MASTER

Synchronizing material planning in an assemble-to-order environment
an improved SCOP method

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Synchronizing material planning in an assemble-to-order environment: an improved SCOP method

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By S.B. (Simon) Tax

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Supervisors:

1st supervisor: dr. ir. V.C.S Wiers, Eindhoven University of Technology
2nd supervisor: prof. dr. A.G. de Kok, Eindhoven University of Technology
M.Verdonschot, VDL Apparatenbouw
D. Toussaint, VDL Apparatenbouw

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Abstract

Material planning has a high impact on the performance of ATO companies. Many of these companies use MRP logic to translate their production plans into material requirements and corresponding purchasing orders. However, MRP has several shortcomings that create both an unstable planning and inefficient purchasing decisions. In this master thesis an improved SCOP method is suggested for the material planning at VDL Apparatenbouw. This SCOP method is based on an extension of the SBS model by de Kok & Fransoo (2003). The model was extended with lot-sizing for purchased materials, since these have an important impact on the inventories in place at VDL A. A simulation study showed that the extended SBS model can provide significant improvements compared to MRP logic regarding inventory efficiency. Most importantly it ensures feasible demand and production plans that create more stability both internally and towards suppliers. This new SCOP method was implemented in an operational planning tool, such that it can be applied in VDL A's planning process.

Executive summary

This report describes the process and outcomes of the master thesis project that was executed at VDL Apparatenbouw (VDL A). The project was aimed at improving the material planning process at VDL A, such that planning stability is increased and inventories can be reduced.

Problem definition

VDL A acts as a supplier for different mechatronic systems and subassemblies. The products that they assemble are designed and owned by their customers and therefore all activities at VDL A are customer specific. VDL A aims to unburden their customers logistically by completely managing the supply chain for their customers' products. The assembly times are typically short, while material lead times can be very long. In the final assembly of materials into final products, relatively little value is added. Therefore, the purchasing and planning of materials has a large impact on the performance of VDL A as a company. Uncertainties in the environment of VDL A have incentivized buffering, which has resulted in high inventories. Simultaneously, material shortages still disrupt the production planning, resulting in many rescheduling activities. To address these issues, the following main research question was formulated:

How can VDL Apparatenbouw improve their supply chain planning such that their inventories are reduced, while a more stable planning and a high service level are achieved?

Analysis

An analysis of the current planning process and environment of VDL A showed that inventories are indeed relatively high. From the analysis, two important causes for the unstable planning and high inventories were identified.

Lack of tactical planning functionality

Safety stocks are often not aligned with demand processes accurately, resulting in high inventories. Uncertainties in VDL A's environment in terms of supplier lead times and customer demand have incentivized excessive buffering, while the accuracy of these buffering methods is barely reviewed. Additionally, supplier agreements such as minimum order quantities often have a material cost-price focus resulting in inefficient agreements. Currently, there is no structured function in place that analyzes these tactical parameters and links them to high-level, companywide objectives.

Shortcomings of MRP and poor alignment of material planning and production planning

An analysis of the planning process showed that material and production planning are clearly split. The demand plans are processed by the ERP system using MRP logic to generate material requirements. The suggestions created by the ERP system are then processed by the purchasing department and forwarded towards suppliers. This has resulted in mismatches between material planning and production planning as production plans are often rescheduled. An important shortcoming of MRP is the fact that it does not consider material availability constraints in creating production schedules and releasing orders accordingly. Due to VDL A's high

dependency on its suppliers and material availability, this results in many rescheduling activities on an operational level. Additionally, MRP does not consume inventory buffers resulting in higher inventories than required.

An analysis of academic supply chain planning concepts and inventory management in assemble-to-order (ATO) environments gave insights into the requirements of effectively managing and planning ATO supply chains and revealed a supply chain operations planning (SCOP) method that overcomes the previously mentioned shortcomings of MRP.

Diagnosis

By combining academic knowledge with the practical findings, two important opportunities for improvement were identified. The high impact of purchased materials on VDL A's performance, make the shortcomings of MRP as a SCOP method a large contributor to the unstable planning and misaligned inventories. Secondly, from a tactical and organizational perspective, objectives and plans are often not aligned properly. Due to the operational focus of the project, the solution design has focused on the shortcomings of MRP as a planning logic.

Solution design

De Kok & Fransoo (2003) introduced a synchronized base stock (SBS) model that overcomes the shortcomings of MRP regarding the lack of feasibility constraints. Their model was used as a basis for a planning tool that helps to generate feasible production plans and release orders accordingly. The basic model was extended with lot sizes for purchased materials, since these have a large impact on the inventories at VDL A. This resulted in an improved SCOP method compared to the currently used MRP.

To validate the functioning of the model with the lot-sizing extension, several simulation studies were conducted. The performance of the new SCOP model was compared to that of MRP ordering logic in terms of service levels and average inventories. The most important conclusion that was drawn from the different simulation studies is that the SBS model performs well. In terms of service levels it performs as well as MRP while it reduces inventories by synchronizing purchasing decisions. The results for one of the simulation studies are displayed in table 1

	Average inventory			Closing inventory			Fill rate	
	MRP	**SBS**	**Δ %**	**MRP**	**SBS**	**Δ %**	**MRP**	**SBS**
(1) Long lead times, high MOQ's	€ 343.657	€ 265.716	**-23%**	€ 331.873	€ 292.214	**-12%**	99,09%	**99.51%**
(2) Short lead times high MOQ's	€ 174.361	€ 135.702	**-22%**	€ 177.653	€ 155.626	**-12%**	95.39%	**97,10%**
(3) No lot sizing	€ 59.023	€ 47.593	**-19%**	€ 48.346	€ 39.576	**-18%**	88,39%	**91,26%**
(4) MOQ D*L	€ 99.172	€ 78.123	**-21%**	€ 88.498	€ 72.521	**-18%**	96,05%	**96,26%**
(5) EOQ	€ 131.882	€ 104.652	**-21%**	€ 120.617	€ 105.436	**-13%**	96.58%	**96,94%**
(6) Current MOQ's	€ 131.138	€ 105.059	**-20%**	€ 125.536	€ 108.647	**-14%**	97.46%	**97.48%**

Table 1 Simulation results for different lot-sizing structures

Arguably, the most important benefit of the improved SCOP method is the fact that it only generates feasible plans. This creates more planning stability both internally at VDL A and towards suppliers as well.

The new SCOP method was implemented in an Excel tool that can be used to generate production plans and purchasing orders accordingly. Figure 1 shows how the tool fits in the operational planning process at VDL A.

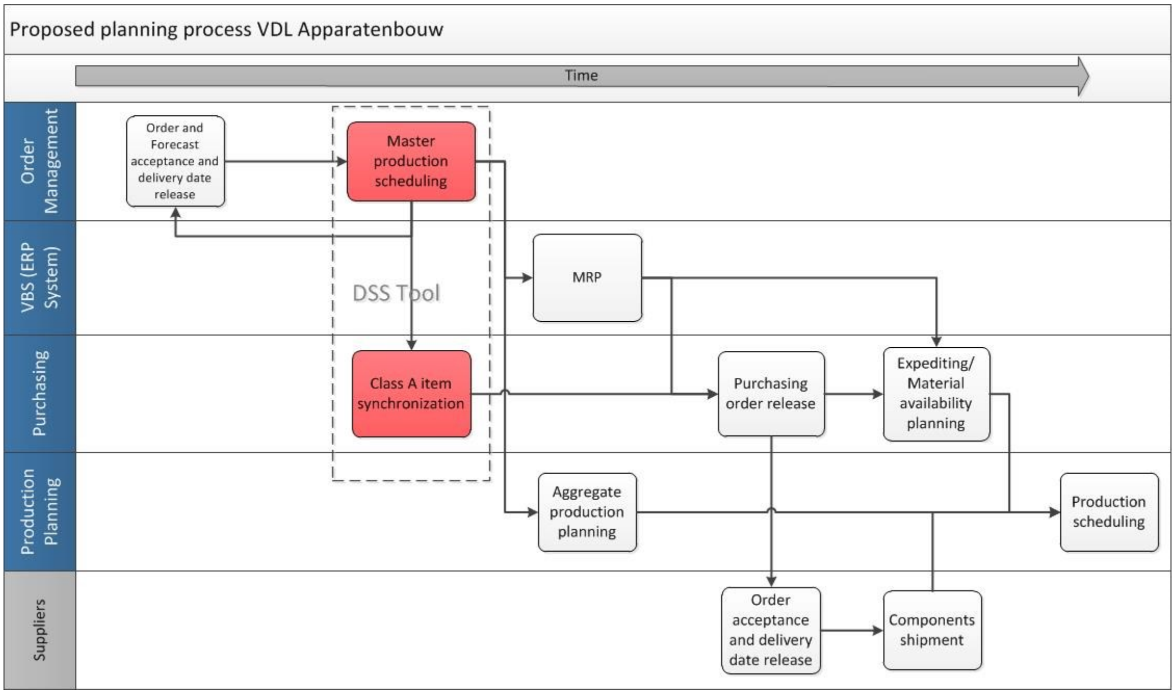

Figure 1 Position of new planning functionality in operational planning process at VDL A

The tool protects production planning from material shortages by generating production plans that are material feasible and it synchronizes the arrival of purchasing orders to reduce inventories. Since the suggested purchasing orders need to be manually inserted in the ERP system, it is suggested that only class A items are synchronized. Because of its quick runtime, the tool can also be used for accepting customer orders and releasing delivery dates towards customers.

Conclusion and recommendations

The analysis that the extension of the SBS model by de Kok & Fransoo (2003) can significantly improve the supply chain planning at VDL A by creating a more stable production planning. Additionally, the new SCOP method reduces inventories by synchronizing purchasing orders.

Based on the analysis the following recommendations are made to VDL A:

- It is recommended that VDL A implements the tool in creating production schedules and releasing production and purchasing orders as suggested in section 5.4.
- Tactical planning and parameter evaluation should be structurally included in the planning process at VDL A. It is recommended that a cross-functional approach is taken in order to align decision making between different departments such that companywide objectives can be accomplished. Academic literature on hierarchical planning and S&OP provide import insights for the organization of these planning functions.
- Available data from the ERP system provides many opportunities for the evaluation of current activities and parameter settings. Therefore, it is recommended that the available data is used more extensively.

Besides the practical value of the thesis results, this thesis also contributes to scientific knowledge as it shows the application of the SBS model in a two-echelon assemble to order environment. It also shows its superiority over MRP in the case study simulation as described in section 5.2. Additional research is still required to test the performance of the model in different environments, with different demand process, BOM structures or multiple echelons for example.

Preface

The completion of this master thesis project would not have been possible without all the people that supported me along the way. I would like to grab the opportunity to thank several people that played a very important role for me during this turbulent period in which I have learned so much more than I could have imagined.

First of all, I would like to thank my first supervisor Vincent Wiers, who gave me the freedom to conduct and plan my own project. Simultaneously, he was always able to point me in the right direction whenever I needed it. His extensive knowledge and experience with advanced planning and scheduling systems, both in business and academic environments, helped me to make the right decisions and to find a good balance between scientific relevance and practical applicability. Secondly, I would like to thank Ton de Kok who found the time in his ever busy schedule to read my report and provide valuable feedback on my work. His enthusiasm about the topic and his drive to spread and extend the available knowledge are truly admirable.

Next, I would like to thank all my colleagues at VDL Apparatenbouw for the pleasant work environment and the willingness to help me with anything I needed. In particular I would like to thank Mark Verdonschot en Daan Toussaint. It was great to feel the confidence and support during my project. Our discussions were always interesting and truly helped me to keep a practical focus in the project. I have learned just as much from being in the middle of the operational environment of VDL Apparatenbouw as I have from the academic work.

Last, but definitely not least, I would like to thank my family and friends for supporting me throughout the project and lending an ear even though they could not stand the words MRP, feasibility and synchronization anymore. In particular I would like to thank Larissa. Thank you so much for your unconditional support and for putting up with me during this busy period.

Thanks again everybody, I would not have been able to do this on my own!

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MOQ	Minimum Order Quantity
EOQ	Economic Order Quantity
MPS	Master Production Schedule
S&OP	Sales And Operations Planning
ATO	Assemble To Order
BOM	Bill Of Materials
ETO	Engineer To Order
SKU	Stock Keeping Unit
KPI	Key Performance Indicator
CODP	Customer Order Decoupling Point
MRP	Material Requirements Planning
ERP	Enterprise Resource Planning
SCOP	Supply Chain Operations Planning
ATP	Available To Promise
SBS	Synchronized Base Stock
WIP	Work In Progress
DS	Decision Support

Contents

1. Introduction

This report describes the research project that has been executed at VDL Apparatenbouw (VDL A). The project was aimed at improving the operational control and material planning at VDL A in order to achieve more planning stability and to reduce material inventories.

1.1 Company introduction

VDL A acts as a supplier for different mechatronic systems and subassemblies. They assemble products which are designed by their customers. Depending on the customer, VDL A acts as a tier-one supplier, delivering subassemblies, or as an original equipment manufacturer, delivering complete final products. Because of the unique characteristics and requirements of the different products that they assemble, the products are managed in separate customer projects. Some examples of the products that are assembled at VDL A are electric vehicle charging posts, large agricultural air scrubbers, 3D-printers and pharmaceutical packaging machines. The subassemblies that they make are mainly components for medical equipment.

VDL A aims to unburden their customers logistically by completely managing the supply chains of the products that they deliver. This roughly includes the supply management and material planning of parts and the final assembly of these parts into final products. Because VDL A adds relatively little value in the assembly process, the purchasing of components has a large impact on their performance as a company. VDL A operates according to the assemble-to-order (ATO) strategy. This means that they keep components on stock, while the assembly of final products is only done based on customer orders. For new projects with many uncertainties regarding demand and design changes, the purchasing is also done on customer orders completely. This depends on specific agreements made with customers on lead times and service levels.

Following an ATO strategy requires special attention to the alignment of material purchasing orders and production planning (Stadtler, Kilger, & Meyr, 2015). Combined with complex bill-of-material structures, long and uncertain material lead times, high risk of obsolescence and high customer service requirements this makes for a challenging planning environment. This project was initiated to find planning and control concepts and methods that enable companies to operate both effectively and efficiently in an assemble-to-order environment.

1.2 Methodology

The aim of this research project was to improve the current situation at VDL A by applying scientifically proven concepts and methods to the practical situation of VDL A. To structure this research project, the problem solving cycle by Aken, Bij, & Berends (2012) was used (figure 2). This cycle describes the structure of design-oriented and theory-informed research projects.

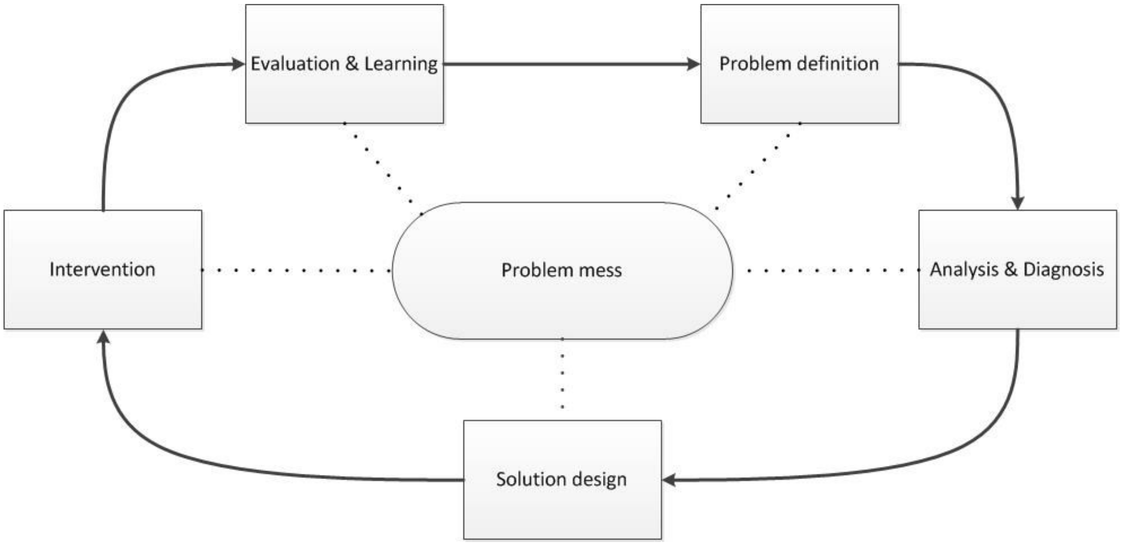


Figure 2 Problem solving cycle as described by van Aken et al. (2012)

The project was initiated because management at VDL A identified several problems regarding material planning and inventories, which are discussed more extensively in section 1.3. The first part of the research project was aimed at thoroughly understanding the situation and the root causes for the identified problems. By collecting both quantitative data from the ERP system at place and qualitative data from conducting interviews and performing desk research on company documents and reports, a thorough understanding of the situation and the identified problems was achieved.

A literature study was conducted in advance of this master thesis project (Tax, 2017). This literature study is focused on the high level problem definition that was available at that point in time. Therefore, additional literature was gathered to fill the gaps between the literature study and the required literature for the analysis and diagnosis of this project. The gained insights from literature and practice were combined to come to a diagnosis and to identify opportunities for improvement.

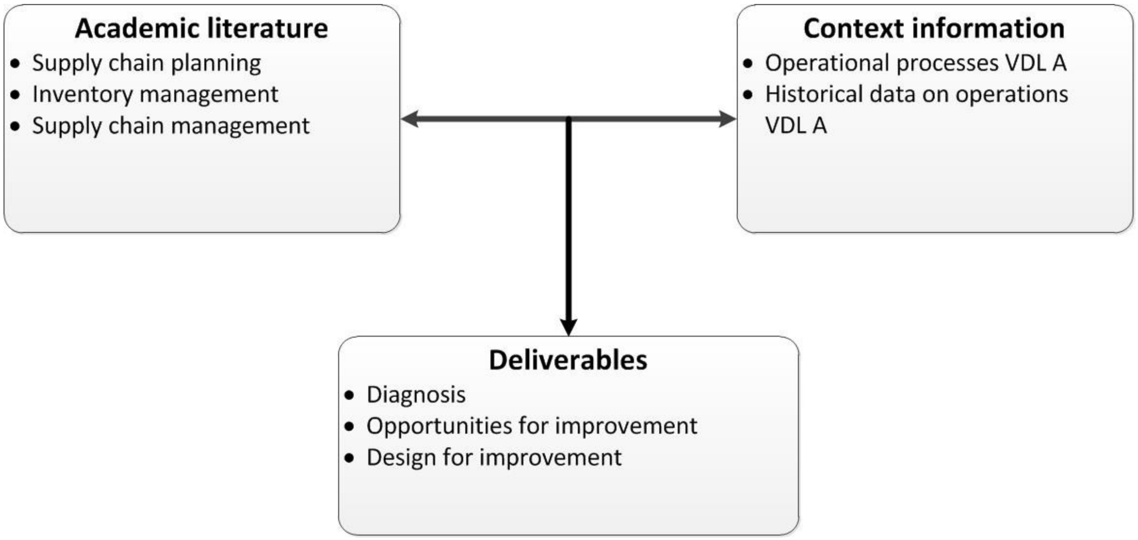


Figure 3 Conceptual project design as described by van Aken et al. (2012)

Because of the design oriented nature of this master thesis project, the analysis and diagnosis of the current situation was followed by a solution design that aims to improve the situation at VDL A. A solution design was made based on the diagnosis in the shape of a new planning process which includes a planning support tool based on an improved planning logic.

1.3 Problem definition

1.3.1 Supply chain challenges

Revenues at VDL A have increased considerably in the past five years. This is the result of an increased amount of different customers, which has resulted in increasingly complex planning activities. VDL A faces several challenges related to their supply chain operations.

The following characteristics of both the internal and external situation at VDL A make planning a challenging and complex activity:

- Complex bill of material (BOM) structures
- Large variations in both physical and operational characteristics of products and materials
- Engineering changes
- Dependency on single customer demand for each product
- Long and uncertain supply lead times
- High customer service levels
- Uncertain demand
- High dependence on external suppliers
- Different customer agreements
- High risk for anonymous inventory

1.3.2 Problems and causes

Resulting from interviews and desk research, several problems along with their causes and effects were identified. These are displayed in a cause and effect diagram. This diagram is displayed in figure 24 in appendix A.

Because VDL A assembles products specifically for individual customers, they are fully dependent on these customers in terms of demand. Like in all companies, purchasing components ahead of demand realization results in a risk. Customers might decide not to order, or to order less than expected. In the worst case, customers might even go bankrupt, all of which results in obsolescence of materials. Design and engineering changes are an important cause of materials to become obsolete as well. Because of VDL A's dependence on a single customer for their products, these risks are even larger because materials are specific and unique for these customers' products.

Besides the involved risks, holding inventories results in holding costs such as material handling, storage space, insurance costs and interest rates. On the other hand, the production planning at VDL A is mainly restricted by material availability, which has incentivized material planners and purchasers to install relatively high stocks. In the past this has caused issues regarding warehouse space, risk management and material obsolescence.

Because of the specific and unique components that are used in the different products, material supply lead times are usually long. These long lead times force VDL A to purchase components ahead of demand. With the increasing amount of customers, the planning complexity and the planning workload are becoming more and more challenging for VDL A.

