{ij}$</td>
<td>number of items $i$ required to produce one item $j$, $j \in M$</td>
</tr>
<tr>
<td>$L_i$</td>
<td>lead time for a work/procurement order of item $i$</td>
</tr>
<tr>
<td>$L_{ij}$</td>
<td>sum of lead times of all items on the path between $i$ and $j$ (both items included)</td>
</tr>
<tr>
<td>$S_i$</td>
<td>target base stock level for stationary base stock control</td>
</tr>
<tr>
<td>$\theta_i \in \mathbb{R}$</td>
<td>target service level (probability of no stock out per order cycle) for item $i$</td>
</tr>
<tr>
<td>$SS_i$</td>
<td>cumulative safety stock in the echelon of $i$</td>
</tr>
<tr>
<td>$\mu_i \in \mathbb{R}$</td>
<td>mean demand during lead time for item $i$</td>
</tr>
<tr>
<td>$\sigma_i \in \mathbb{R}$</td>
<td>standard deviation of demand during lead time for item $i$</td>
</tr>
<tr>
<td><strong>State variables defined for</strong> $z \in Z$ <strong>in each time period</strong> $t \geq 1$</td>
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</tr>
<tr>
<td>$Y_z(\tau)$</td>
<td>quarterly forecast of demand for S&amp;OP family $z \in Z$</td>
</tr>
<tr>
<td>$X_z(t)$</td>
<td>weekly forecast of demand for S&amp;OP family $z \in Z$</td>
</tr>
<tr>
<td><strong>State variables defined for (a subset of)</strong> $i \in M$ <strong>in each time period</strong> $t \geq 1$</td>
<td></td>
</tr>
<tr>
<td>$D_i(t)$</td>
<td>forecast of demand for end item $i \in N$ in period $t$</td>
</tr>
<tr>
<td>$V_i(t)$</td>
<td>estimated starts of ${i \in N : G_i \neq \emptyset}$ in period $t$</td>
</tr>
<tr>
<td>$I_i(t)$</td>
<td>physical stock of item $i$ in period $t$, immediately after scheduled receipts</td>
</tr>
<tr>
<td>$Q_i(t)$</td>
<td>inventory on order of item $i$ at the start of period $t$</td>
</tr>
<tr>
<td>$IP_i(t)$</td>
<td>inventory position of item $i$ at the start of period $t$</td>
</tr>
<tr>
<td>$EIP_i(t)$</td>
<td>echelon inventory position of item $i$ at the start of period $t$</td>
</tr>
<tr>
<td>$SR_i(t)$</td>
<td>scheduled receipt of item $i$ planned to arrive at the start of period $t$</td>
</tr>
<tr>
<td>$\hat{SR}_i(t)$</td>
<td>planned scheduled receipts for aggregate MRP</td>
</tr>
<tr>
<td>$R_i(t)$</td>
<td>order released for item $i$ at the start of period $t$</td>
</tr>
<tr>
<td>$PR_i(t)$</td>
<td>provisional order released for item $i$ at the start of period $t$</td>
</tr>
<tr>
<td>$AR_i(t)$</td>
<td>additional release for item $i$ at the start of period $t$</td>
</tr>
<tr>
<td>$S_i(t)$</td>
<td>target base stock level for dynamic base stock control</td>
</tr>
<tr>
<td>$Q_j^{(i)}(t)$</td>
<td>order released for item $j$ if item $i$ would be the only predecessor</td>
</tr>
<tr>
<td>$\mathcal{R}$</td>
<td>set of release options</td>
</tr>
</tbody>
</table>
Appendix E

Constraint-based MAP algorithm

Without loss of generality and for ease of presentation, we assume that $a_{ij} \in \{0, 1\}$. We define the following general definitions:

\[
I_i(t) - \sum_{j \in C_i} a_{ij} R_j(t) \geq 0, \quad i \in M \setminus N \quad (E.1)
\]

\[
O_i(t) = \sum_{\gamma=1}^{L_i-1} SR_i(t + \gamma), \quad i \in M \quad (E.2)
\]

\[
IP_i(t) = I_i(t) + O_i(t), \quad i \in M \quad (E.3)
\]

\[
EIP_i(t) = IP_i(t) + \sum_{j \in C_i} EIP_j(t), \quad i \in M \quad (E.4)
\]