Decisions on the timing and quantities of purchased components are of great importance to VDL A, both in terms of risk, holding costs and customer service. VDL A currently uses MRP to manage their material planning. Therefore, purchasing orders are essentially always triggered by customer orders or forecasts. However, due to high minimum order quantities agreed with suppliers, inaccurate forecasts and both implicit and explicit buffering, the inventories often exceed customer orders and forecasts. Simultaneously, production has run dry because of the absence of a single component.

Since suppliers do not always meet the agreed delivery dates, safety times are used to make sure that materials are available for assembly on time. Because supplier performance is not monitored structurally, it is not clear how accurate the agreed lead times are. Therefore, a standard safety time of two weeks is used for all materials and for some materials safety stocks are installed. Both of these parameters are not monitored and updated structurally.

Additionally, forecasts are often included in the master production schedule (MPS) with due dates which are earlier than required to ensure material availability and to anticipate on forecast deviations. Often, these due dates cannot be met because of material availability issues. This results in many shifts in the MPS, which results in internal scheduling problems. This does not only cause an internally unstable planning, but it also corrupts demand processes towards VDL A's suppliers.

Combined, the previously mentioned issues contribute to high inventories at VDL A, while the delivery performance of VDL A is still often disturbed by the absence of required materials. Therefore, VDL A is looking for planning approaches that enable them to realize short lead times with a high reliability for their customers, while keeping the total inventory investments to a minimum and increasing the planning stability.

1.4 Project scope

The focus of this project has been on the material planning for the customer projects that are managed according to the assemble-to-order (ATO) strategy. For some customer projects that are new or subject to many engineering changes, another approach is used by VDL A that is closer to the engineer-to-order (ETO) strategy. For these projects, customer lead times are generally long enough to purchase the required components after customer orders arrive, making these projects less interesting in terms of material planning. The focus was therefore on the ATO projects in which the purchasing of components with long lead times needs to be aligned with uncertain demand realizations in order to provide high customer service.

1.5 Research questions

The aim of this study is to find academically sound solutions to the identified problems at VDL A. Additionally, the insights gained from the analysis aim to extend scientific knowledge on improving supply chain planning in ATO environments. Resulting from the problem analysis as described above, several research questions were formulated to address the identified problems for VDL Apparatenbouw.

Main research question:

How can VDL Apparatenbouw improve their supply chain planning such that their inventories are reduced, while a more stable planning and a high service level are achieved?

Sub-questions:

1. *What are the characteristics of the environment in which VDL Apparatenbouw operates and how do these characteristics affect their operations?*
2. *How does VDL Apparatenbouw currently manage their supply chain planning and operational control and how does this relate to the problems identified?*
3. *How can VDL Apparatenbouw improve its operational control and material planning such that inventory investments are reduced and high customer service levels are realized?*
    a. *Which planning approaches and concepts from academic literature can be applied to improve their current supply chain planning?*
    b. *How do these approaches fit within their operations?*
4. *How can VDL Apparatenbouw implement these improvements?*

2. Analysis of current situation at VDL A

This section describes the analysis that was conducted in order to understand the described problems and to identify their root causes. First, an analysis of the environment in which VDL A operates is described along with the impact of the environment on their operations. Secondly, the internal supply chain planning processes are analyzed in order to understand how VDL A currently copes with its demanding environment.

2.1 Characteristics of operational environment at VDL Apparatenbouw

2.1.1 Supply

Because the larger part of VDL A's revenues consist of purchased goods and the actual assembly of products is rather straightforward, VDL A's performance is highly dependent on their suppliers and their deliveries. This section describes the environment on the supply side of VDL A and how it impacts their operations in practice.

Supplier base

VDL Apparatenbouw currently purchases over 9.000 unique materials from just over 400 different suppliers. Despite the aim of the purchasing department to keep the amount of different suppliers as low as possible, the often very specific and custom characteristics of the required materials force VDL A to manage a wide range of different suppliers. When the volumes of purchased products at a single supplier are relatively low and few alternative suppliers exist, suppliers have a powerful position in negotiations. This can make it difficult to arrange logistically efficient delivery agreements. This often results in high minimum order quantities (MOQ's) agreed with suppliers to keep material prices at an acceptable level. On the other hand, there is also a group of suppliers with whom VDL A cooperates closely to ensure mutually beneficial agreements. With this group of suppliers, agreements like vendor managed inventory, lead time reductions and call contracts have been made before to enable smooth and efficient operations for both parties.

In practice, the aforementioned opportunities are not always utilized to their full potential. For many projects, agreements made in the past are not evaluated or revised. This is also the result of a lack of insight and awareness on the impact of such agreements on the operational performance of VDL A. Supplier agreements are mostly focused on the most visible aspect of a purchased product, which is its cost price.

Lead time uncertainty

As mentioned in the problem description, the reliability of supply lead times is currently unclear at VDL A. Therefore, we conducted a data analysis on historical purchasing orders which are stored in their ERP system.

VDL A demands from their suppliers that they confirm delivery dates within three days after purchasing orders are placed. When purchasing orders are confirmed by suppliers, VDL A counts on the on time delivery of that purchasing order. However, it does happen that confirmed delivery dates are not met by suppliers. Figure 4 shows the deviation in days between the actual delivery date and the planned delivery date confirmed by the supplier. The average lead time deviation for the set of analyzed deliveries is 1.77 days with a standard deviation of 12.72 days.

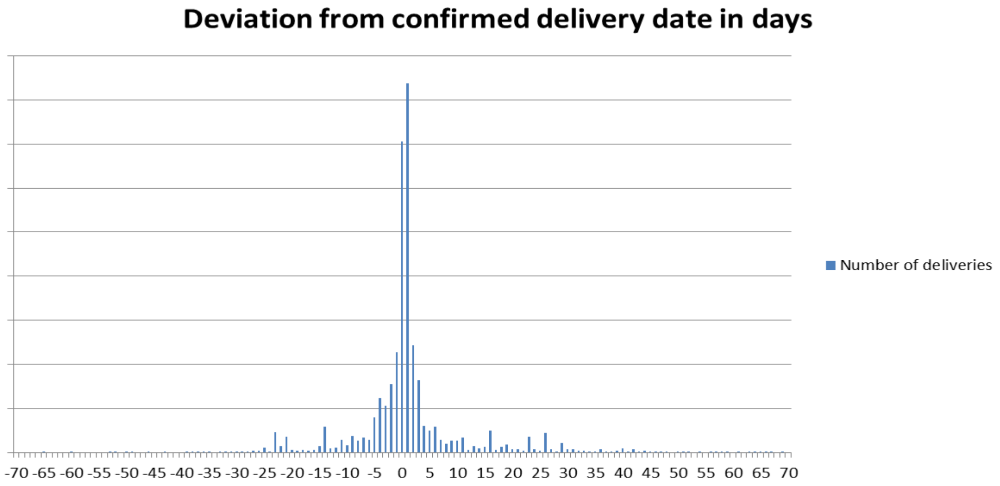


Figure 4 Delivery date deviation of historical purchasing orders

Figure 4 shows that despite the supplier commitment, planned delivery dates are not always met by suppliers. In practice, this often results in material shortages and this forces VDL A to act on this source of uncertainty. Currently, there is limited insight into the detailed performance of individual suppliers. In order to enable the purchasers of VDL A to act on their suppliers' performance, these insights are required. Additionally, on a tactical level the lead time uncertainty forces VDL A to include material and time buffers in order to protect their production planning from the effects of late deliveries.

2.1.2 Demand

The demand processes at VDL A differ for different customer projects. For several projects, customers provide forecasts. For other projects, reorder levels are used to generate purchasing orders. An example of a forecast provided by a large customer for one of their products is shown in figure 5. The figure shows the cumulative shipments and forecasts during the cumulative lead time of the product for the year 2016.

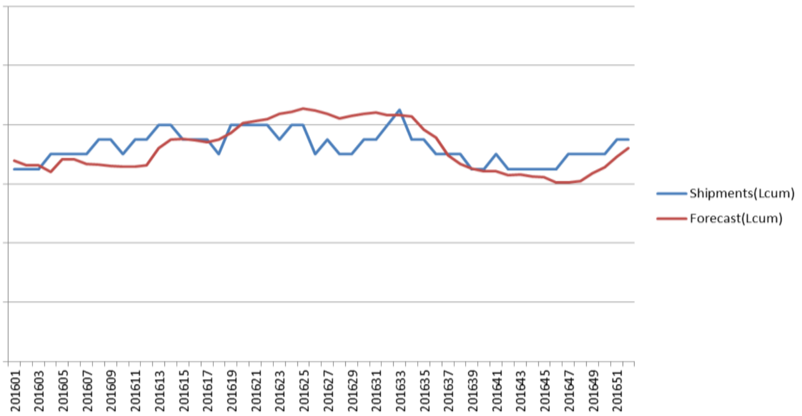


Figure 5 Example forecast and shipments for large customer of VDL A

Silver, Pyke, & Peterson, (1998) discuss that in order to anticipate on forecast errors, the standard deviation of the forecast errors of total demand during lead times is required. Using formulas 4.57 and 4.60 in their book, the standard deviation is calculated as follows.

$$x_t = Actual\ shipments\ during\ cumulative\ lead\ time\ in\ period\ t$$

$$\hat{x}_{t-1,t} = Forecasted\ demand\ during\ lead\ time\ in\ period\ t, made\ in\ period\ t-1$$

$$MSE = \frac{1}{n} * \sum_{t=1}^{n} \left(x_t - \hat{x}_{t-1,t}\right)^2$$

$$\sigma = \sqrt{MSE}$$

For the forecast error of the example product in figure 5 this resulted in a standard deviation of 30.18 and a coefficient of variation of 1.25. The forecast error can be used as a basis for the determination of safety stock levels (Silver et al., 1998). Currently, forecasts errors are not calculated for any of the products managed by VDL A, while there is sufficient data available for many of their products.

When no forecasts are provided by customers, VDL A typically uses reorder points to generate purchasing orders. The reorder points are based on the expected demand for final products that use this material during the material's lead time. To estimate expected demand, historical material usage is often used, otherwise a periodic sales amount is estimated. A more extensive discussion on the use of reorder levels is provided in section 2.2.4 on uncertainty buffering.

2.1.3 Inventory

Since VDL A operates according to the ATO policy, no final products are kept on stock. Therefore, VDL A only considers individual materials as stock keeping units (SKUs) and this analysis focuses on material inventories only.

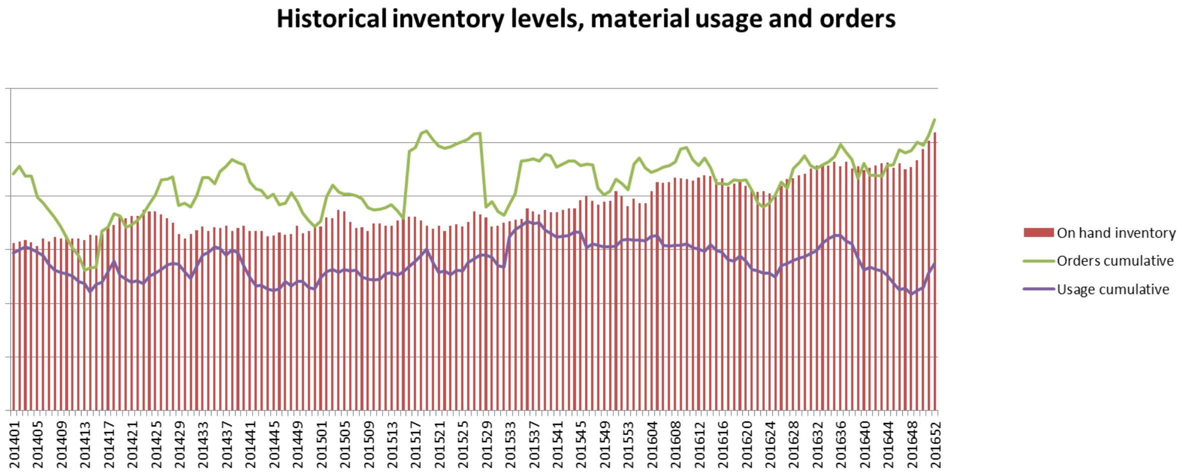


Figure 6 Historical inventory levels, material usage and the order book

Figure 6 shows the value of the physical inventories at VDL A at the end of each week for the years 2014 to 2016. Additionally, the cumulative material usage in 13 weeks (one quarter) is displayed as well as the cumulative orders for 13 weeks to be completed. This figure shows the increasing inventory levels at VDL A. It can be seen that the physical inventory structurally exceeds the cumulative material usage of 13 weeks, indicating that VDL A generally has over three months' worth of materials available on stock. VDL A, manages a KPI of keeping the average inventory value below a certain target percentage of the yearly turnover. In the past two years this target was not met. It can be questioned whether inventories should be evaluated by comparing them with annual turnover, because turnover includes other margins like labor, overhead and profits. In order to get an accurate view of the inventory efficiency, an alternative KPI is suggested.

Surie & Wagner (2000) discuss inventory turns as a KPI to assess inventory efficiency. Inventory turns are a ratio of the yearly material consumption over the average inventory level. The inventory turns were calculated for several large project groups and VDL A as a whole. These are displayed in figure 7.

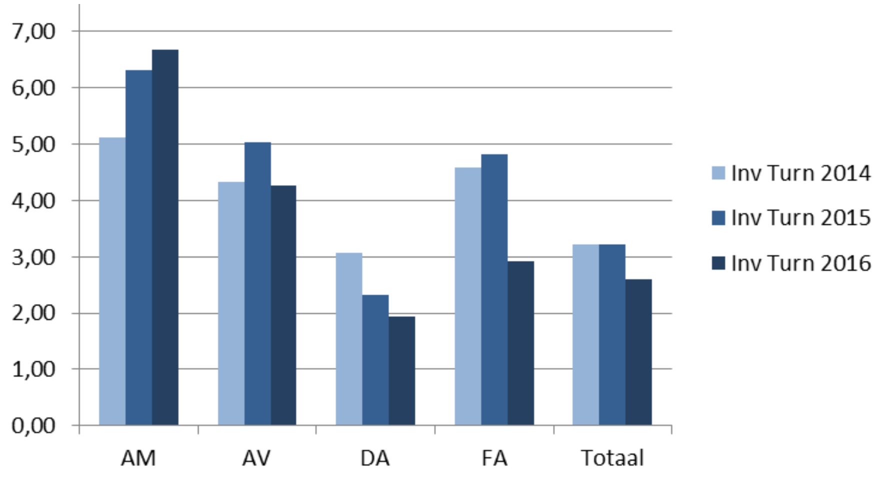


Figure 7 Inventory turns for several large product groups at VDL A

It is remarkable that the AM project has the highest inventory turnover, and has increased in the past three years. Simultaneously, the inventory turnover of project group DA has been decreasing for the past three years. An analysis showed that the good performance in terms of inventory turns of the AM group can be largely explained by the size of MOQ's applied for the materials in this project group. Compared to other project groups the MOQ's are much smaller in relation to the material usage. The bad performance of project group DA is the result of supply issues for several bottleneck materials. Materials were still being purchased, while only a fraction of demand could be satisfied due to the limited availability of several parts with supply issues. Another explanation of the bad performance are the relatively high safety stocks, which are often based on historical material usage, which is not representative for the current situation anymore.

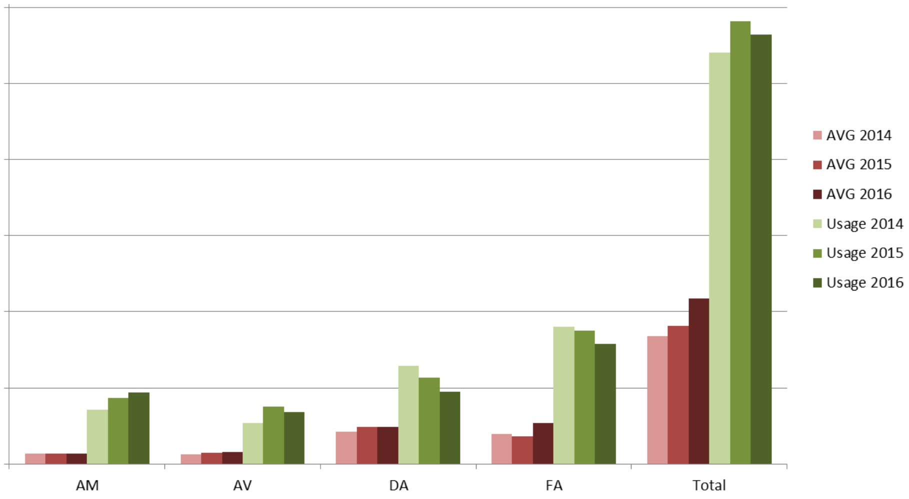


Figure 8 Inventories and material usage of several project groups

Figure 8 shows the material usage and average inventories for the years 2014-2016 for several large project groups and for VDL A as a whole. It is remarkable that for example at project groups FA and DA, the material usage has been decreasing for the past three years while the inventories remain almost constant or even increase. This indicates that the inventories are not aligned efficiently with demand. This can also be recognized when looking at the the previously discussed inventory turns in figure 7. For project group DA, the inventory turns have decreased due to the decreasing material usage and unrevised safety stocks. Overall, VDL A as a whole had a yearly inventory turnover ratio of 2.59 in 2016. This means that, roughly speaking, the average inventory corresponds to 20 weeks of material consumption.

Obsolete inventories

As mentioned in the problem definition, engineering changes, customer bankruptcy and overestimated sales can cause materials on stock or in the pipeline to become obsolete. This section describes the current state of obsolete inventories amongst the stocks of VDL A.

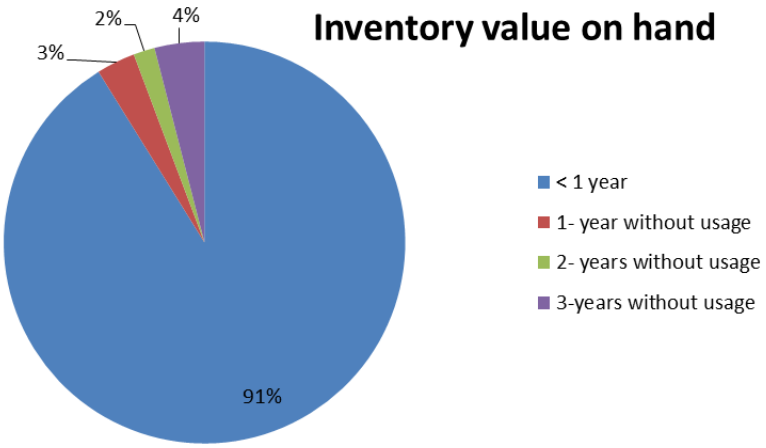


Figure 9 Material inventories and percentages

Figure 9 shows the fractions of the current inventory value that has not been used in the past year, the year before that and the fraction that has not been used for at least three years. A total of 9 percent of the inventory value at VDL A, has not been used for at least one year. This fraction makes for a large cost factor for VDL A, since these materials are likely to be disposed in the future. The actual disposal of obsolescent materials is often postponed, resulting in the high obsolescence percentages above.

The most common cause for materials becoming obsolete are engineering changes. In other (less frequent) cases, customers go out of business or demand for certain products has turned out to be much lower than expected, resulting in leftover material stocks. If no contractual agreements were made on obsolete materials, the investment in the materials is at the loss of VDL A.

A large part of obsolescence can be avoided by purchasing materials in smaller quantities and revising safety stocks more often such that the purchased materials match demand more closely. At the same time, purchasing in high quantities often reduces material prices. Especially from a sales point of view this is an incentive to purchase materials in large quantities in order to reduce final product prices. The risks of purchasing ahead of demand have not been considered adequately in the past, resulting in high amounts of obsolescent materials and high inventories in general.

Function of stocks

Besides the previously mentioned costs and risks involved with holding inventories, inventories also have a function and can provide important benefits. Surie & Reuter (2015) identified several benefits of stocks and grouped them by different components of stocks, which are displayed in table 2.

Stock component	**Determinants**	**Benefits**
Production lot-sizing stock	Setup frequency	Reduced setup time and costs
Transportation lot-sizing stock	Shipment quantity	Reduced setup time and costs
Inventory in transit	Transportation time	Reduced transportation costs
Seasonal stock	Demand peaks, tight capacity	Reduced cost for overtime and for investments
Work-in-process	Lead time, production planning and control	Increased utilization, reduced investments in additional capacity
Safety stock	*Demand and lead time uncertainty, process uncertainties*	*Increased service level, reduced costs for emergency shipments and lost sales*
Purchasing lot-sizing stock	*Supplier contracts, volume discounts, physical restrictions*	*Reduced material prices*

Table 2 Stock components and their benefits

Due to the ATO strategy and the corresponding absence of final product inventories, seasonal stock and production lot-sizing stock are not relevant for VDL A. Also the work-in-process stock component is not explicitly present at VDL A, due to the short assembly lead times. Incidentally, some products are assembled earlier than required to prevent gaps in the personnel planning, however this is not done from an inventory perspective. Especially the safety stock and transportation lot-sizing stock components can be recognized at VDL A. Another stock component can be recognized at VDL A, which is not mentioned by Surie & Reuter (2015); referred to as purchasing lot-sizing stock. This stock component is added to the table. As discussed before, VDL A often purchases large quantities of material at once to reduce the cost prices of their products. This is often done at customers' request.

Safety stocks at VDL A are installed to buffer against unexpected demand changes, late deliveries by suppliers and quality issues. They are discussed more elaborately in section 2.2.4.

2.1.4 Supply chain attributes

Different configurations of supply chains require different decision making and planning activities. Surie & Reuter (2015) describe several supply chain attributes that help to classify supply chains and to identify their unique characteristics. Using their typology, the supply chain attributes of VDL A's supply chain were analyzed and displayed in table 7 in appendix C. In table 3, the most relevant attributes of VDL A's supply chain are displayed along with their impact on planning tasks at VDL A.

	Attribute	Impact on VDL A's planning decisions/task
	Functional attributes	
Procurement type	Long supply lead times	Forecasts or reorder levels are required to ensure on time delivery
	Unreliable supply lead times	Safety time buffering Safety stocks
	Material life cycles of months/years	Risk of obsolescence
Production type	Flexible assembly capacity	Rough-cut long and mid-term production planning is sufficient
	No structural bottlenecks	Rough long and mid-term production capacity planning is sufficient
Distribution type	Direct shipments to customers by third party logistic service provider	Transportation planning is not a concern for VDL A
Sales type	Availability of forecasts and orders differs per customer	MPS based on both (fixed) orders and (dynamic) forecasts Reorder levels applied in absence of forecasts
	Dynamic, low volume demand	Demand-supply matching
	Structural attributes	
Topography of supply chain	Assemble-to-order	Buffering at material level Order promising
	Upstream material availability constrains supply chain	Material planning has high impact on output
Integration and coordination	Inter-organizational coordination	Demand information sharing
	Powerful customers	Quick and reliable delivery requirements
	Powerful suppliers	Long-term contracts High MOQ's

Table 3 Supply chain attributes and their impact on VDL A's planning

2.2 Current supply chain planning activities

This section describes the analysis of the current planning activities that VDL A uses to enable their operations in the previously described environment.

2.2.1 Customer Order Decoupling Point

The customer order decoupling point (CODP) is defined as the point after which operations are completely customer order based (Hoekstra & Romme, 1992). For VDL A this means that their CODP is on a material level. Following this definition, all operations after the CODP are not subject to demand uncertainty, since fixed customer orders are the driver for all operations here. Therefore, from an efficiency perspective, the CODP should be positioned as far upstream as possible in order to exclude as much uncertainty as possible. However, it is the requested customer lead time that pulls the CODP more downstream (Hoekstra & Romme, 1992).

VDL A operates according to the ATO strategy. This means that their material inventories are positioned at the CODP and the assembly of final products happens downstream from there. Assembly lead times for final products generally fit well within the lead times that are promised towards customers. Essentially, all products can be assembled within two weeks, given that all materials are available and production quantities are not unreasonably high. The CODP separates forecast-based operations upstream from the order-based operations downstream (Olhager, 2010). All assembly operations are fully order-based, while purchasing of materials is done in anticipation of customer orders because purchasing lead times often extend customer lead times. Both supply and demand uncertainty play an important role in determining the timing and quantities of purchasing orders for materials. To cope with both sources of uncertainty, inventory buffers are installed in the shape of materials ready to be converted into final products. This is discussed more extensively in section 2.2.4.

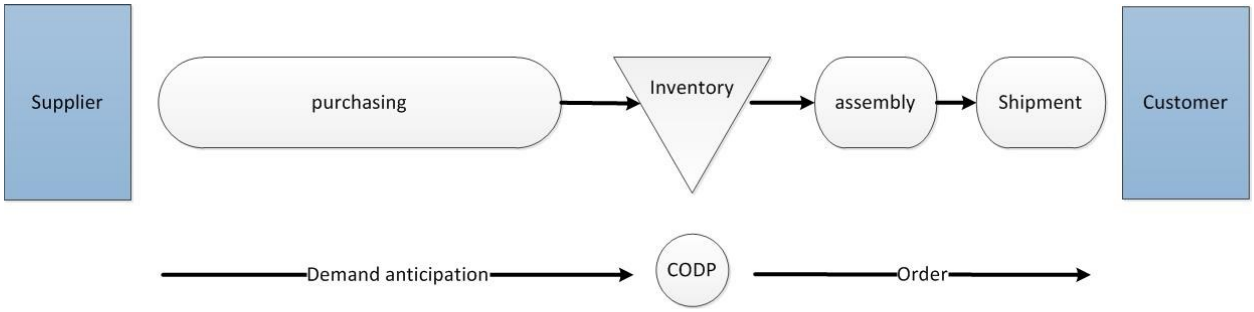


Figure 10 Customer order decoupling point at VDL A

2.2.2 Order flows

To get a thorough understanding of the operational processes and the corresponding planning and decision making activities at VDL A, the internal order flow was mapped. This section describes the mapped planning process and the insights that were gained during the analysis of the planning process.

A swim lane diagram of the order flow at VDL A is shown in figure 11. The swim-lane diagram shows how customer orders flow through the organization at VDL A and it shows the corresponding activities that are performed in order to process the orders. In appendix D the inputs, outputs, control variables and mechanisms that are used in each planning step are explicitly stated. To structure the figures, the 1DEF0 modelling notation was used.

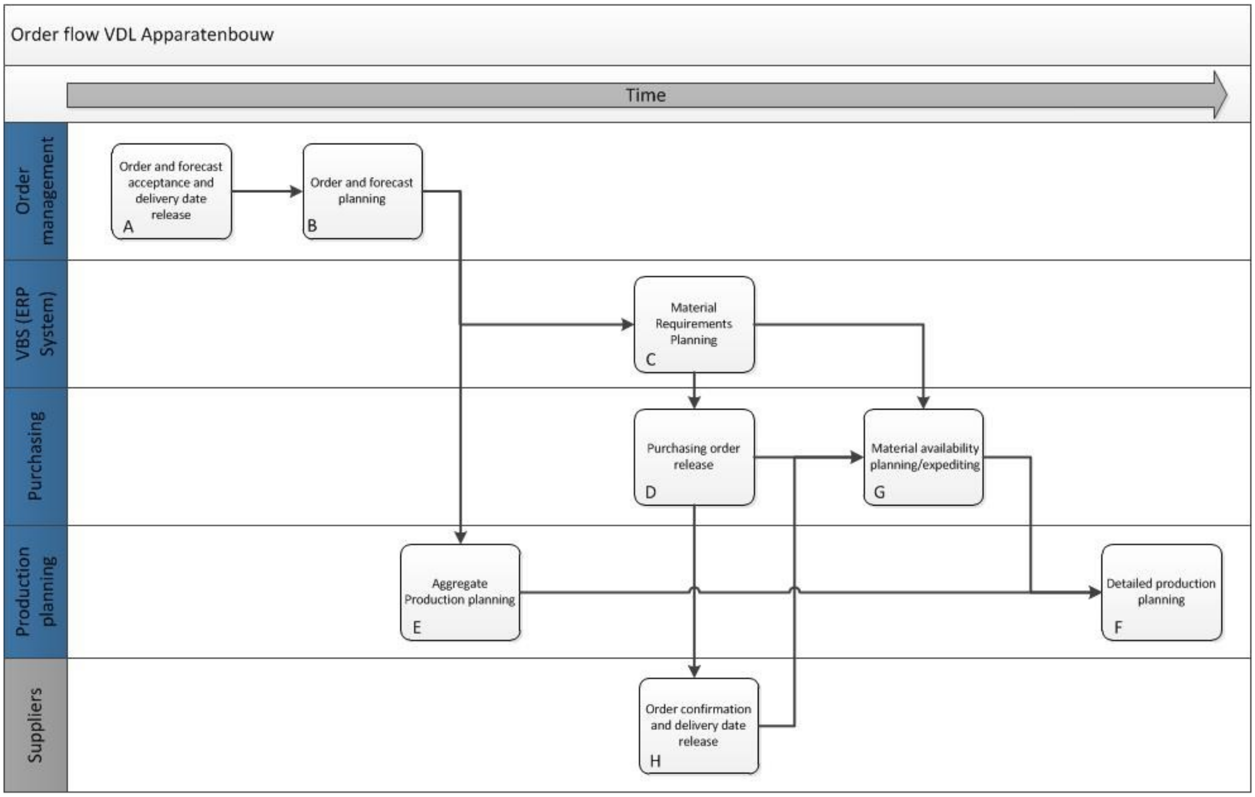


Figure 11 Swim-lane diagram of order flows and corresponding planning activities

Essentially, all orders and forecasts received from customers are accepted and included in the MPS on their requested date as long as the request is in line with contractual agreements. As soon as customer orders are accepted, the agreed customer lead time is used to determine a delivery date confirmation. While creating the MPS, a rough-cut production capacity check is made. However, no feasibility checks are conducted on the availability of required materials.

Based on the MPS, the ERP system uses MRP logic to translate the orders and forecasts into material requirements. Combined with available inventory and pipeline inventory, MRP generates the required purchasing orders. If materials are required earlier than what is possible within the supply agreements, orders are expedited to receive them as early as possible. When all materials are available, the customer orders are assembled.

The activities in the figure above are all quite reactive to the orders and forecasts received from customers. Because of the different sources of uncertainty as described in section 2.1, this reactive approach has resulted in material shortages and consequently in rescheduled orders. Naturally, these material shortages have incentivized purchasers to buffer against uncertainties by installing high stocks. However this is often not done in a structured and adequate manner. This is explained more elaborately in section 2.2.4

Another observation, that was made during the mapping of the planning process, is that the planning functions are clearly split. Production plans are made based on (forecasted) customer demand, without considering material availability. These plans are then processed into material requirements by the ERP system using MRP logic. The purchasing department processes the order suggestions made by the ERP system, without having much insight into the MPS that generates these purchasing orders. Simultaneously, the sales department does not structurally consider production and material planning when accepting customer orders and promising delivery dates towards customers. Currently, representatives from different departments typically come together in case of exceptional events or at the start of new projects. There is no structural planning function, in which relevant information from the different departments is shared, such that their planning activities can be aligned.

2.2.3 Material Requirements Planning

As described in the previous section, VDL A uses material requirements planning (MRP) to translate production orders and forecasts into material requirement and purchasing orders.

MRP is a planning logic that determines which materials are needed at which point in time and in which quantities in order to execute a certain production plan. The material requirements are derived from a MPS, in which both fixed customer orders are included as well as forecasted orders or dummy orders in anticipation of demand (Hopp & Spearman, 2008). In practice, MRP is usually applied using a rolling horizon. The MPS is made for the current planning period until the end of a specified planning horizon. At VDL A, the planning horizon is not fixed and it depends on the available future demand information and the supply lead times of components. In practice, forecasted orders usually deviate from actual demand realizations. The MPS is adapted as more information becomes available in time, which causes rescheduling of both production and purchasing orders.

Frequent rescheduling results in a concept denoted as MRP nervousness or planning instability (Blackburn, Kropp, & Millen, 1986; de Kok & Inderfurth, 1997). MRP nervousness is a result of the deterministic nature of MRP applied in a non-deterministic environment. MRP is based on a presumably fixed production schedule, which in practice changes as more information becomes available on for example late deliveries or unanticipated demand. When these changes occur within the internal lead time of products, MRP often generates infeasible requirements and orders. The root source of these infeasibilities is often difficult to determine with the information that is available in ERP systems.

MRP nervousness has several negative consequences, which cannot always be expressed in costs or lost sales. Nervousness results in a high planning workload, potential loss of goodwill towards the planning system and in negative behavior as a consequence (de Kok & Inderfurth, 1997).

MRP has several more inherent issues related to its planning functionality and logic. One of these issues, which is particularly applicable in the context of VDL A, is the fact that MRP neglects material constraints (de Kok & Fransoo, 2003). As discussed in section 1.3, the production planning largely depends on material availability. If a single required component is not available, production cannot be started. MRP does not consider material availability during the planning of production orders. MRP assumes that infeasibilities at the material level will be resolved before the planned production date (de Kok & Fransoo, 2003). If these issues are not resolved, purchasing orders are generated for production orders that cannot be completed anyway because other materials are not available. This results in excess material inventories and rescheduling of production orders, which also contributes to the previously described MRP nervousness.

Another drawback of MRP planning is the way it treats safety stocks. MRP considers a safety stock as material that needs to be on hand in the warehouse at any point in time. Therefore, whenever the physical inventory drops below the safety stock within the lead time of this material, MRP will generate a backorder on this material (i.e. purchasing orders with a due date in the past). Thus, MRP does not treat its buffers as a way to cope with unexpected changes and to create stability, but it generates infeasible material purchasing orders instead. For assembly systems, this way of dealing with safety stocks is especially inefficient as is demonstrated in an example shown in figure 27 in appendix F.

After MRP generates purchasing orders for the required materials, the materials are purchased in fixed quantities agreed with suppliers. These quantities are typically determined during the startup phase of new projects. Depending on the purchased quantities, the material prices are determined and used in the price calculations of VDL A's final products. As identified in the cause and effect diagram, high order quantities are used to achieve lower final product prices. However, the impact of these high order quantities on the operational performance of VDL A is not considered. Additionally, when the demand of products decreases, this often goes unnoticed and the same high purchasing quantities are sometimes used for the next replenishment orders during the end of life of the material.

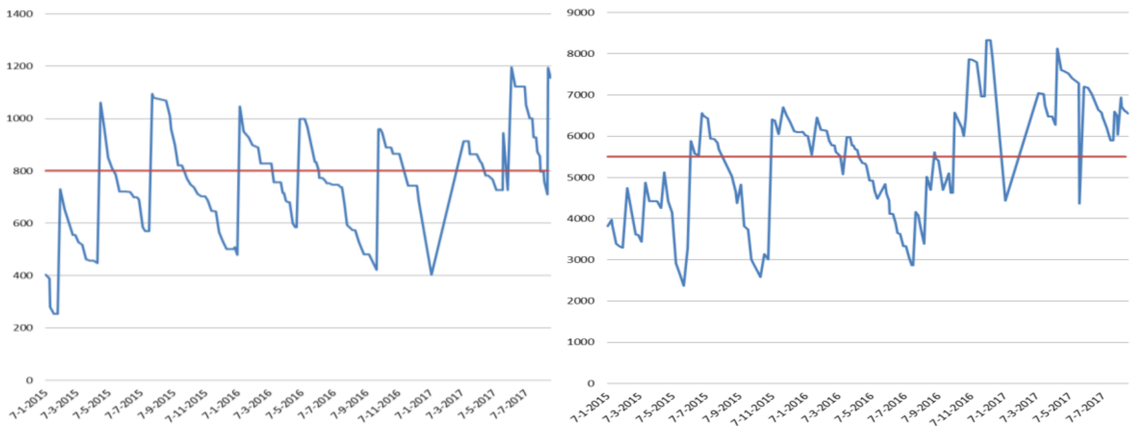
2.2.4 Uncertainty buffering

Because only the activities upstream of the CODP are subject to demand and supply lead time uncertainty, inventory buffers are positioned at the material level, which is VDL A's CODP.

The generation of purchasing orders in anticipation of demand is currently done either by using forecasts or by reorder levels when forecasts are not available. Reorder levels are based on the expected demand during the lead time of a certain item. Mostly, the expected demand during the lead time is based on historical demand or expectations from customers. Historical demand can provide an indication of future expectations. However, demand decreases have often gone unnoticed in the past which has resulted in excess inventories and obsolescent materials.

Figure 12 shows two examples of materials from a project group that is managed by reorder levels due to the absence of forecasts.

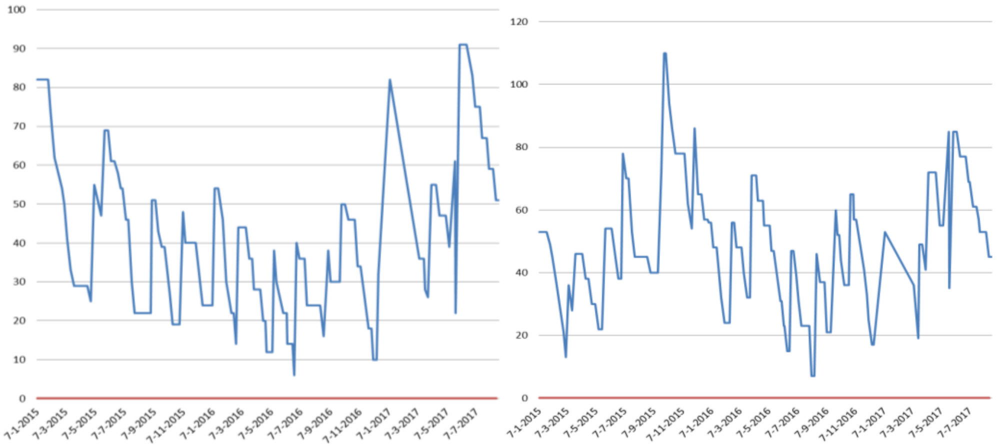
Figure 12 Examples of material inventories managed by reorder levels



The difficulty with using reorder levels in an ATO context is that material demand is dependent on the often lumpy demand for final products. Especially when multiple final products use the same materials, it is difficult to estimate dependent material demand correctly. Figure 12 shows that the reorder levels for these products are too high. The system is well protected against stock-outs, but the inventories are much higher than required. From the ERP system, the material usage can be derived and is often used to determine the reorder levels. However, material usage is not always a good indicator of material demand, since it is often corrupted by the interaction with the production planning which is influenced by the availability of other materials in the assembly system. Essentially, by considering material usage, a decoupling is made from the actual demand process for the final products that use the materials, which can corrupt the analysis.

Figure 13 shows the inventory levels for two materials from a product group that is managed by forecasts. For these products, the excess inventories are relatively much lower compared to the ones in figure 12. Especially since both materials have a lead time longer than 10 weeks. To prevent stock-outs, planners often pull forecasts forwards to ensure the on time availability of the required materials. As with the high reorder levels, this does indeed ensure material availability, but it also results in excess inventories, especially since a safety time of two weeks is in place already.

Figure 13 Examples of material inventories managed by final product forecasts



In order to buffer against unreliable supply lead times, VDL A uses a standard safety time of two weeks for all materials. As mentioned before, the variability of supply lead times has been unclear for VDL A in the past. Therefore a fixed safety time of two weeks is used for all materials. The safety times are also applied to give the purchasing department enough time to process the purchasing orders and for suppliers to confirm delivery dates.

2.3 Problems and causes identified in VDL A's supply chain planning

The analysis discussed in this chapter showed that several factors in the environment of VDL A such as short customer lead times, long material lead times and variability in both supply and demand relate to the high inventories and planning issues. Simultaneously, the planning activities that aim to deal with these factors, contribute to the identified problems as well. In this section, the identified issues are summarized to form a basis for the diagnosis.

There is a lack of tactical planning functionality incorporated in the planning process at VDL A:

- Orders are processed in a rather reactive way. Issues are often identified too late, such that the only possible action is to reschedule orders.
- Tactical parameters like safety stocks, order quantities and safety lead times are not evaluated structurally and there is a lack of insight on the impact of these parameters on operational performance. This results in both overages and shortages of materials.
- There is a lack of insight on the reliability of supply lead times.
- Tactical decision making on parameters, purchasing plans, sales plans and production plans is insufficiently integrated and aligned between the different departments. This has resulted in conflicting and infeasible plans in the past.

Secondly, on an MPS level, the material feasibility of orders and forecasts is not checked. This causes many rescheduling activities, while most material constraints could have been identified beforehand. This results in an unstable production planning and unsynchronized material planning.

Thirdly, MRP has several inherent problems with regard to its efficiency, planning stability and planning functionality as explained in section 2.2.3. Combined with the lack of feasibility checks and the reactive approach to processing customer orders at VDL A, these shortcomings contribute to the high amounts of rescheduling and a poor alignment between material supply and production planning.

Finally, agreements with suppliers are often focused on the material prices and quality, rather than operational performance, often resulting in operationally inefficient contractual agreements with suppliers.

3. Discussion of academic supply chain planning concepts

In this chapter, several supply chain planning concepts and insights from academic literature are discussed which are relevant to the situation at VDL A. Together these concepts describe and structure the required planning functionality for effectively managing supply chains. An explanation of the planning concepts is given in this chapter along with a discussion of their relevance for the situation at VDL A as an ATO company.

3.1 Inventory management in assemble-to-order systems

Pursuing an ATO strategy enables companies to quickly convert material inventories into final products, such that short customer lead times can be achieved against low costs. This strategy is especially useful for products of which components have long lead times (Benjaafar & ElHafsi, 2006).

Analyzing the inventory performance of assembly systems is challenging as it is difficult to explain the relation between material inventories and service levels for final products. In classical inventory models, service levels can be calculated by analytically estimating the probability of no stock outs, for example. However, in ATO systems, customer service levels are measured on a final product level, while inventories are positioned on a material level. For such systems the “no stock out probability” of all components combined will approach zero when many components are required. Additionally, materials are often used in multiple final products, which makes it even more difficult to predict service levels by using analytical expressions.

A literature review on inventory management in ATO manufacturing systems was conducted in advance of this project (Tax, 2017). The main findings and insights of this literature review and their relevance are discussed here. ATO inventory systems have been discussed extensively in academic literature and several analytical models have been developed for different configurations of assembly systems (Atan, Ahmadi, Stegehuis, de Kok, & Adan, 2017; Song & Zipkin, 2003). Most work focuses on finding optimal inventory policies for the specific assembly system that is considered. These systems are often highly simplified and based on assumptions which are difficult to generalize to real life assembly systems. Realistically sized systems often consist of hundreds of different materials, many final products and multiple echelons. Using the same optimization approaches for such systems is often very difficult in terms of computational effort. Therefore, finding truly optimal policies for realistically sized ATO systems is perceived to be out of question (Atan et al., 2017).