Planned events occur in the following order: i) scheduled or planned items are received immediately after the start of a period; ii) orders for each item are released immediately after this; iii) fulfillment of end-item forecasts is just before the end of a period. The procedure to update state variables is as follows:

\[
SR_i(t + L_i) = R_i(t), \quad i \in M \quad (E.5)
\]

\[
I_i(t + 1) = I_i(t) - D_i(t) + SR_i(t + 1), \quad i \in N \quad (E.6)
\]

\[
I_i(t + 1) = I_i(t) - \sum_{j \in C_i} a_{ij} R_j(t) + SR_i(t + 1), \quad i \in M \setminus N \quad (E.7)
\]

Important to a proper calculation and a requirement for guaranteeing material feasible work orders, is the sequencing of decisions to be taken at the start of a period. Computations start with the most upstream items of the network, i.e. items with no predecessors. All subsequent decisions should be determined recursively, up and until the orders for the end items.

The unconstrained order decision $q_j$ is the result of a basestock policy with a dynamic (time-dependent) base stock level. For end items $i \in N$ this policy is equivalent to an MRP policy (Proof given in Arts (2015)).

\[
q_j(t) = (S_j(t) - EIP_j(t))^+ \quad (E.8)
\]

\[
S_i(t) = \sum_{k \in E_i} \left\{ \sum_{\gamma=0}^{L_{i,k}} D_k(t + \gamma) \right\} + SS_i, \quad i \in M \quad (E.9)
\]

The algorithm continues with the creation of material feasible order releases, which is guaranteed through an allocation mechanism. Let us consider item $i \in G_j$, for which we want to determine $Q_{j(i)}$. We can distinguish between two situations:

1. $\sum_{k \in C_i} q_k(t) \leq I_i(t)$, then we can satisfy all orders for $i$ and thus $Q_{j(i)}(t) = q_j(t)$;
2. $\sum_{k \in C_i} q_k(t) \geq I_i(t)$, then we must allocate available stock $I_i(t)$.
Appendix E. Constraint-based MAP algorithm

The allocation mechanism is different than proposed by De Kok et al. (2005), since their method does not allow for zero safety stock. We adapt the formula to determine $EIP^*_j$, by changing the fraction in order to ration the available inventory on the basis of the mean and standard deviation of demand during lead time (Van der Heijden, Diks, & De Kok, 1997, Equation 21).

$$Q^{(i)}_j(t) = \left\lfloor \frac{(EIP^*_j(t) - EIP_j(t))^+}{\sum_{k \in C_i}(EIP^*_k - EIP_k)^+} I_i(t) \right\rfloor$$ (E.10)

$$EIP^*_j(t) = S_j(t) - \frac{1}{2} \left( \frac{\sigma^2_j}{\sum_{k \in C_i} \sigma^2_k} + \frac{\mu^2_j}{\sum_{k \in C_i} \mu^2_k} \right) \left( \sum_{k \in C_i} q_k(t) - I_i(t) \right)$$ (E.11)

As a conclusion, we determine the provisional order released as

$$PR_j(t) = \min_{\forall n \in G_j} Q^{(n)}_j(t)$$ (E.12)

The formulation of $Q^{(i)}_j(t)$ is such that it is an integer and that it necessarily represents a feasible release. As a result, the algorithm is inefficient in that there still might be required and feasible releases left. Therefore, we introduce a procedure to use the leftover material. Identify two possible cases:

1. $q_j(t) = PR_j(t)$, then the actual release is the unconstrained release, and there is no possibility to release additional orders.