While the optimization of real-life ATO systems appears to be infeasible, generally applicable policies such as the one discussed in de Kok & Fransoo (2003) are valuable in order to evaluate the performance of different system configurations and parameter settings (Atan et al., 2017). These models make use of discrete event simulation to apply all practical constraints, BOM relations, dependent demand relations and modeling requirements. By means of simulation the results of certain parameter settings and service levels can be explained. The model by de Kok & Fransoo (2003) is discussed more extensively in section 3.5.

3.2 Hierarchical planning

Fleischmann, Meyr & Wagner (2015) describe planning as follows: “Planning supports decision making by identifying alternatives of future activities and selecting some good ones or even the best one.” They divide the planning process in the following steps:

- Recognition and analysis of a decision problem
- Definition of objectives
- Forecasting of future developments
- Identification and evaluation of feasible activities (solutions)
- Selection of good solutions

These steps can be made on different hierarchical levels and for different business processes. The hierarchical nature of supply chain planning is widely recognized in academic literature (de Kok & Fransoo, 2003; Miller, 2013; Stadtler & Kilger 2015). The use of three hierarchical planning levels is widespread. Miller (2013) describes the following three levels: strategic planning, tactical planning and operational planning. The distinction between these levels is mainly made on their time scope and the impact of the decisions made on these levels. Anthony (1965) describes the same levels, however these levels are denoted here as: long-term planning, mid-term planning and short-term planning. On each hierarchical planning level, different decisions have to be made for different supply chain processes. Decisions made on higher hierarchical levels impose restrictions on the planning decisions that can be made in the levels below. Simultaneously, the results of these decisions are fed back upwards as input for the higher planning levels.

The Supply Chain Planning Matrix as discussed by Fleischmann et al. (2015) combines the separation in hierarchical levels with the functional separation of planning functions. The supply chain planning matrix is shown in figure 14. This combination makes their framework particularly interesting for positioning the required planning functionality at VDL A, because of the identified issues with cross-functional alignment as discussed in section 2.3.

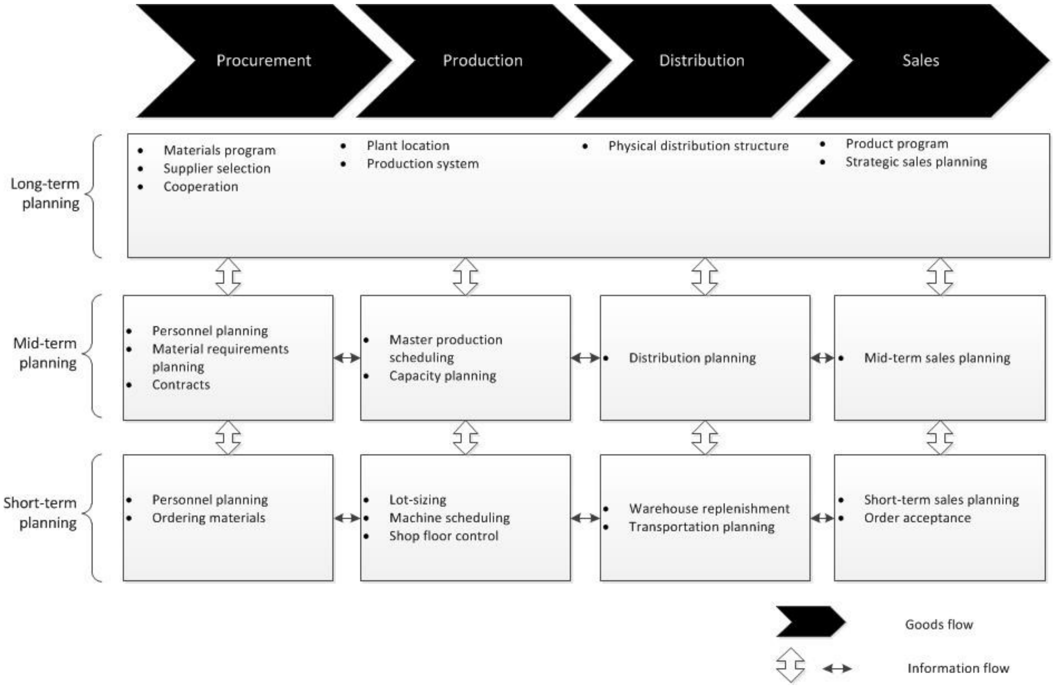


Figure 14 Supply chain planning matrix as described by Fleischmann et al. (2015)

The supply chain planning matrix provides an overview of the planning functions that are required to enable operations in a typical manufacturing company. The different planning functions are connected by horizontal and vertical information flows. Horizontal information flows mainly go upstream consisting of orders and forecasted demand such that operations are driven by customers. However, Fleischmann et al. (2015) stress that information exchange in both directions can improve supply chain performance significantly. Vertically, the downwards information flow consists mainly of the results of high level plans on subordinate plans. The upward information flow contains detailed information on the operational performance of the supply chain, which can be used in the decision making on new high-level plans (Fleischmann et al., 2015). The supply chain planning matrix provides a complete framework for positioning and defining required planning functionality across different planning functions. For VDL A, this framework provides important insights into the ideal positioning and interaction between different required planning functions.

3.3 Supply chain responsiveness

In order to provide good customer service in an uncertain and variable environment, a responsive supply chain is required. Reichhart & Holweg (2007) defined supply chain responsiveness as the speed with which a supply chain can adapt its output in terms of quantities, products, mix and delivery as a result of customer orders. Their model gives a complete overview of the main determinants of supply chain responsiveness. Reichhart & Holweg (2007) argue that responsiveness is especially relevant for built-to-order supply chains, in which operations are highly customer-oriented, making their insights particularly interesting for VDL A.

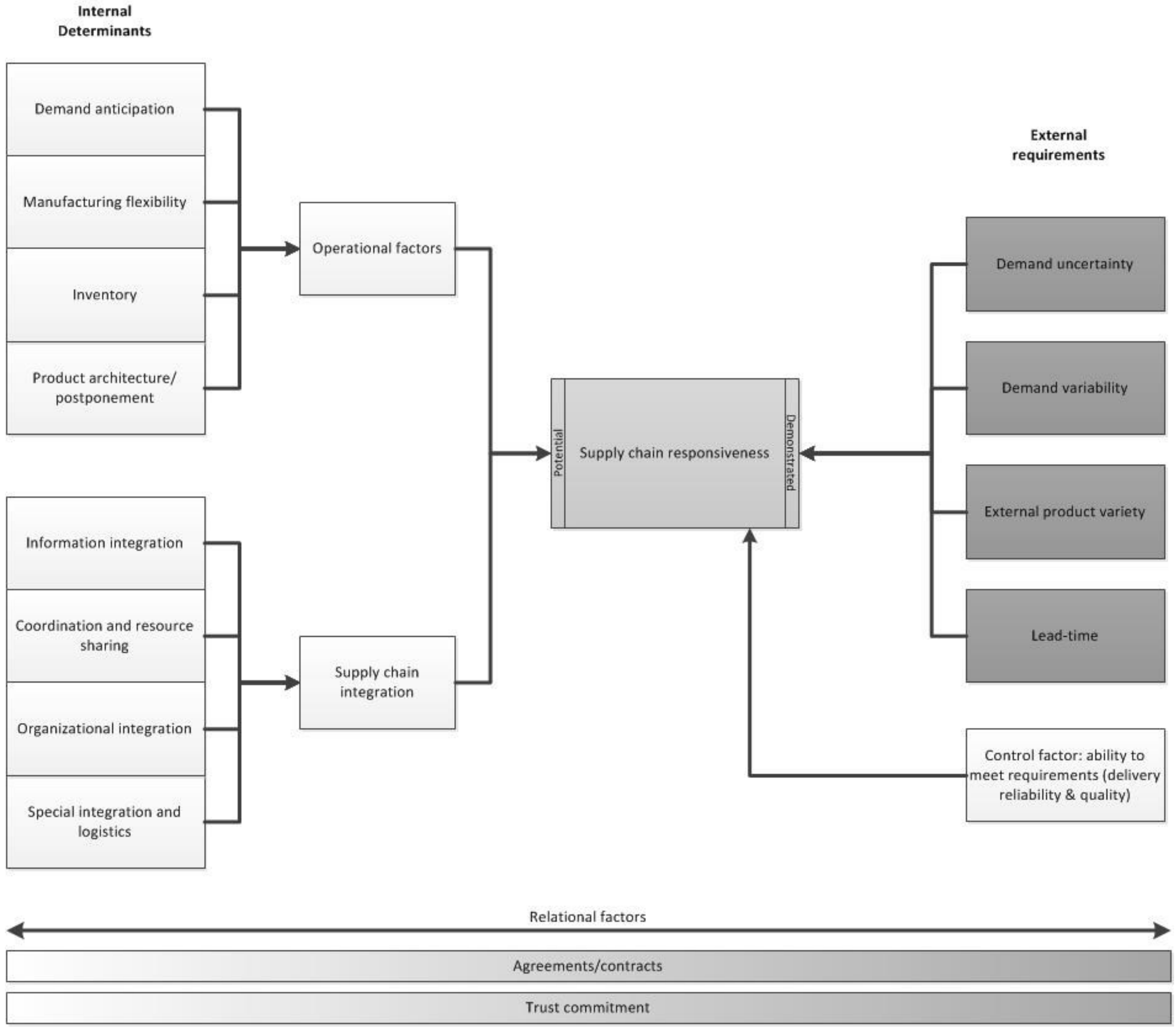


Figure 15 Supply chain responsiveness as described by Reichhart & Holweg (2007)

According to Reichhart & Holweg (2007), supply chain responsiveness is mainly determined by a set of operational and supply chain integration factors. These factors are displayed in figure 15. All of these factors can be recognized in the situation of VDL A. In this section, the factors along with a link to the environment at VDL A are discussed.

Operational factors

Demand anticipation at VDL A requires close communication with their customers. As mentioned before, the products that VDL A assembles only receive demand from a single customer. For most projects, customers share forecasts of their own sales with VDL A. For other projects, agreements on the minimal available inventory at VDL A are made with the customers in order to ensure certain service levels. Despite the close communication with customers, it still happens quite often that unexpected demands occur, which are sometimes inevitable. However, the occurrence of these situations could be reduced by more accurate and frequent information sharing. Since VDL A's customers are a link in the supply chain themselves, this also relates to supply chain integration factors, which will be discussed later in this section.

As discussed before, the manufacturing flexibility at VDL A is relatively high. The assembly of final products is not restricted by specific machinery which makes increasing or decreasing production volumes quickly, relatively easy. Changing to completely new products does require learning for the assembly personnel and rearrangement of the shop floor. The general tools and workstations which are required for most products, give VDL A a relatively high product mix flexibility.

Since production at VDL A is mainly restricted by material availability, inventories play a large role in the responsiveness of VDL A. This insight is broadly carried by VDL A personnel and therefore the inventories generally exceed estimated demand during lead times. Despite the fact that their inventories contribute to their responsiveness, management realizes that inventories are currently too high.

The placement of the CODP (see section 2.2.1) also contributes to the flexibility of a supply chain. The CODP is closely related to the inventory discussed above, because this is the inventory point where customer demand meets forecast based activities (Reichhart & Holweg, 2007). Placing the CODP more upstream increases flexibility in terms of product mix, at the cost of longer customer lead times. Placing the CODP more downstream decreases the responsiveness in terms of product mix flexibility, while it increases the responsiveness in terms of delivery time flexibility. At VDL A, the CODP is deliberately positioned at the material level to enable short customer lead times. All inventory buffers are therefore positioned at a material level, either at their own warehouse, or at their suppliers' warehouses.

Supply chain integration

Supply chain integration for VDL A includes collaboration with customers downstream and direct suppliers upstream.

A key element of downstream integration with customers is the sharing of demand information. The corrupting effects of a lack of demand visibility have been identified by Lee, Padmanabhan, & Whang (1997). These effects are amplified towards suppliers by the use of reorder levels and large batch sizes. This phenomenon is denoted as the bullwhip effect (Lee et al., 1997). Because of the detrimental effects of the bullwhip effect on supply chain performance, information sharing with customers is of great value. The value of sharing customer demand information has been recognized widely and this value increases when fewer customers exist (Jonsson & Mattsson, 2013). Since VDL A has only one customer for each of their products, this is especially relevant for them. On the other hand, it is essential that VDL A also shares this information with their suppliers. Otherwise, suppliers are bound to anticipate on the corrupted information in the shape of VDL A's purchasing orders, which will decrease their responsiveness and performance as a supplier. As mentioned before, VDL A is highly dependent on their suppliers because VDL A adds relatively little value in the final assembly of their products. In Jahnukainen & Lahti, (1999), it is stressed that coordination and integration of operations with suppliers is especially important for manufacturers that follow an ATO strategy.

In order to enable effective information sharing with suppliers, close collaboration between the involved parties is required. This can be difficult when the benefits of collaboration are unclear or if it is difficult to distribute the benefits amongst the involved parties (Sahin & Robinson, 2005). This insight can be recognized in VDL A's operations. If efficient supplier agreements lead to higher product prices, VDL A will cut its own profits. Customers are always pushing to reduce product prices, which can make it difficult to make efficient agreements with suppliers.

3.4 Master Planning and Sales & Operations Planning

Sales and operations planning (S&OP) is a monthly tactical planning process that aims to balance supply capabilities with external demand (Feng, D'Amours, & Beauregard, 2008). The S&OP team should include representatives from sales, operations and finance, such that all relevant information can be considered during the meetings (Thomé, Scavarda, Fernandez, & Scavarda, 2012). S&OP enables both vertical and horizontal alignment. Vertically, the strategic objectives are aligned with operational action plans. Horizontally, S&OP enables cross-functional alignment between different planning processes (Thomé et al., 2012). Since the problem analysis revealed that plans between different functional departments are often misaligned, insights from academic literature on S&OP are discussed here.

When matching supply with demand two extreme approaches can be distinguished. In the so called "aggressive" approach, demand is adapted to match supply capabilities. On the opposite side of that approach is the "reactive" approach, in which supply capabilities are adapted to match sales plans (Olhager, Rudberg & Wikner, 2001). The aim of S&OP is to find a balanced outcome for this consideration. The result of the S&OP process are aggregate plans for all involved departments that are coherent and non-conflicting.

Thomé et al. (2012) developed a framework that synthesizes the dispersed and diverse body of literature on S&OP. Their framework gives a complete overview of the inputs, processes, contextual factors and results that are involved in the S&OP process. Their framework can be found in figure 26 in appendix E.

Thomé et al. (2012) identified that the dominant perception of S&OP is that it can be applied as a tactical planning tool which is used after strategic business objectives are determined. The S&OP process bridges these plans towards all involved functional areas. Typical inputs for S&OP processes are initial plans from different functionalities, forecasts of future events and objectives such as inventory reductions, profit maximization or customer service improvements. They found that it is important to create formal S&OP teams and to also include key suppliers and customers early in the process. For VDL A this would imply that for each customer project, a cross-functional S&OP team should be formed. Thomé et al. (2012) also discuss that information systems are deemed essential to align strategy and operations. This introduces the need for VDL A to develop tools that can simulate or predict the impacts of decisions.

Stadtler, Kilger, & Meyr (2015) discuss the need for a master planning function that coordinates the flow of materials throughout the entire supply chain. It is the task of the master planning function to apply all material, time and production constraints to forecasted demand in order to generate a feasible master production schedule. They argue that a centralized approach in master planning decreases the need for material buffers to ensure a continuous flow of materials. Because of the high interdependency between demand forecasting, purchasing and production planning, master planning has a high level of interaction with S&OP. In Stadtler et al. (2015) it is even stated that S&OP is an important extension of master planning.

3.5 Supply Chain Operations Planning

De Kok & Fransoo (2003) discuss that the main objective of supply chain operations planning (SCOP) is to coordinate the release of materials and resources in a supply chain such that customer service requirements are met at minimal cost. They also discuss how the SCOP function can be positioned in the hierarchy of supply chain planning (See figure 16).

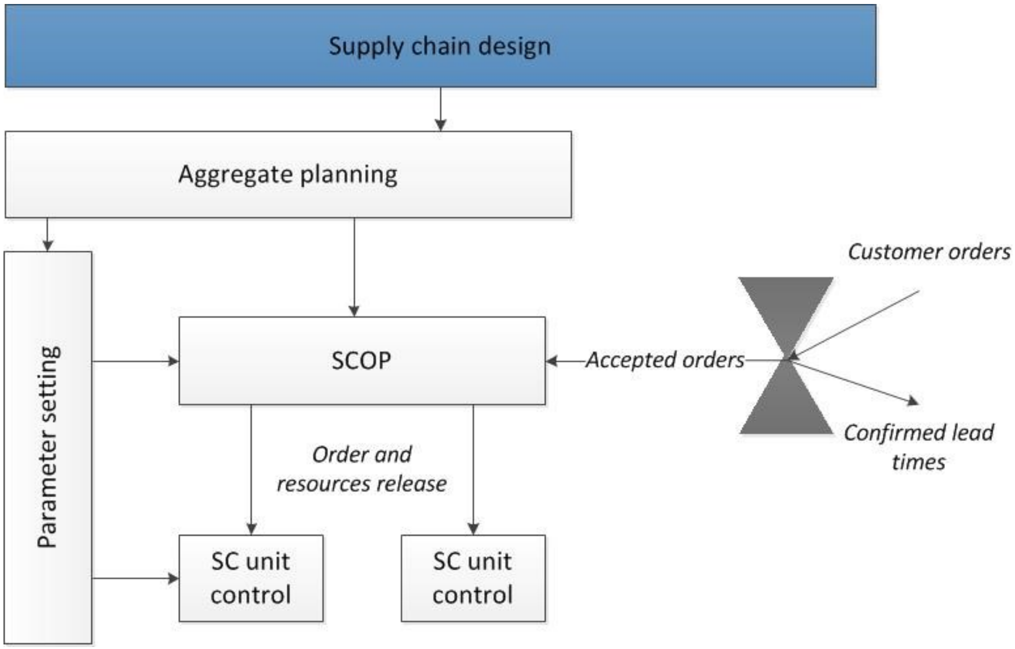


Figure 16 Hierarchical position of SCOP function as described by de Kok & Fransoo (2003)

Considering the supply chain planning matrix as discussed by Fleischmann et al. (2015), the SCOP problem overlaps both mid-term and short-term planning levels. In line with the goods flow control concept discussed by Bertrand, Wortmann & Wijngaard (1990) a decomposition is made by introducing more or less independent supply chain units, which manage their internal control independently. These units are assumed to deliver goods within fixed lead times and the goods flow control function coordinates the flow of materials and orders to and from the supply chain units (de Kok & Fransoo, 2003). The lead times are set such that they can be met with very high reliability, which enables the SCOP function to assume that they are fixed. Simultaneously, the SCOP function is responsible for controlling the workload such that the requirements are always feasible and the production units can indeed deliver within the agreed lead times.

Push vs pull order releases

In practice, the release of orders and resources is often executed by MRP-II logic or statistical inventory control models. In a paper by de Kok (2001) it is discussed that order releases are either based on a pull or a push concept. The misconceptions that exist around push and pull concepts are discussed in this paper as well. It is explained that push concepts are generally perceived to perform worse than pull concepts. This is mainly due to the fact that pull concepts respond directly to demand changes and are based on visible information like inventory levels. However, by defining push and pull concepts based on their order release rules, every pull concept is essentially a special case of a push concept (de Kok, 2001). This is the main argument for the conclusion that by definition, push concepts have the potential to be superior to pull concepts. For the complete reasoning behind this conclusion we refer to de Kok (2001).

Even though, conceptually, push concepts should be superior over pull concepts. De Kok (2001) argues that in practice, push concepts often perform worse than pull concepts. This is mainly due to the simplicity in usage of pull concepts and the "wrong" application of push concepts in practice. Due to inaccurate forecasting and unjustified decoupling of final product demand and material demand, infeasible production plans are often generated in push concepts. Combined with high material order quantities this leads to large fluctuations in the supply chain and a bad performance of the overall system. Pull concepts are much easier to apply in practice, since the only required information for generating order releases is the currently available inventory, the scheduled receipts and known demand, all of which are visible in any ERP system. However, pull concepts such as statistical inventory control models, do not capture the complexity in ATO scenarios between lumpy final product demand and dependent material demand. The demand characteristics of ATO demand processes, require simulation based, rolling-schedule planning methods (Sahin & Robinson, 2005). The differences in inventory performance of pull and push concepts can also be recognized in the discussion on inventory buffering in section 2.2.4.

De Kok (2001) also argues the need for order release methods which handle demand information correctly and simultaneously use operationally visible information such as inventory levels and open orders to restrict order releases. In de Kok & Fransoo (2003) a set of constraints on order releases is defined that ensures planned orders to be feasible both in terms of capacity and material availability. They argue that any SCOP method should satisfy these constraints to ensure feasible production plans. The material order releases are directly derived from final product demand information via the defined relations is the bill of material (BOM). Their model can be used to generate feasible production plans based on actual real time material availability, resource capacity and demand information. Consequently their model generates all required production and purchasing orders, without violating capacity or material availability constraints. Therefore, their model is an improvement in comparison to MRP as a SCOP method.

3.6 Order acceptance

De Kok & Fransoo (2003) discuss the need for an order acceptance function that controls the workload of the system. In Stadtler et al. (2015) this function is referred to as available-to-promise (ATP). They discuss that the main purpose of ATP is to provide reliable delivery dates towards customers and to shield production and material planning from infeasibilities.

Because of the ATO strategy, order promising needs to be done by evaluating material availability. Order acceptance should be based on a previously determined master plan. Figure 17 shows how Stadtler et al. (2015) link order acceptance to master planning. ATP quantities can be determined by evaluating final product demand and exploding the BOM lists to generate material requirements. The ATP quantities provide the basis for order acceptance and delivery date releases on an operational level.

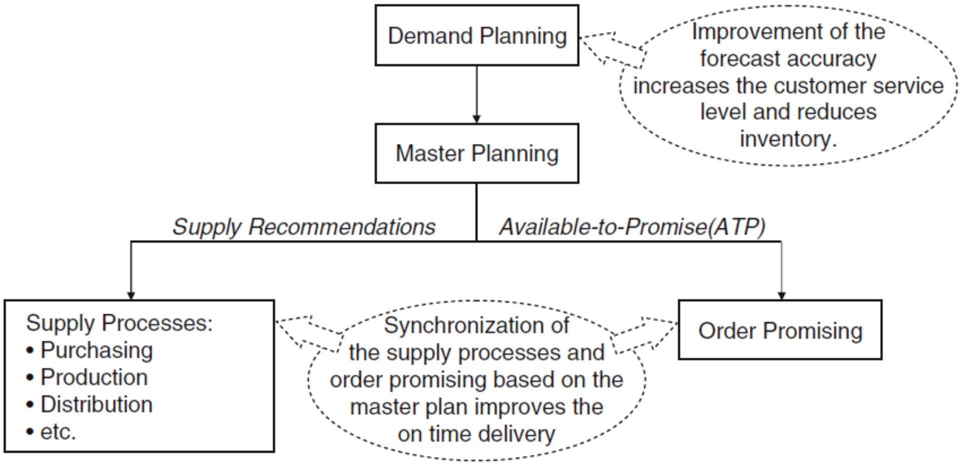


Figure 17 Relation between master planning and ATP, copied from Stadtler et al. (2015)

From the analysis in chapter 2, it became clear that such a function is not in place at VDL A. Planners incidentally make estimations on feasibility in case of exceptional customer orders, but there is no ATP or order acceptance function which is structurally integrated in their planning process. However ATP plays an important role in ensuring stable and feasible plans.

4. Diagnosis

From the analysis of both the current situation at VDL A and academic literature on supply chain planning, several opportunities for improvement were identified. This chapter discusses the two most important improvement opportunities and how they relate to the identified problems. It is also explained how these problems have been addressed in the solution design.

Shortcomings of the current SCOP method: MRP

Currently, VDL A uses MRP logic implemented in their ERP system to plan customer orders and to generate material requirements accordingly. Considering the definition of planning from Fleischmann et al. (2015) described in section 3.2, both ERP and MRP do not provide the required functionality to actually make planning decisions. They do not allow for the evaluation of alternative plans and objectives within the applicable practical constraints in order to truly support decision making. This observation has been recognized by several other researchers (de Kok & Fransoo, 2003; Fleischmann & Meyr, 2003). From an efficiency perspective, MRP does not synchronize purchasing orders for materials and it does not consume inventory buffers, such that inventories are higher than required (See figure 27 in Appendix F). Potentially the most problematic shortcoming of MRP for VDL A is the fact that MRP does not consider material availability constraints in planning production orders.

The shortcomings of MRP as a planning method are recognized by planners at VDL A as well. As discussed before, the most important constraint on production planning for VDL A is material availability. Therefore, considering material availability constraints when releasing production orders is crucial to ensure a stable and continuous production process.

The SCOP method proposed in de Kok & Fransoo (2003) solves the issues with regard to material constraints and material synchronization. Because this method uses material availability as a starting point, material shortages of a certain production schedule can be recognized immediately and a feasible production schedule can be determined easily. Their planning logic has the same functionality as MRP logic with regard to processing BOM relations, dependent material demand and forecast dynamics. In addition to the operational application, their planning logic can also be used at a master planning level in order to construct feasible sales and production plans in a collaborative planning context (De Kok et al., 2005).

Lack of hierarchical planning structure

While a large part of the problems regarding high inventories and planning instability can be contributed to the shortcomings of MRP as described in the previous section, there are also opportunities for improvement on a tactical and strategic planning level. Decision making on these planning levels on for example pricing decisions, customer agreements and tactical parameters are often not aligned properly such that they conflict with each other or result in inefficient operations. By comparing hierarchical planning frameworks described in academic literature to the current planning process in place at VDL A, several gaps were identified. Tactical planning is insufficiently integrated in their planning process and strategic objectives are often not aligned properly between different departments.

Conclusion

The high impact of material planning and availability on the performance of VDL A make the shortcomings of MRP as a SCOP method a large contributor to the high inventories and planning instability. In general, companies that are highly dependent on material planning are likely to experience the same issues. Therefore, the improvement design has focused on resolving these shortcomings by suggesting an improved SCOP method based on the model by de Kok & Fransoo (2003). Additional academic insights on supply chain planning and planning hierarchies were used to position the improved SCOP method in the planning process of VDL A.

5. Improvement design

The purpose of this research project was to improve the current planning and control activities at VDL A, such that a more stable planning can be achieved and inventories can be reduced. Solving the shortcomings of MRP as an order and material planning mechanism has been the main focus of the improvement design, as they lead directly to planning instability and high inventories. The synchronized base stock model by de Kok & Fransoo (2003) was used as a basis for an improved SCOP method for operational planning at VDL A. Their model and the extensions that were made to tailor the model for planning at VDL A are discussed in the first section of this chapter. Secondly, the improved SCOP method was implemented in a planning tool that generates feasible production plans and synchronizes material supply accordingly. Finally, the new SCOP method and tool were positioned in the operational planning process of VDL A.

5.1 New SCOP method

5.1.1 Model requirements

The new SCOP method should be able to provide the same functionality as the currently applied MRP logic, while providing an improvement regarding the discussed shortcomings involved with MRP. The practical requirements of the new SCOP method are summarized below.

- The new SCOP method should take lot sizing (MOQs) into account for purchased materials.
- The new SCOP method should be able to position safety stocks at a material level only.
- The new SCOP method needs to be able to treat dependent material demand from multiple final products via a BOM structure.
- The order releases need to incorporate practical constraints on material availability and rough-cut assembly capacity into account.
- Required input data needs to be retrievable from the ERP system.

5.1.2 Required extensions to the basic model

The basic model as discussed in de Kok & Fransoo (2003) meets these requirements except for the first two. Their model does not take lot-sizing into account and the inventory allocation mechanism in their model uses safety stocks to allocate inventories in case of material shortages for all materials and final products. For final products, the model should allow zero safety stock, since VDL A's assembly operations are completely order based. Linear allocation mechanisms have already been applied in the original model to overcome the safety stock issues for final products (Kraaij, 2017).

The lack of lot sizing restrictions is not a problem for final products because VDL A does not use any lot-sizing restrictions there. However, for purchased materials, MOQ's have a considerable impact on the inventories at VDL A. Therefore, these have been included in the new SCOP method. Since to our knowledge this has not been done before, the impacts of this extension were analyzed by means of a simulation.

5.1.3 Synchronized base stock model

In this section, the mathematical model is introduced that is used to generate feasible production plans and the corresponding material purchasing orders. The model is referred to as Synchronized Base Stock (SBS) model. The SBS model is based on the model as discussed by de Kok & Fransoo (2003) and it is adapted to meet the practical requirements as discussed before. In this section the model is explained step by step including the modifications that were made to allow implementation at VDL A.

Variable	Description
Indicators	
i	item
t	time period (weeks)
Sets and subsets of items	
M	set of all items
N	set of all end items $N \subset M$
C_i	set of all direct successors (parent set) of item i, $i \in M$
P_i	set of all direct predecessors (child set) of item i, $i \in M$
F_i	set of all end items delivered by item i, $i \in M$
K_i	set of all items required to make item i, $i \in N$
Parameters	
H	planning horizon (weeks)
Z	maximum production capacity in products per week
a_{ij}	number of items i required to produce one unit of item j, $i \in M, j \in N$
L_i	lead time of item i
L^*_{ij}	cumulative lead time of all items on path between item i and j, $i \in M$, $j \in N$
ST_i	safety time associated with item i,
SS_i	cumulative safety stock in echelon of item i,
μ_i	average demand during lead time for item i
ϕ_i	priority factor for item i
State variables for i ∈ M for each period t	
$D_i(t)$	forecasted demand for end item $i \in$ M in period t
$I_i(t)$	net stock of item i at the start of period t
$IP_i(t)$	inventory position of titem i at the start of period t
$EIP_i(t)$	echelon inventory position of item i at the start of period t
$EIP^*_i(t)$	echelon inventory position of item i at the start of period t
$POH_i(t)$	projected on hand inventory of item i at the start of period t
$SR_i(t)$	scheduled receipts of item i planned to arrive at start of period t
$PO_i(t)$	planned order for item i released at the start of period t
$O_i(t)$	actual order for item i released at the start of period t
$q_i(t)$	unconstrained order for item i at start of period t
$Q_j^{(i)}$	order released for item j if item i would be j's only predecessor

The following equations are used to derive work order releases for final products and purchase order releases for materials, as this is the core functionality of a SCOP method (de Kok & Fransoo, 2003).

$$IP_i(t) = I_i(t) + \sum_{s}^{L_i-1} SR(t+s), \qquad i \in M \qquad (1)$$

$$EIP_i(t) = IP_i(t) + \sum_{j \in C_i} a_{ij} EIP_j(t), \qquad i \in M \qquad (2)$$

Formulas (1) and (2) are used to calculate the (echelon) inventory positions of all items for each period. For each period the same sequence of events is applied as in the algorithm of de Kok & Fransoo (2003). First, all scheduled receipts arrive. Secondly, all work and purchase orders are released. Finally customer demands and internal work orders are fulfilled. Equations (3), (4) and (5) are used to update the net inventories for all materials after the order releases have been determined and demand has been fulfilled. It is assumed that suppliers have infinite supply capacity and deliver materials within a fixed and known lead time, such that the ordered amount of materials in period t is equal to the scheduled receipts in period $t + L_i$.

$$SR_i(t + L_i) = PO_i(t), \qquad i \in M \qquad (3)$$

$$I_i(t+1) = I_i(t) - D_i(t) + SR_i(t+1), \qquad i \in N \qquad (4)$$

$$I_i(t+1) = I_i(t) - \sum_{j \in C_i} a_{ij} PO_j(t) + SR_i(t+1), \qquad i \in M \backslash N \qquad (5)$$

In order to handle changes in forecasted demand correctly, the model uses dynamic base stock levels. The base stock levels are calculated by summing the forecasted demand during the items cumulative lead time plus a pre-specified amount of safety time. By using safety time as a buffer instead of a fixed base stock level, inventory buffers are automatically aligned with forecasted demand developments such as ramp ups or downturns.

$$S_i(t) = \sum_{m \in F_i} \left(\sum_{\gamma=0}^{L^*_{i,m} + ST^*_{i,m}} a_{im} D_m(t+\gamma) \right) \qquad i \in M \qquad (6)$$

The amount of buffer inventory to cope with unexpected deviations from forecasted demand can be calculated with equation (7). In the original model from de Kok & Fransoo (2003)this variable is used to allocate material shortages between final products. In our model, a different approach is used to meet the model requirement of zero safety stocks for final products (See equation 11).

$$SS_i(t) = \sum_{m \in F_i} \left(\sum_{\gamma=0}^{L^*_{i,k} + ST^*_{i,m}} a_{im} D_m(t+\gamma) \right) - \sum_{m \in F_i} \left(\sum_{\gamma=0}^{L^*_{i,m}} a_{im} D_m(t+\gamma) \right) \quad i \in M \quad (7)$$

For all items, the unconstrained order can be determined, which would be ordered if infinite materials would be available (See equation 8).

$$q_i(t) = \left(S_i(t) - EIP_i(t)\right)^+ \qquad i \in M \qquad (8)$$

Now that the unconstrained orders are determined, they need to be transformed to material feasible orders. Note that this unconstrained order is similar to the orders released by MRP.

Now two situations can occur, either the available inventory of item *i* is sufficient to fulfill the cumulative unconstrained orders of all items that require item *i* (See equation 9) or the cumulative unconstrained orders exceed the available inventory of material *i* (See equation 10). In the latter case, the shortage needs to be allocated amongst the items that require material *i*.

$$\sum_{m \in C_i} a_{im} q_m \leq I_i \quad (9)$$

$$\sum_{m \in C_i} a_{im} q_m > I_i \quad (10)$$

Since our model does not include final products safety stocks, a different allocation mechanism is applied from the mechanism used in de Kok & Fransoo (2003). Our model uses a predetermined priority factor. The product with highest priority receives priority factor equal to 1, the product with the second highest priority receives factor 2 and so on. This ensures that the product with the highest priority is allocated the lowest amount of shortage. This was agreed with planners at VDL A. The allocated shortage is then subtracted from the dynamic base stock level. This results in the echelon inventory position of item *j* after allocation of the available inventory of material *i*, EIP_j^+.

$$EIP_j^+ = S_{j(t)} - \frac{\phi_j}{\sum_{m \in C_i} \phi_m} \left(\sum_{m \in C_i} a_{im} q_m - I_i \right) \quad i \in M, j \in N \quad (11)$$

The difference between the current echelon inventory position of item *j* and the echelon inventory position after allocation of available inventory is the basis for the current order for item *j*. This order is rationed for the other orders that require item *i* and multiplied by the availability of item *i*. This results in the order for item *j* if item *i* would be only required item.

$$Q_j^{(i)}(t) = \frac{\left(EIP_j^+(t) - EIP_j(t)\right)^+}{\sum_{m \in C_i} \left(EIP_j^+(t) - EIP_j(t)\right)^+} I_i(t) \quad i \in M, j \in N \quad (12)$$

The smallest $Q_j^{(n)}$ is selected in order to find an order release for item *j* that is feasible for all required materials (See equation 13).

$$PO_j(t) = \min_{\forall n \in P_j} Q_j^{(n)}(t) \quad j \in N \quad (13)$$

The model as described so far is able to release feasible assembly orders for all materials and therefore overcomes the lack of feasibility constraints of MRP. However, it still does not ensure synchronized material arrivals. To include material synchronization in the model, the logic described in de Jong (2010) is applied. In his master's thesis the approach by de Kok & Fransoo (2003) is adapted to enable more flexibility in assigning materials to final products. Since this flexibility is also desirable at VDL A, this approach was selected for our model. The equations used in de Jong (2010) have been modified slightly to ensure their functioning in the context of VDL A, resulting in equations 14, 15 and 16.

For all materials, the maximum output potential of item *i* in units of item *j* for the coming periods, is calculated by adding the scheduled receipts to the current net inventory for the periods *t* until $t + L_i$. Because inventories at VDL A are only kept at a material level, no inventory is tied up in downstream items, which is why the net inventory can be used rather than the echelon inventory position used in de Jong (2010). Using inventory positions does not give the right outcomes, since these are immediately increased with the ordered amount in period t, even if it only arrives in period $t + 20$.

In period *t* equation 14 is calculated for all purchase items *i* for *a = t + 1 until t + LeadTime(i).*

$$POH_i(a) = I(t) + \sum_{x=t}^{a} SR_i(x) \quad i \in M \backslash N \quad (14)$$

$$W_j(a) = \min_{i \in k_j \,|\, L_{ij} > a-t} \left\lfloor \frac{POH_i(a)}{a_{ij}} \right\rfloor \quad j \in N, i \in M \quad (15)$$

Equation 15 is used to calculate the maximum output potential of product *j* in period *a*, which is used as a constraint for the material purchasing orders in period *a – LeadTime(i).*

$$q_i(t) \leq \sum_{j \in F_i} a_{ij} W_j(t + L_i) \quad i \in M \backslash N \quad (16)$$

Formula 16 ensures that the ordered amount of materials does not exceed the maximum output potential of the final products that it serves.

For materials which are purchased at suppliers, MOQ's are in place. For the model, it is assumed that suppliers have infinite capacity. Therefore, the synchronized orders are converted to (a multiple of) the agreed MOQ (See equation 17).

$$PO_i(t) = \left\lceil \frac{q_i}{MOQ_i} \right\rceil * MOQ_i \quad i \in M\backslash N \quad (17)$$

Due to the use of MOQ's the purchasing order can still exceed the maximum output potential in $t + Leadtime(i)$, however it will never exceed the maximum output more than the MOQ.

The mathematical model was implemented in Excel vba code. Using this code, the previously described decision support tool was built and simulations were conducted to compare the performance of the SBS model to standard MRP ordering logic. This simulation is discussed in section 5.2.

5.2 Model validation.

To test the functionality of the model, it was applied to two different product groups. The discussion of the results in this section focuses on the group with the largest revenues and largest impact on VDL A's performance. This product group consists of two final products. Both products consist of more than 700 unique parts with supply lead times varying between 1 and 16 weeks. The assembly of both final products can be done within two weeks. The production capacity is restricted on the short term based on the available work stations and trained personnel, but capacity can be expanded within a matter of weeks if necessary. Therefore, capacity restrictions are not considered in this analysis. The main goal of this analysis is to explore the performance of the new SCOP method in terms of service levels and inventory efficiency in a stochastic environment.

5.2.1 MRP vs SBS

The model was implemented in MS Excel VBA to evaluate its performance and functionality. Additionally, MRP ordering logic was implemented in VBA as well, such that the new SCOP model could be compared with the currently applied MRP logic.

The MRP logic has the same basis as the SBS model. However, in the MRP model the material availability and synchronization constraints are not applied. The order releases for final products are the unconstrained orders calculated in equation 8. Purchasing orders are converted into multiples of the MOQ according to equation 17. The same shortage allocation procedure is used for the MRP model (see equation 11). The actual production order are constrained by material availability to construct accurate backorders in the simulation. Essentially the model represents MRP-1 logic in a two echelon assembly system, with infinite supply capacity from suppliers, within the corresponding lead times.

The main difference between both models is the way both models deal with unexpected demand within material lead times. The MRP model immediately replenishes stocks whenever an item's inventory position drops below a certain level by placing an order. The SBS model checks for material availability and potential output before placing orders, such that material arrivals are synchronized and all released orders are feasible. This concept is shown in figure 27 in appendix F.

To demonstrate this difference, a simulation study was conducted on the inventory and delivery performance of both models. Figure 18 shows the order of events in each period in the simulation.

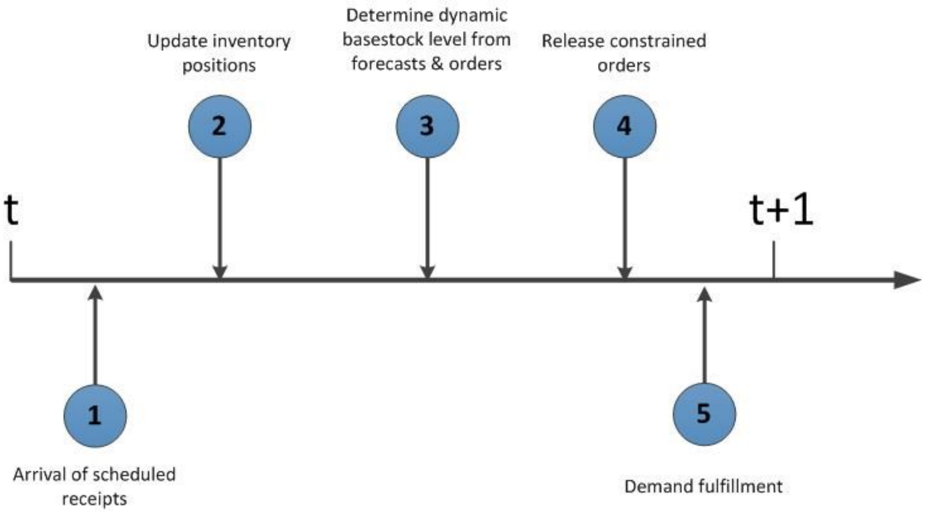


Figure 18 Order of events in simulation

Both models use the same forecast for one year as a basis for their planning. This forecast is based on historical customer orders for the considered product group. Actual demand is assumed to follow a normal distribution with a mean equal to the average forecasted weekly demand and a standard deviation of 50% of the mean. This assumption was used for both final products. This demand distribution was not selected based on any statistical analysis of demand data, since the aim of this analysis is only to show how both models respond to stochastic demand realizations potentially resulting in material shortages. Both models start without any inventories and they have enough time to order all required materials before the first forecasted demand occurs.

Actual demand becomes available to the system three weeks beforehand. For most materials this is well within their purchasing lead time. These demand changes within material lead times show the differences between the two SCOP methods and are comparable to typical demand processes for products of VDL A.