2. $q_j(t) > PR_j(t)$, then the unconstrained release is larger than the currently calculated order release. Proceed by determining the set with items with a possible release $R$ by determining if there is leftover material for predecessors:

$$R = \left\{ j : \min_{v k \in G_j} \left( I_k(t) - \sum_{m \in C_k} PR_m(t) \right) > 0 \land q_j(t) > PR_j(t) \right\}$$ (E.13)

It might not be feasible to release all $j \in R$. Therefore, we should determine which of the possible items to release through another allocation mechanism. A stationary fraction based upon item characteristics would result in structural imbalance (Van der Heijden et al., 1997). Therefore, determine the item through randomization over an empirical distribution determined on the basis of a similar fraction as the one we use in Equation E.11:

$$P(k = j) = 0.5 \left( \frac{\sigma_k}{\sum_{m \in R} \sigma_m} + \frac{\mu_k}{\sum_{m \in R} \mu_m} \right)$$ (E.14)

Note that these chances sum up to 1, such as is necessary. Then, pull a random variable $j$ from the distribution, and adapt $PR_j(t) = PR_j(t) + 1$. Determine $R$ again through Equation E.13, and repeat the subsequent steps until $R = \emptyset$.

If $R = \emptyset$, then stop calculation and set for all $j$, $R_j(t) = PR_j(t)$. This concludes the algorithm.
Appendix F

Planning process at FEI

In this appendix, we present the representation of FEI’s planning process. Figure F.3 is a cross-functional flowchart (swimming lane model) of planning at FEI. Each node represents a decision function. Another way to represent planning and control is Figure F.2; this emphasizes how different departments interact with each other. We further specify the decision functions in the cross-functional flowchart using the IDEF0 method (Figure F.1): we explicitly state input, outputs, control variables and mechanisms for each decision function and present an overview of these in Table F.1.

**Figure F.1: Description of the IDEF0 modeling method**

**Figure F.2: Planning and control at FEI**
Figure F.3: Cross-functional flowchart of the planning process at FEI
### Table F.1: Definition of variables in IDEF0 scheme

<table>
<thead>
<tr>
<th>ID</th>
<th>Variable</th>
<th>ID</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>Competitive environment</td>
<td>O1</td>
<td>Revenue forecast</td>
</tr>
<tr>
<td>I2</td>
<td>Market projections</td>
<td>O2</td>
<td>Strategic objectives</td>
</tr>
<tr>
<td>I3</td>
<td>Technology developments</td>
<td>O3</td>
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<td>I4</td>
<td>Technical product specifications</td>
<td>O4</td>
<td>BOM</td>
</tr>
<tr>
<td>I5</td>
<td>Financial product specifications</td>
<td>O5</td>
<td>Configuration modification costs</td>
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<tr>
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<td>Bookings forecast BU’s</td>
<td>O6</td>
<td>Manufacturing configuration structure</td>
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<tr>
<td>I7</td>
<td>PLM/NPI/EOP details</td>
<td>O7</td>
<td>Supplier contracts</td>
</tr>
<tr>
<td>I8</td>
<td>Inventory levels</td>
<td>O8</td>
<td>Planned lead times</td>
</tr>
<tr>
<td>I9</td>
<td>Procurement capabilities</td>
<td>O9</td>
<td>Safety stock levels</td>
</tr>
<tr>
<td>I10</td>
<td>Customer order</td>
<td>O10</td>
<td>Lotsizing algorithms</td>
</tr>
<tr>
<td>I11</td>
<td>Customer reservation</td>
<td>O11</td>
<td>Control policies</td>
</tr>
<tr>
<td>I12</td>
<td>Slot status</td>
<td>O12</td>
<td>Decoupling Points</td>
</tr>
<tr>
<td>I16</td>
<td>Ship request</td>
<td>O13</td>
<td>Quotation</td>
</tr>
<tr>
<td>I17</td>
<td>Feasible shipment plan</td>
<td>O14</td>
<td>Order priorities</td>
</tr>
<tr>
<td>I18</td>
<td>Agreed ship request</td>
<td>O15</td>
<td>Customer contract</td>
</tr>
<tr>
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<td>Supply-demand disagreements</td>
<td>O16</td>
<td>Ship request</td>
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<td>Approved shipment plan</td>
<td>O17</td>
<td>Feasible shipment plan</td>
</tr>
<tr>
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<td>O18</td>
<td>Agreed ship request</td>
</tr>
<tr>
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<td>Accepted order</td>
<td>O19</td>
<td>Supply-demand disagreements</td>
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<td>O20</td>
<td>Approved shipment plan</td>
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<tr>
<td>I25</td>
<td>Master Production Schedule</td>
<td>O21</td>
<td>S&amp;OP improvements</td>
</tr>
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<td>Released work order</td>
<td>O22</td>
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<td>I27</td>
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<td>S&amp;OP Principal</td>
<td>O27</td>
<td>Planned procurement order</td>
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<td>M4</td>
<td>ERP system</td>
<td>O28</td>
<td>Detailed production planning</td>
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<td>S&amp;OP Principal</td>
<td>O29</td>
<td>Procurement forecast</td>
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<td>Manager Ops. Eng.</td>
<td>O30</td>
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<td>VP Sourcing</td>
<td>O31</td>
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<td>Director Operations</td>
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<td>M9</td>
<td>Supervisor Order Desk</td>
<td>C2</td>
<td>Strategic objectives</td>
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<td>M10</td>
<td>Supervisor Planning</td>
<td>C3</td>
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<td>M11</td>
<td>Supervisor Procurement</td>
<td>C4</td>
<td>BOM</td>
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<td>ERP</td>
<td>C5</td>
<td>Configuration modification costs</td>
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<td>CRM</td>
<td>C6</td>
<td>Manufacturing configuration structure</td>
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<td>M14</td>
<td>&quot;Final Test&quot;</td>
<td>C7</td>
<td>Supplier contracts</td>
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<tr>
<td>M15</td>
<td>BPC</td>
<td>C8</td>
<td>Planned lead times</td>
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<td>M16</td>
<td>S&amp;OP tools</td>
<td>C9</td>
<td>Safety stock levels</td>
</tr>
<tr>
<td>M17</td>
<td>SVP Business Unit</td>
<td>C10</td>
<td>Lotsizing algorithms</td>
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<td>Financial controller</td>
<td>C11</td>
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<td>C13</td>
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<tr>
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<td>C21</td>
<td>S&amp;OP improvements</td>
</tr>
</tbody>
</table>
Appendix F. Planning process at FEI
Appendix F. Planning process at FEI