For both systems the same parameters were used for lead times and MOQ’s. In the MRP model, safety stocks were determined for each material by stocking 3 weeks of average material requirements. This method is commonly used at VDL A.

$$SS_i = 3 * \sum_{j \in C_i} \widehat{D}_i * a_{ij} \quad i \in M \backslash N \quad (18)$$

The SBS model uses safety time to buffer against unexpected demand as discussed in section 5.2. A safety time of three weeks was used in this analysis. Essentially, it looks three weeks further than the material lead times to include the forecasted demand for three extra weeks.

The fill rate was calculated according to equation 19. It is determined by calculating the percentage of demands that are delivered at their due date for each final product separately. The separate fill-rates are weighed by the relative final product demand to determine a combined fill-rate.

$$P_2 = \frac{\sum_{i=1}^{n}\left(\left(1-\sum_{t=1}^{T}\left(\frac{(\max(B_i(t)-B_i(t-1),0))}{D_i(t)}\right)*\bar{D}_i\right)\right)}{\sum_{i=1}^{n}\bar{D}_i} \quad i \in N \quad (19)$$

Because demand is generated randomly, the simulation was ran 500 times to ensure stable results for both models. This resulted in average fill rates and inventory levels for the total amount of simulation runs. The inventory values are presented in euros, the material prices that were used are fictional to protect confidentiality. The results are displayed in table 4.

	Average inventory			Closing inventory			Fill rate	
	MRP	**SBS**	**Δ %**	**MRP**	**SBS**	**Δ %**	**MRP**	**SBS**
(1) Long lead times, high MOQ's	€ 343.657	€ 265.716	**-23%**	€ 331.873	€ 292.214	**-12%**	99,09%	**99.51%**
(2) Short lead times high MOQ's	€ 174.361	€ 135.702	**-22%**	€ 177.653	€ 155.626	**-12%**	95.39%	**97,10%**
(3) No lot sizing	€ 59.023	€ 47.593	**-19%**	€ 48.346	€ 39.576	**-18%**	88,39%	**91,26%**
(4) MOQ D*L	€ 99.172	€ 78.123	**-21%**	€ 88.498	€ 72.521	**-18%**	96,05%	**96,26%**
(5) EOQ	€ 131.882	€ 104.652	**-21%**	€ 120.617	€ 105.436	**-13%**	96.58%	**96,94%**
(6) **Current MOQ's**	€ 131.138	€ 105.059	**-20%**	€ 125.536	€ 108.647	**-14%**	97.46%	**97.48%**

Table 4 Simulation results

From the results in table 4, it can be seen that the SBS model achieves similar service levels with considerably less inventory. This is not the result of smart buffer management or optimization procedures, but it results from generating smarter order releases. As discussed before, SBS ensures that purchasing orders are restricted by the potential output of the system, such that the system never orders more materials than required.

Impact of order quantities on service levels and inventories

To our knowledge, the lot-sizing extension of the basic SBS model has not been applied before. Therefore, it was explored how the model responds to different lot-sizing configurations. Especially since the synchronization is based on the availability of items with long lead times, it is explored whether assigning large MOQ's for long lead time items, resulted in big differences in service levels compared to a situation with high MOQ's for short lead time items. The following different configurations were explored:

(1) Items with a lead time longer than 8 weeks were given MOQ's with a magnitude of the total forecasted requirements for a year, while materials with lead times shorter than 8 weeks were given MOQ's as large as the expected demand during lead time.

(2) Items with a lead time longer than 8 weeks were assigned MOQ's with a magnitude of the expected demand during their lead time, while materials with a lead time shorter than 8 weeks were assigned MOQ's as large as the total forecasted demand for a year.
(3) In this scenario, no lot-sizing restrictions were applied.
(4) In this scenario, the MOQ's of all materials equal the expected demand during its lead time.
(5) In this scenario, all materials are assigned the economic order quantity (EOQ) which is calculated with Camp's formula (equation 20).

$$EOQ = \sqrt{\frac{2DK}{ph}} \quad (20)$$

$D = annual\ demand$
$K = fixed\ order\ costs\ per\ order$
$p = material\ price$
$h = annual\ holding\ cost\ percentage$

(6) The currently applicable MOQ's from the ERP system at VDL A were used here.

From the results displayed in table 4, it became clear that the SBS model structurally outperforms the MRP logic, also with different MOQ configurations. The analysis also shows that MOQ's impact the service levels and inventories considerably. An important insight is that the SBS model is not more sensitive to these impacts than the MRP model. Which supports the validity of the MOQ extension of the SBS model.

Impact of buffering method on service levels and inventories

In the previous analysis on the impact of the lot-sizing extension to the model, both models used a different buffering method. In the SBS model, safety time was used while the MRP model included a safety stock. Obviously, these buffering methods impact the performance of both models as well. Therefore, a second analysis was conducted in which both models use the same buffering method. Several configurations of inventory and time buffers are evaluated as well.

Originally, the SBS model does not include fixed safety stocks. Therefore, they were included in the SBS model to make a direct comparison between both models using the same buffering method (see equation 21).

$$S_i(t) = \sum_{m \in F_i} \left(\sum_{\gamma=0}^{L_{i,m}^{*}+ST_{i,m}^{*}} a_{im} D_m(t+\gamma) \right) + SS_i \qquad i \in M \qquad (21)$$

In this analysis the standard MOQ's and the same fictional demand process were used. The results are shown in table 5.

	Average inventory			Fill rate	
	MRP	**SBS**	**Δ %**	**MRP**	**SBS**
$SS_i = \mu * L_i$, ST = 0	€ 158.460	€ 137.366	**-13%**	98.74%	**98,93%**
$SS_i = 0$, ST = L_i	€ 149.666	€ 133.432	**-11%**	97,33%	**97,99%**
$SS_i = \mu$, ST=5	€ 157.358	€ 134.091	**-15%**	99.64%	**99,79%**

Table 5 Simulation results for different buffering methods

The most important conclusion that can be drawn from the results in table 5 is that, also with the same buffering methods, the SBS model outperforms the MRP model throughout the different configurations. It reaches comparable service levels with considerably lower inventories. Additionally, it appears that a combination of safety times and safety stocks leads to the highest service levels. Another interesting conclusion that can be drawn by comparing table 5 to table 4, is the fact that the superiority of SBS over MRP is higher when safety times are applied for the SBS model and safety stocks for the MRP model. Since the demand process is fictional and not necessarily representative of demand at VDL A, this is not an exact analysis to find efficient configurations of safety buffers in practice. It only shows the general differences between both models.

Performance of SBS with real life demand data

In addition to the fictional demand processes in the previous sections, the SBS model was also tested against historical demand data from VDL A's ERP system. The product discussed in section 2.2.1 is used for this. For this product, forecasts for one year ahead are updated weekly and used as a basis for the material planning at VDL A. The same forecasts as shown in figure 5 in section 2.1.2 were used, while the actual shipments were used as demand input. Again, it was compared how MRP and SBS deal with the forecast and demand information in order to arrange material an production planning. The results are shown in table 6. Only safety times were used here since this product group does not contain any safety stocks and is completely managed by forecasts.

	Average inventory			Fill rate	
	MRP	**SBS**	**Δ %**	**MRP**	**SBS**
ST=3, ss=0	€ 123.483,-	€ 96.982,-	**-21%**	96,77%	**97,32%**
ST=1, ss=0	€ 107.245,-	€ 81.335,-	**-24%**	94,40%	**96,77%**

Table 6 Simulation results for historical data comparison

From this analysis, the same conclusions can be drawn again, indicating that the SBS model also performs well for this example product with historical demand and forecast data.

5.2.2 Reflection on simulation results

The most important conclusion that can be drawn from this simulation study is the fact that the extended SBS model performs as well as the MRP model in terms of service levels, while it has the potential to reduce inventories by generating smarter purchasing orders. Therefore, it was validated that the lot-sizing extension does not corrupt the performance of the original SBS model under the conditions of the described two-echelon environment. It also became clear that buffering methods and order quantities have an important impact on the performance of both models. An extensive study on efficient buffering parameters was not executed in this study, but this leaves room for interesting future research efforts.

5.3 Decision support tool

The extended SBS model was implemented in a decision support tool, such that it can actually be applied as a SCOP method and order planning tool. The tool uses simulation to construct feasible plans and to suggest all required purchasing order releases accordingly. The same order of events is used as shown in figure 18.

Whereas MRP lacks the actual functionality of planning as discussed in section 3.2, the new SCOP method included in the tool, enables planners to create plans that satisfy practical constraints on material availability and assembly capacity.

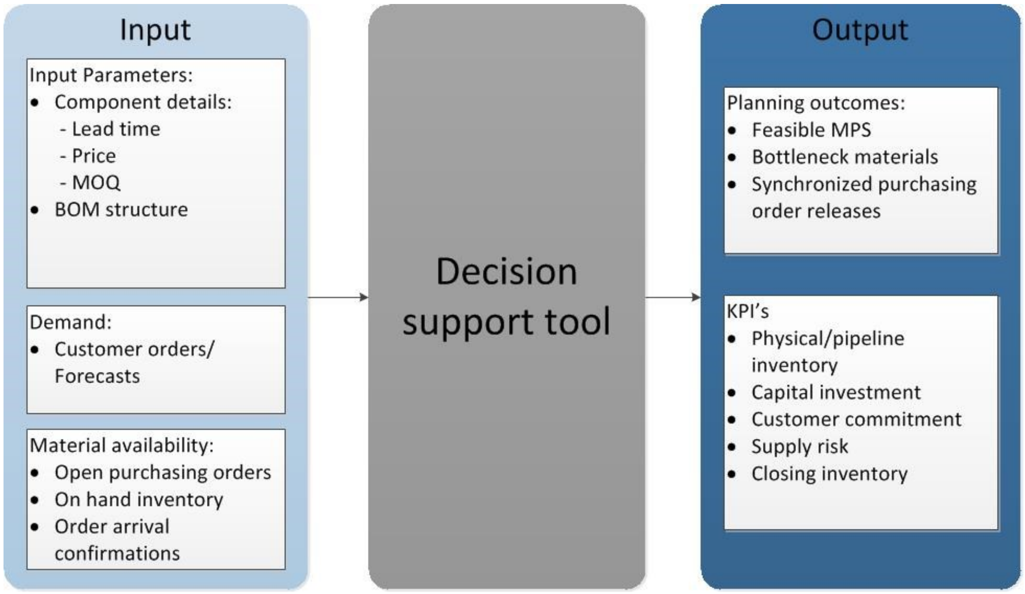


Figure 19 Decision support tool

Input

The tool uses a BOM list consisting of all required materials and their specifications, demand information consisting of customer orders and forecasts and real time information on physical and pipeline inventories as input. This information is available in the ERP system of VDL A and can be retrieved easily. An overview of the in- and outputs of the tool is given in figure 19.

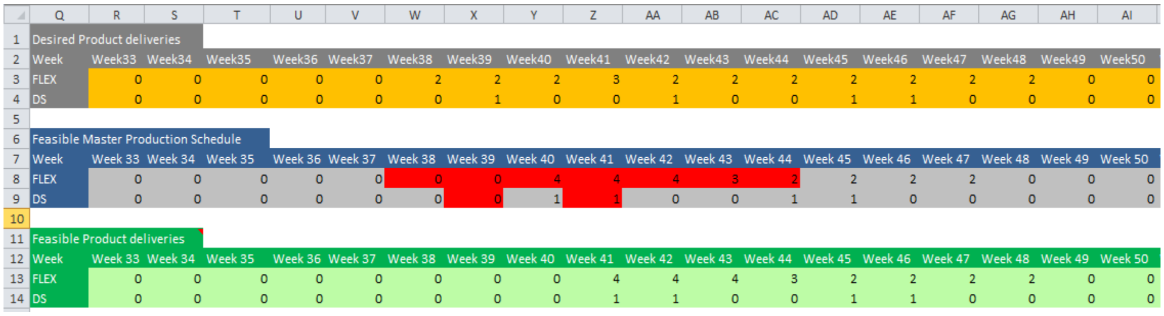
To ensure that the input information on outstanding orders and inventories is accurate, the dynamics of operations at VDL A were considered. For example, materials tied up in (partially) finished products are not withdrawn from stocks by the ERP system as long as they are not shipped towards customers. For the model it is important to know which materials are already tied up in work in process (WIP), so it withdraws materials as soon as a production order is started. The real time inventories from the ERP system are diminished by the current amount of WIP to ensure that all input inventories are actually available for assembly.

Even though assembly capacity is relatively flexible, on the short term it is restricted by allocated shop floor space and available personnel. This is why the assembly capacity in products/week should be entered into the system as well to ensure that the tool suggests feasible plans.

Output

The output of the DS tool consists of both real time planning outcomes and high level KPI's. The tool supports planning by generating the following results:

- *A feasible master production schedule*. By combining material and assembly capacity constraints and demand requirements, the tool determines a production schedule in which all production orders are feasible both in terms of material availability and assembly capacity. This is shown in figure 20.



Desired Product deliveries

Week	Week33	Week34	Week35	Week36	Week37	Week38	Week39	Week40	Week41	Week42	Week43	Week44	Week45	Week46	Week47	Week48	Week49	Week50
FLEX	0	0	0	0	0	2	2	2	3	2	2	2	2	2	2	2	0	0
DS	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0

Feasible Master Production Schedule

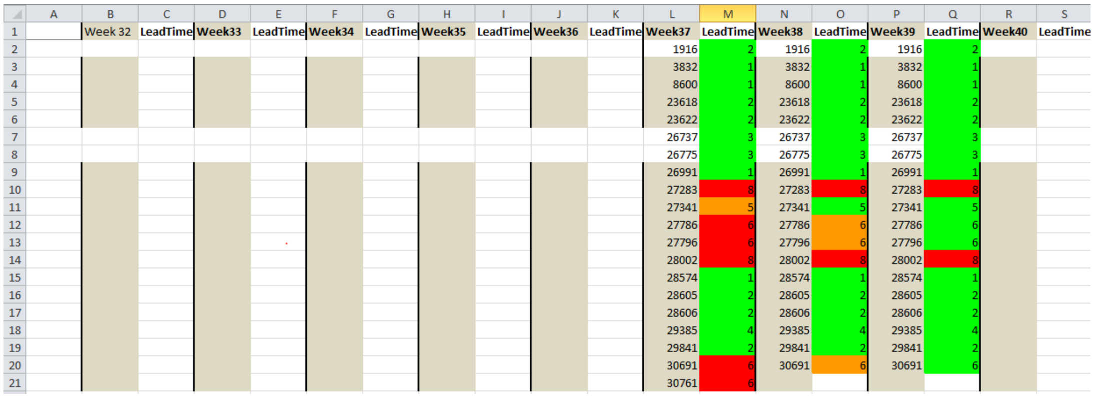
Week	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39	Week 40	Week 41	Week 42	Week 43	Week 44	Week 45	Week 46	Week 47	Week 48	Week 49	Week 50
FLEX	0	0	0	0	0	0	0	4	4	4	3	2	2	2	2	0	0	0
DS	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0

Feasible Product deliveries

Week	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39	Week 40	Week 41	Week 42	Week 43	Week 44	Week 45	Week 46	Week 47	Week 48	Week 49	Week 50
FLEX	0	0	0	0	0	0	0	0	4	4	4	3	2	2	2	2	0	0
DS	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0

Figure 20 Master production scheduling using the tool

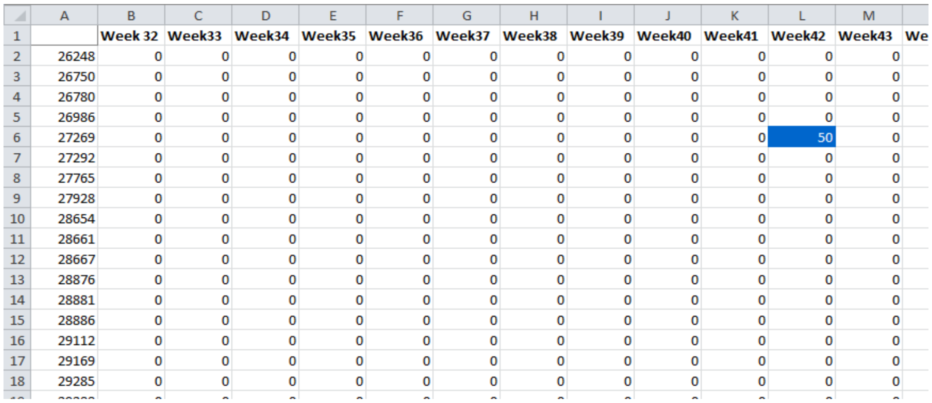
- *Bottleneck materials*. If the feasible MPS does not satisfy the (forecasted) demand, the tool shows which materials restrict the production schedule. It also shows at which point in time the materials become available. Figure 21 shows the materials with insufficient stock in the periods in which the production planning does not satisfy demand. The materials which are colored green are not available because the model postpones their purchasing orders such that they do not arrive before the materials colored in red arrive. The materials in red are the bottleneck items that restrict the production planning. Their material code is shown along with their planned lead time.



Week 32	LeadTime	Week33	LeadTime	Week34	LeadTime	Week35	LeadTime	Week36	LeadTime	Week37	LeadTime	Week38	LeadTime	Week39	LeadTime	Week40	LeadTime
										1916	2	1916	2	1916	2		
										3832	1	3832	1	3832	1		
										8600	1	8600	1	8600	1		
										23618	2	23618	2	23618	2		
										23622	2	23622	2	23622	2		
										26737	3	26737	3	26737	3		
										26775	3	26775	3	26775	3		
										26991	1	26991	1	26991	1		
										27283	8	27283	8	27283	8		
										27341	5	27341	5	27341	5		
										27786	6	27786	6	27786	6		
										27796	6	27796	6	27796	6		
										28002	8	28002	8	28002	8		
										28574	1	28574	1	28574	1		
										28605	2	28605	2	28605	2		
										28606	2	28606	2	28606	2		
										29385	4	29385	4	29385	4		
										29841	2	29841	2	29841	2		
										30691	6	30691	6	30691	6		
										30761	6						

Figure 21 Screenshot of material constraints as displayed in the tool

- *Synchronized purchasing order releases*. Based on the feasible MPS, the tool suggests purchasing order releases that ensure that material arrivals are coordinated to prevent unnecessary early arrivals.



	A	B	C	D	E	F	G	H	I	J	K	L	M	
1		Week 32	Week33	Week34	Week35	Week36	Week37	Week38	Week39	Week40	Week41	Week42	Week43	We
2	26248	0	0	0	0	0	0	0	0	0	0	0	0	
3	26750	0	0	0	0	0	0	0	0	0	0	0	0	
4	26780	0	0	0	0	0	0	0	0	0	0	0	0	
5	26986	0	0	0	0	0	0	0	0	0	0	0	0	
6	27269	0	0	0	0	0	0	0	0	0	0	50	0	
7	27292	0	0	0	0	0	0	0	0	0	0	0	0	
8	27765	0	0	0	0	0	0	0	0	0	0	0	0	
9	27928	0	0	0	0	0	0	0	0	0	0	0	0	
10	28654	0	0	0	0	0	0	0	0	0	0	0	0	
11	28661	0	0	0	0	0	0	0	0	0	0	0	0	
12	28667	0	0	0	0	0	0	0	0	0	0	0	0	
13	28876	0	0	0	0	0	0	0	0	0	0	0	0	
14	28881	0	0	0	0	0	0	0	0	0	0	0	0	
15	28886	0	0	0	0	0	0	0	0	0	0	0	0	
16	29112	0	0	0	0	0	0	0	0	0	0	0	0	
17	29169	0	0	0	0	0	0	0	0	0	0	0	0	
18	29285	0	0	0	0	0	0	0	0	0	0	0	0	

Figure 22 Synchronized purchasing orders suggested by tool

Additionally, the tool shows the outcomes on several KPI's of the constructed plans. It shows the delivery performance and material investments. Because financial risks play an important role for VDL A, the financial risk of the production and purchasing plan is shown as well.

Ensuring acceptance of decision support tool

To ensure that the decision support tool is actually used in practice, several academic insights were considered during the development of the tool. To support the acceptance of the decision support tool, the intended users were closely involved in the design of the tool as suggested in Shepherd & Günter (2011). The purpose of the tool is to extend the capabilities of the human planner, by structuring the complex problem and providing the option to evaluate future scenarios and explain impacts on KPI's. Without the human planner, the tool is worthless and therefore it is essential that the tool is easy to use and that it actually provides insights that would be unavailable to the planner without the tool.

Riedel, Wiers, & Fransoo (2012) investigated the dynamic relations between acceptance of advanced planning and scheduling systems and the perceived ease of use and control by the system's users. They found evidence for their hypotheses that the user's perceived control and ease of use relates to user satisfaction and actual usage of the system. By closely involving the intended users during the development of the tool and considering their suggestions for improvements, the tool was matched to the users desires. The decision support tool does not make any decisions for the planner, but it extends the planners knowledge by evaluating scenario's, visualizing the outcomes of certain decisions and suggesting order releases. Therefore, the full decision control remains with the planner. The involvement of potential users during the development of the tool also aimed to improve the perception of control by providing insight in how the tool works and where the tool's results originate from.

5.4 Positioning the new SCOP method in VDL A's planning process

This section provides a description of how the new SCOP method and the DS tool fit in the operational planning process at VDL A.

A swim-lane diagram (figure 23) was constructed that shows the planning steps required to process and plan al orders and forecasts from the moment they arrive from customers until the point at which they can be delivered.