Create ship request

- Revenue forecast (E1)
- Strategic objectives (E2)
- Customer contract (E3)

The Director Sales & Service (E1)

Director Sales & Service (E1)

ERP (M12)

Manufacturing capacity (C2)

Supplier contracts (C7)

Supplier contract (M13)

Planned lead time (C8)

This process is established through "speak meetings" for each factory.

Analyze supply feasibility

- S&OP tools (M16)
- Supplier contracts (M13)
- Inventory levels (M15)

Ship request (E2)

Ship request (E5)

Ship request agreement

- S&OP improvements (C11)
- Feasible shipment plan (E17)

The ship request agreement is established through the "speak meeting".

Agree request

- SVP Operations (M4)
- SVP Business Unit (M17)
- Financial controller (M32)

Approved shipment plan (E22)
Appendix F. Planning process at FEI

---

**Approve order**

- Customer order (O10)
- Customer reservation (O11)
- Quotation (O11.3)
- Customer contract (O15/C15)
- G1
- OMM (M13)
- Approved order (O22/O22)
- Manufacturing capacity (O21)
- Strategic objectives (O20)
- Order priorities (O21/O4)
- Approved order (O22/O22) (G4)
- Director Sales & Service (M12)
- Approved order (O22/O22)
- Approved shipment plan (O20)
- Shift status (O12)

**Prioritize orders**

- G4
- Director Sales & Service (M12)
- OMM (M13)

---

**Specify and accept manufacturing configuration**

- Approved order (O22)
- Accepted order (O23/O23)
- Manufacturing configuration structure (M6)
- OMM (M13)
- LSI Manager (M19)
- Supervisor order desk (M19)
- Manufacturing order (O24/C4)
- Manufacturing capacity (O31)
- Planned lead time (O8)
- Approved shipments plan (O20)
- Release production schedule (O27)
- Supervisor order desk (M12)
- Work instruction system (M12)
- Manufacturing order (O24/C4)
- Planned delivery date (O20)

---

**Accept order configuration**

- Mode: H1
- Title: Accept order configuration
- Node: H1
Appendix F. Planning process at FEI

Diagram: Initiate order shipment

- Customer contract (C13)
- Compliance & customs regulations (C13)
- Approved shipment plan (C20)
- Work order confirmation (C20)
- Customs clearance (C20)
- Transportation order (C41)
- ERP (AM13)
- CRM (AM13)
- Supervisor order desk (AM46)