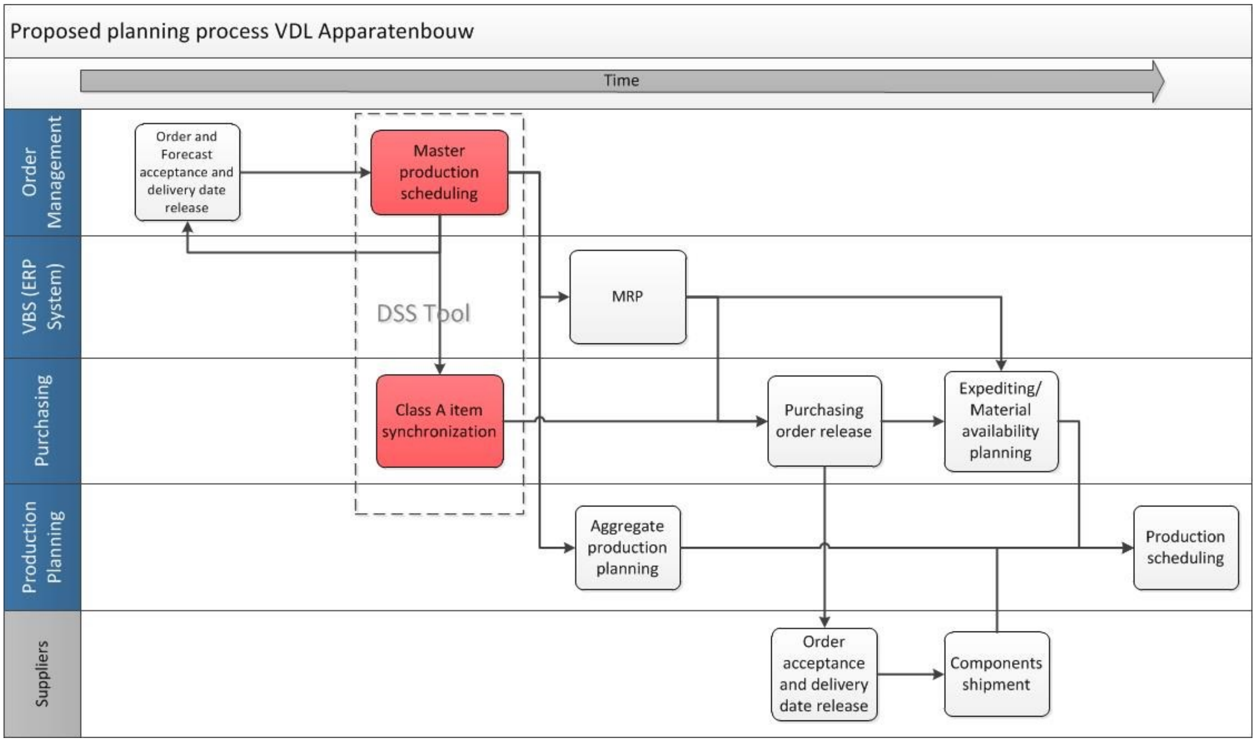


Figure 23 Swim-lane diagram of proposed planning process VDL A

Compared to the current planning process, two changes can be recognized. For both of these added planning functions it is discussed how they should be executed in practice and how they relate to the other planning functions in place.

Master production scheduling

In this planning step, a feasible MPS is constructed based on forecasts, customer orders, material inventories and outstanding purchasing orders using the DS tool as explained in section 5.3. The tool translates material availability and customer orders and forecasts into a feasible MPS. If (forecasted) demand cannot be met, the tool identifies bottleneck materials that restrict the potential output.

Because of the time-scope of this planning step, the only available actions at this stage are short term solutions such as expediting materials from suppliers or working overtime in production in case the sales plans are infeasible. If these options are available, they can be entered into the tool to generate a new plan based on the extra assembly capacity due to overtime or shorter lead times due to material expediting. The tool will then generate a new feasible production plan with the new settings. This also works the other way around, if certain materials have supply issues, the (temporary) new lead times should be entered to evaluate the effect on the production planning. The tool allows calculations for both situations.

The master production scheduling with the DS tool, should be done by the order managers that are responsible for the project. Material availability issues that are discovered during master production scheduling, should be communicated immediately with the responsible purchasers to identify the possible solutions. If materials cannot be expedited, the orders should not be released.

Class A material synchronization

After a definitive feasible MPS is constructed, the tool makes suggestions for purchasing order releases. Using a feasible MPS at this stage ensures that all purchasing orders can be met in time with the agreements that are in place. Currently, it is not possible to manage all material purchasing orders using the new SCOP method, since it has to be calculated outside of the ERP system in MS Excel and the results have to be inserted in the ERP system manually. However, by means of an ABC analysis, critical materials can be determined (Silver et al., 1998). To classify the different materials, characteristics such as price, lead times and handling difficulties can be used to determine which materials benefit the most from a more efficient approach. As can be seen in figure 29 in appendix H, 80% of the material value in the BOM originates from 22% of the materials. The class A, consists of this 22% of materials.

The purchasing orders generated by the tool for the "A-class" materials should be entered as firm orders into the ERP system. For the B and C class items it is suggested to use the standard MRP logic in the ERP system to generate purchasing orders. Figure 22 shows a screenshot of purchasing order releases for class A materials generated by the tool.

As with the master production scheduling, close collaboration is required between order management and the purchasers to ensure that both the material and order planning are properly aligned.

Order promising

Finally, the DS tool allows a quick feasibility check for customer order requests to support order promising and delivery date releases towards customers following the procedure described in section 3.6. By adding customer orders to the MPS, their earliest feasible delivery dates can be determined and communicated towards customers. Since all products only have one customer associated with them, there is no need for an allocation procedure of (forecasted) demand amongst different customers.

6. Conclusion and recommendations

This report is concluded with a reflection on the findings from the research project, the solution design and recommendations for VDL A. This chapter starts with the answers to the research questions which were formulated in the problem description. Secondly, recommendations for VDL A resulting from the analysis are discussed. Finally, a reflection on the scientific contribution and relevance of this research project is discussed and opportunities for further research are identified.

6.1 Answering research questions

In order to answer the main research question, the sub-questions were answered separately first.

1. ***What are the characteristics of the environment in which VDL Apparatenbouw operates and how do these characteristics affect their operations?***

   The operational environment of VDL A is characterized by a high dependency on suppliers and purchased materials which often have long lead times. Operations are impacted by both supply and demand uncertainty. This requires VDL A to place material buffers to protect their production from material shortages. The combination of short customer lead times, long material lead times, complex BOM structures and component commonality, make it challenging to anticipate on material demand efficiently. In the past, this has led to high inventories, while the desired customer service was not always achieved.

2. ***How does VDL Apparatenbouw currently manage their supply chain planning and operational control and how does this relate to the problems identified?***

   VDL Apparatenbouw uses the MRP logic embedded in their ERP system to translate planned customer orders and forecasts into material requirements. MRP has several shortcomings regarding the absence of material availability constraints and material synchronization as discussed in section 2.2.3. Because of VDL A’s high dependency on purchased materials, these issues have a large impact on the performance of VDL A. Infeasible production plans result in frequent rescheduling of orders and the lack of material synchronization results in higher inventories than required. Additionally, it was discovered that decision making on both a tactical and a strategic planning level is not aligned properly, resulting in inefficient operations.

3. ***How can VDL Apparatenbouw improve its operational control and material planning such that inventory investments are reduced and high customer service levels are realized?***
    a. ***Which planning approaches and concepts from academic literature can be applied to improve their current supply chain planning?***
    On an operational level, a new SCOP method is suggested to release feasible production orders and to synchronize the planning of "class A" materials. The model behind the SCOP method is largely based on the Synchronized Base Stock model introduced by de Kok & Fransoo (2003). This SCOP method overcomes the identified shortcomings of MRP. Their model reduces inventory investments by synchronizing material arrivals and reduces rescheduling by applying operational constraints on the planning of production orders.

    Additionally, qualitative supply chain planning concepts as S&OP and hierarchical planning provide valuable insights in the alignment and structuring of tactical and strategic decision making. Since the focus of this project has been on operational planning, these concepts were not explicitly addressed in the solution design, but they are taken along in the recommendations for VDL A.

    b. ***How do these approaches fit within their operations?***
    To apply the new SCOP method in the planning process of VDL A, the model was implemented in a decision support tool that can be used during master production scheduling. Besides generating feasible production plans, the tool also suggests synchronized purchasing orders for critical materials. In section 5.4, an extensive discussion is provided on the position of the tool in the operational planning process at VDL A.

4. ***How can VDL Apparatenbouw implement these improvements****?*
It is suggested that the operational planning process described in 5.4 is implemented. The synchronization of material purchasing orders should be done in close cooperation with master production scheduling to ensure the alignment between the production and material plans. Therefore, it is suggested that both purchasing and order management apply the tool collaboratively in a weekly planning meeting.

How can VDL Apparatenbouw improve their supply chain planning such that their inventories are reduced, while a more stable planning and a high service level are achieved?

To improve the current planning and control at VDL Apparatenbouw, the operational planning process is extended with new planning functionality. By structurally including the new SCOP method in operational planning at VDL A, both the planning instability and material inventories can be reduced. To implement the SCOP method, a planning tool was developed that generates feasible master production schedules to reduce rescheduling. Additionally, the tool suggests synchronized purchasing orders that result in lower inventories as shown in section 5.2.

Planning more deliberately and cooperatively on a tactical level is expected to improve the inventory efficiency and planning stability as well. The supply chain planning matrix by Fleischmann et al. (2015) can be used as a starting point to structure and position the required planning functionality. We did not extensively address the application in the solution design, but it is recommended that the opportunities are explored in other projects in the future.

6.2 Recommendations to VDL Apparatenbouw

- *Implement the new planning tool in the operational order and material planning process.* Including the tool in the operational planning process will make sure that all released orders are material feasible such that a more stable planning can be achieved. Simultaneously, it generates smarter purchasing orders to reduce material inventories.
- *Use insights from S&OP and hierarchical planning to structurally integrate and position tactical and strategic planning functionality.* The issues regarding the misalignment of objectives and the inefficient tactical parameters can be addressed by investigating the organizational aspects and responsibilities between different departments. An extensive analysis of these issues is required to provide conclusive and specific improvements. Therefore it is recommended that VDL A initiates a project that aims to structurally solve these issues.
- *Use available data in ERP.* The ERP system at VDL A contains large amounts of data, which can be used to support decision making. Decisions on tactical parameters such as safety stocks can be supported by evaluating forecast errors or supplier performance from the past. Currently, these possibilities are not used to their full potential, leaving important opportunities for improvement untouched.
- *Explore the possibilities for embedded synchronization and feasibility constraints in material requirements planning in the ERP system.* Because of the high efforts required to process all synchronized purchasing orders manually, only critical "class A materials" can be synchronized with the tool. It is recommended to explore the possibilities of applying the synchronization constraints to the purchasing orders generated by the ERP system.

6.3 Contributions to scientific research

- We linked the specific characteristics of the assemble-to-order situation at VDL A to generally applicable supply chain planning concepts.
- We showed the superiority of the SBS model from de Kok & Fransoo (2003) and de Kok et al. (2005) over MRP as a SCOP method in a case study in the ATO environment of VDL A, which helps to build evidence of its applicability. The analysis was conducted both with fictional demand data and an example of real-life historical demand.
- The benefits of SBS over MRP are explored under both safety stock buffering and safety time buffering.
- We extended the original SBS model by adding lot-sizing for purchased materials and using a different allocation mechanism that allows for zero safety stock for final products. Since lot-sizing restrictions are a common requirement for purchased materials, this extension contributes to demonstrating the broad practical applications of the SBS model.
- The research project contributes to finding methods that explain inventory performance in ATO environments by means of discrete event simulation.

6.4 Limitations of the study

- The lot-sizing extension of the model is only explored for the two-echelon structure present at VDL A, with lot sizes applying only to purchased materials. The applicability of lot-sizes between multiple echelons is not explored.
- The quantitative performance evaluation of the SBS model is limited to fictional demand processes and an example of historical demand at VDL A. An extensive analysis of different demand distributions was not considered in this study.
- The causes for material shortages in practice, such as quality issues, supplier failures, limited supplier capacity etc, were not included in the simulation.
- The solution design has focused on operational planning. Decisions on tactical and strategic planning levels have a high impact on operational performance as well, but these were left out of scope for the solution design.
- Organizational change theory was not applied to support the actual implementation of the proposed improvement design. This should be considered by management at implementation to ensure that the solution design is implemented as intended.
- The SBS model as it is, cannot be used to truly optimize parameterization of the system. It does allow the evaluation of different parameter configurations on KPI's. However, truly optimizing a system with many different items is difficult because of the required computational effort.

6.5 Opportunities for further research

- Evaluation of the quantitative performance of the SBS model under different demand variability configurations can be valuable in order to explore its applicability in different environments and to explore its superiority over MRP logic under different circumstances. This also goes for different BOM structures, material prices and lead time configurations.
- Exploring the impact of the lot-sizing extension in multi-echelon networks.
- Capturing operational dynamics like infeasible production plans, stochastic lead times and unexpected material shortages in a simulation study might show more interesting results on the differences between MRP and SBS as SCOP methods.
- Even though the SBS model has the ability to evaluate parameter settings, it is still not fit to support true optimization of inventory levels in large ATO systems. Therefore the need for analytical models that explain inventory performance in ATO systems remains.

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Appendix

Appendix A

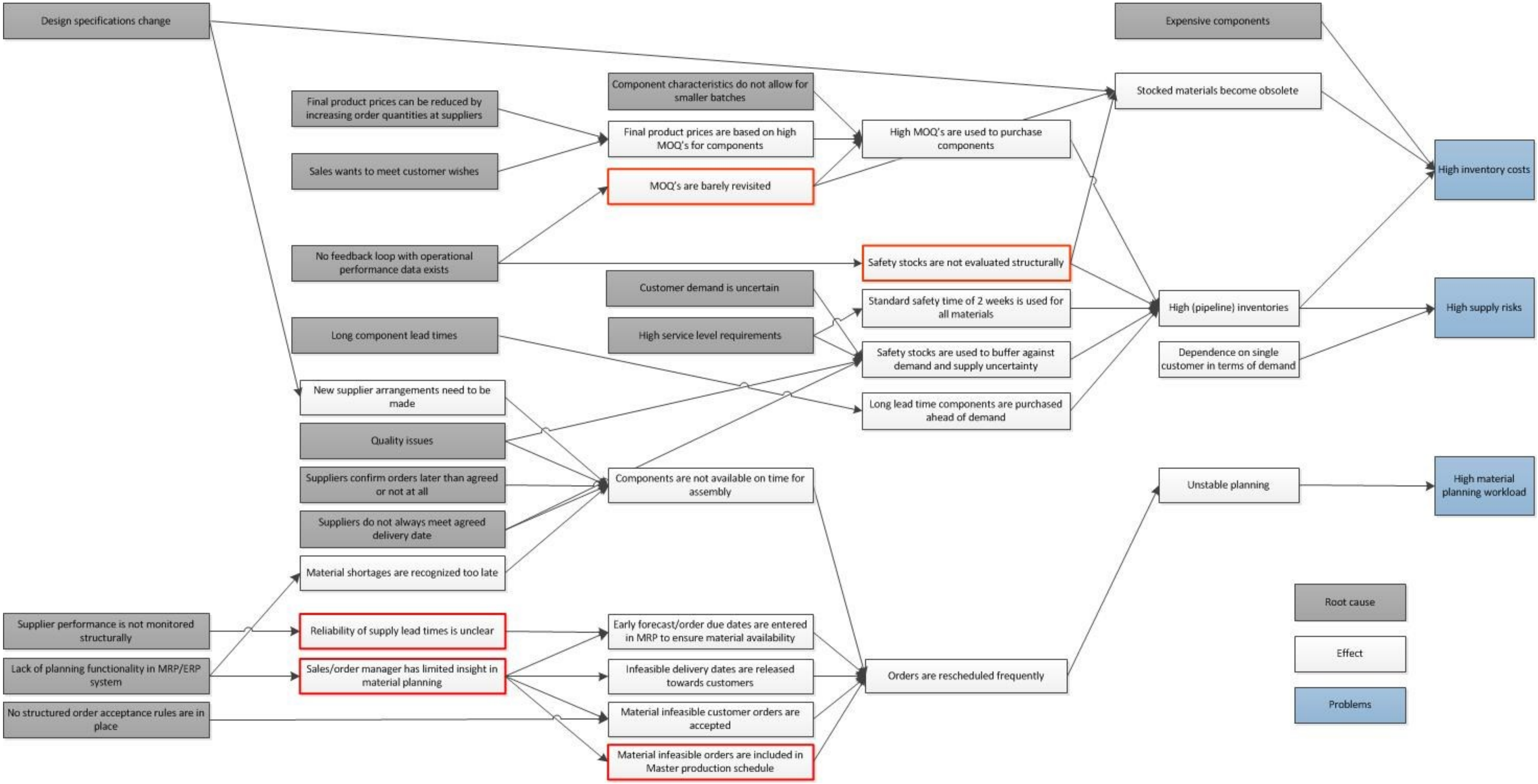


Figure 24 Cause and effect diagram for the identified problems at VDL A

Appendix B

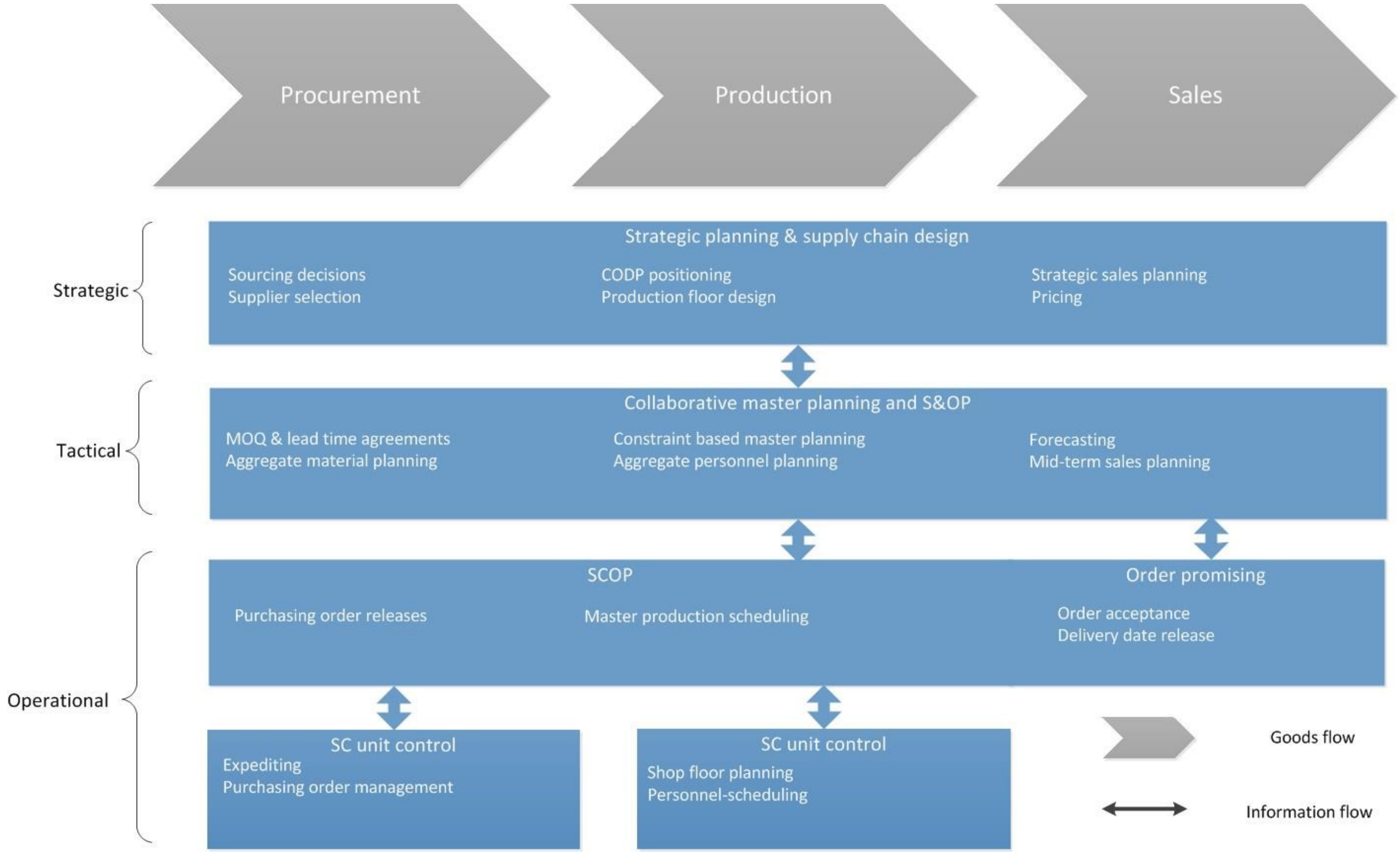


Figure 25 Proposed new planning process for VDL A

Appendix C

Functional attributes		
	Attributes	**Contents**
Procurement type	Number and type of products procured	Many different specific materials
	Sourcing type	Most valuable materials sourced at several suppliers
	Supplier flexibility	Moderately flexible
	Supplier lead time and reliability	Short & long, unreliable
	Materials' life cycle	Months/years
Production type	Organization of production process	Job-shop & cellular
	Repetition of operations	Small, customer specific batches
	Changeover characteristics	Learning curve of assembly personnel
	Bottlenecks in production	No structural bottlenecks, material constrained
	Working time flexibility	High
Distribution type	Distribution structure	Direct shipment to customer
	Pattern of delivery	Dynamic
	Loading restrictions	None
	Deployment of transportation means	Third party logistic service provider
Sales type	Customer relations	Close
	Availability of future demands	Forecasts and orders
	Demand curve	Dynamic, low volumes
	Products life cycle	Years
	Number of product types	Several to dozens of products per customer
	Degree of customization	High
	BOM	Convergent, complex
	Portion of service operations	None
Structural attributes		
Topography of supply chain	Network structure	Convergent
	Degree of globalization	Several countries
	Location of decoupling points	Assemble-to-order
	Major constraints	Material
Integration and coordination	Legal position	Inter-organizational
	Balance of power	Customers and suppliers
	Direction of coordination	Horizontal
	Type of information exchanged	Forecasts

Table 7 Supply chain attributes that characterize VDL A's supply chain planning

Appendix D

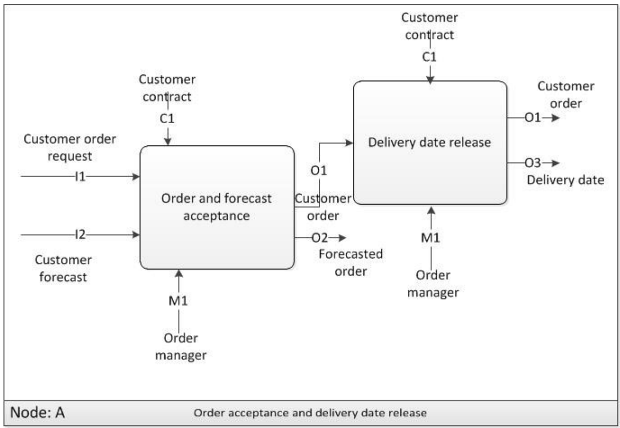
Code	Input variable
I1	Customer order request
I2	Customer forecast
I3	Customer order
I4	Forecast order
I5	Master production schedule
I6	Inventory levels
I7	Open Purchasing orders
I8	MRP purchasing advice
I9	Confirmed delivery dates
I10	Purchasing orders

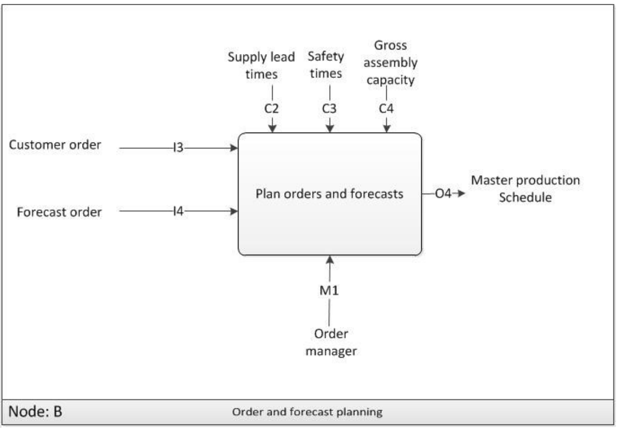
Code	Output variable
O1	Customer order
O2	Forecasted order
O3	Delivery date
O4	Master production schedule
O5	MRP purchasing advice
O6	Purchasing orders
O7	Aggregate production planning
O8	Detailed production schedule
O9	Order arrival dates
O10	Confirmed delivery dates

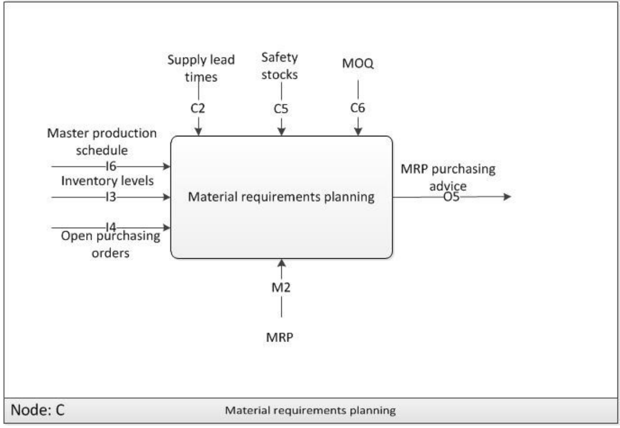
Code	Control variable
C1	Customer contract
C2	Supply lead times
C3	Safety times
C4	Gross assembly capacity
C5	Safety stocks
C6	MOQ
C7	Detailed assembly capacity
C8	Supplier control variables

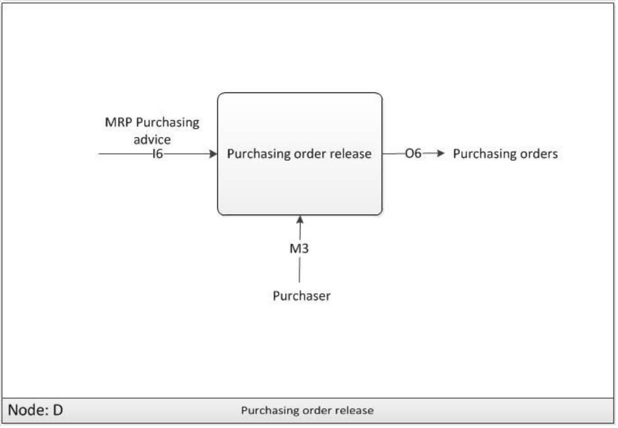
Code	Mechanism
M1	Order manager
M2	MRP
M3	Purchaser
M4	Production planner

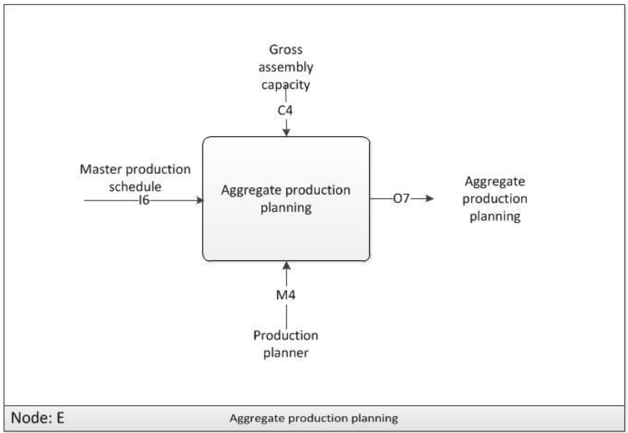
M5 Supplier order management

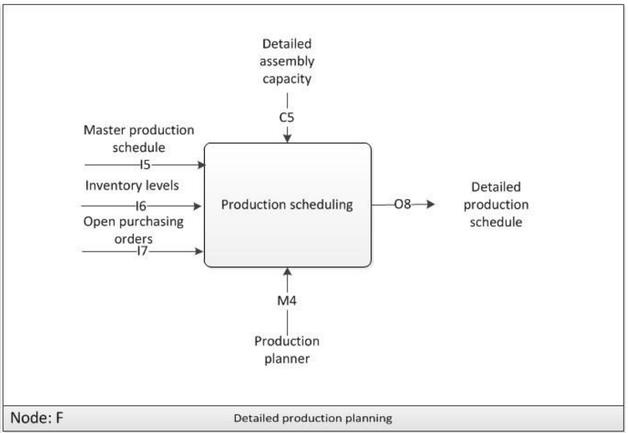


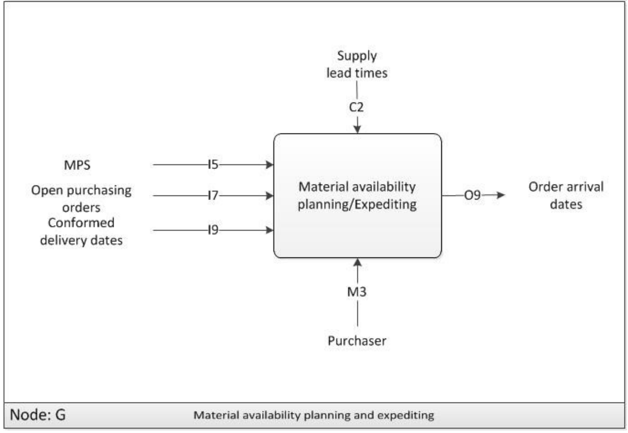


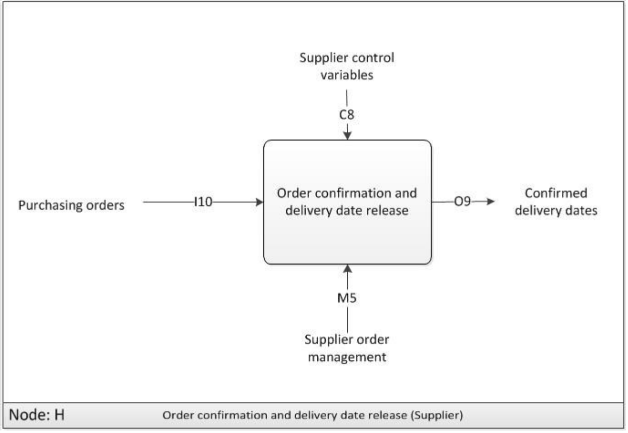





Gross assembly capacity
C4
Master production schedule
I6
Aggregate production planning
O7
Aggregate production planning
M4
Production planner
Node: E
Aggregate production planning


Detailed assembly capacity
C5
Master production schedule
I5
Inventory levels
I6
Open purchasing orders
I7
Production scheduling
O8
Detailed production schedule
M4
Production planner
Node: F
Detailed production planning


Supply lead times
C2
MPS
I5
Open purchasing orders
I7
Conformed delivery dates
I9
Material availability planning/Expediting
O9
Order arrival dates
M3
Purchaser
Node: G
Material availability planning and expediting


Supplier control variables
C8
Purchasing orders
I10
Order confirmation and delivery date release
O9
Confirmed delivery dates
M5
Supplier order management
Node: H
Order confirmation and delivery date release (Supplier)

Appendix E

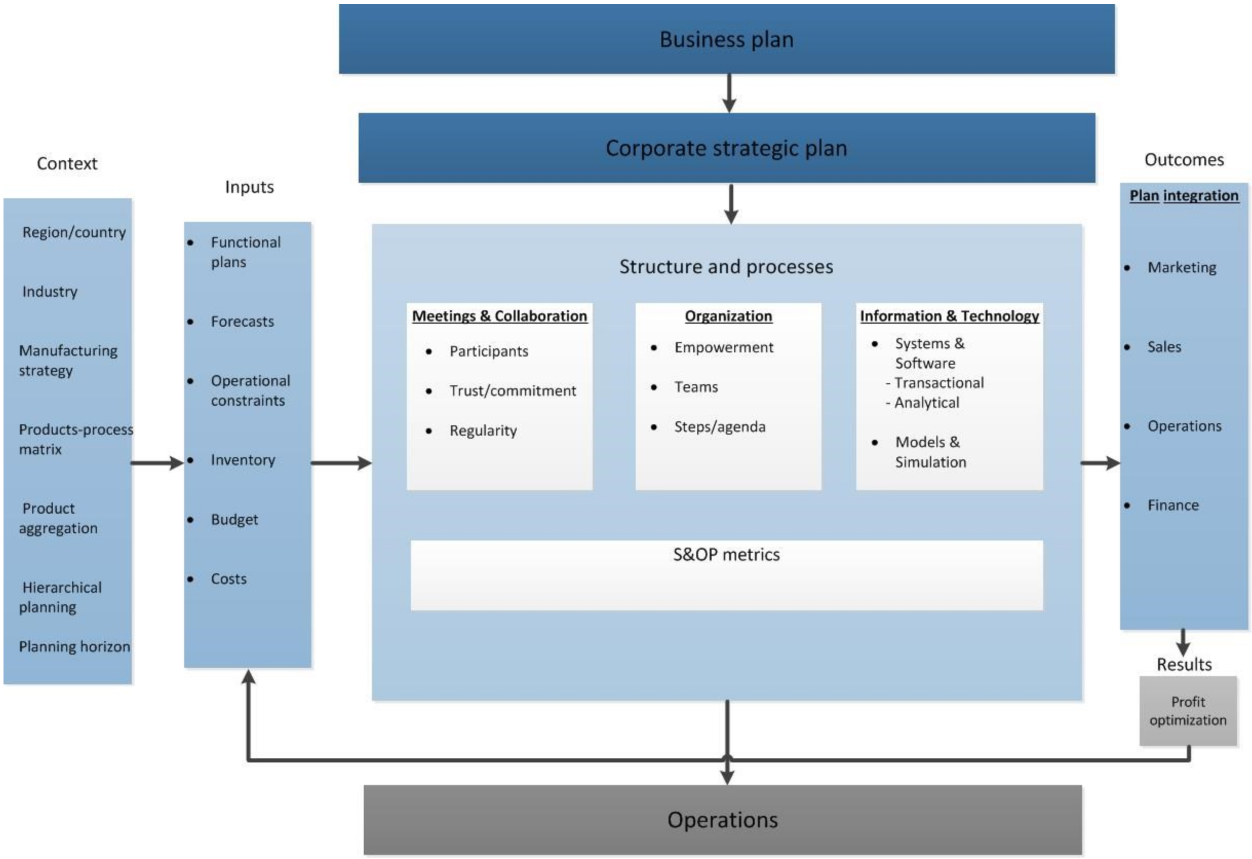


Figure 26 Sales & Operations planning

Appendix F

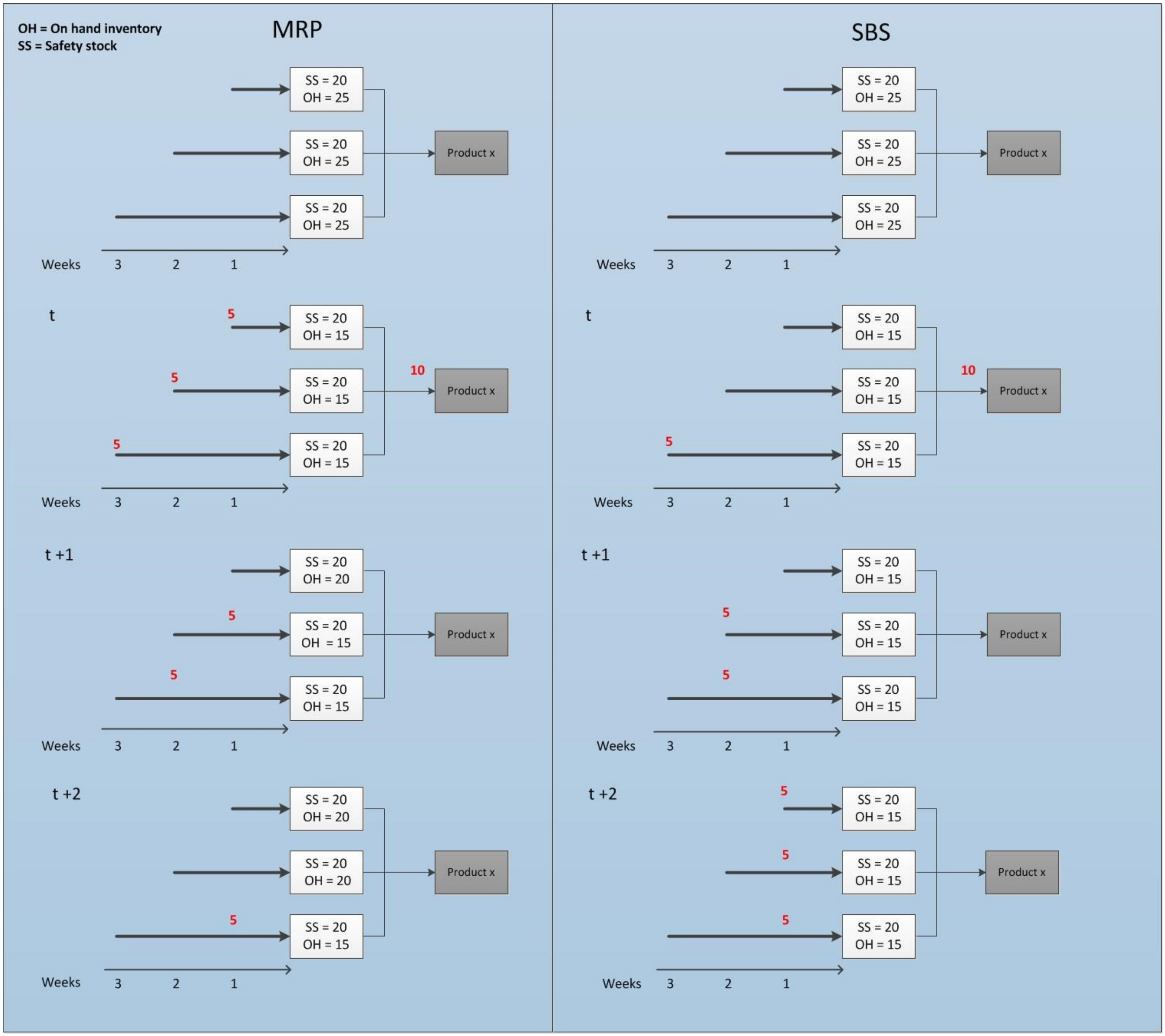
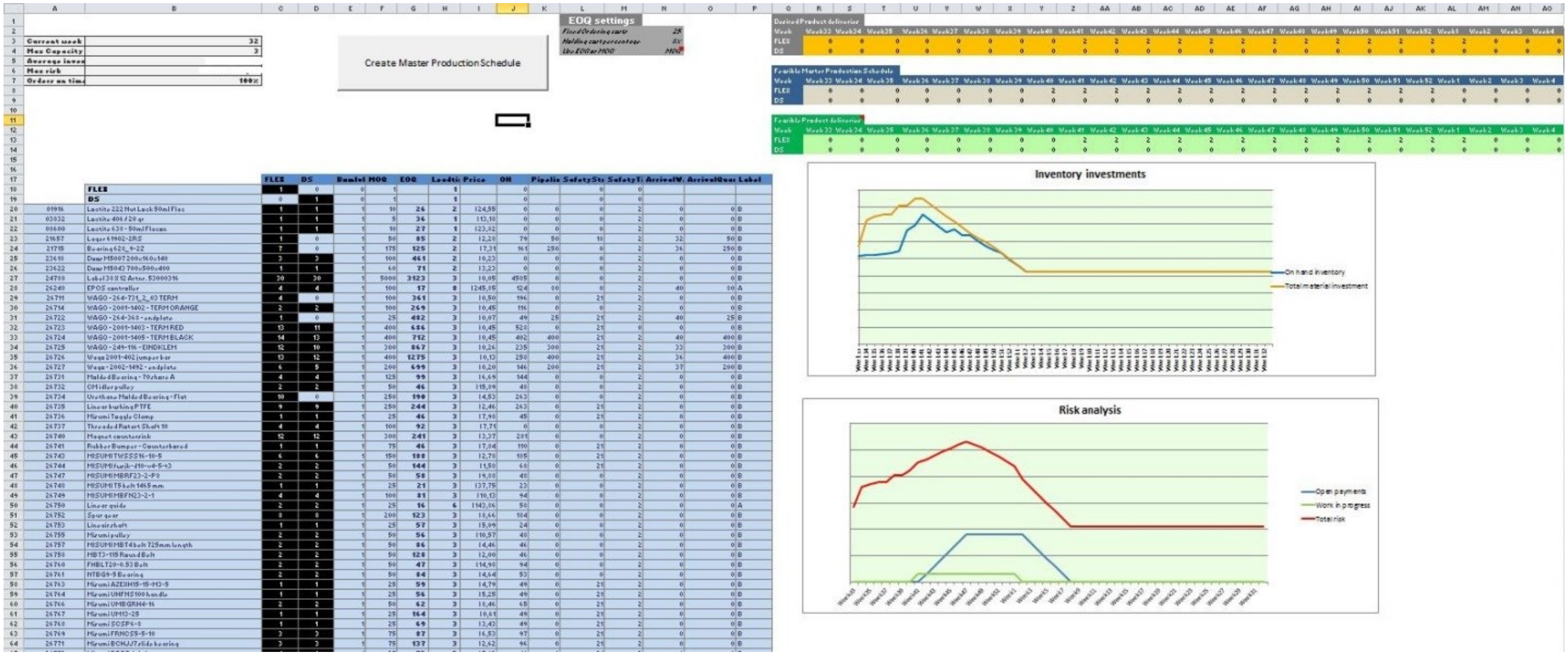


Figure 27 Example of order release behavior of SBS vs MRP

As can be seen in figure 27 the MRP model generates purchasing orders earlier than required. In period t+2, the stocks of the first two components are already replenished by MRP, while the output potential in terms of final product x is still 15. SBS restricts the purchasing orders by evaluating the output potential in t+Leadtime, such that the system never orders more than required. In period t+2 both models have the same output potential in terms of product x, while the SBS model has less materials in inventory. Period t + 3, will be the first period in which any of the two models has replenished its safety buffer completely.

Appendix G



Current week	32
Max Capacity	3
Average inves	
Max risk	
Orders on tim	100%

EOQ settings

Fixed Ordering costs	25
Holding cost percentage	8%
Use EOQ or MOQ	MOQ

Desired Product deliveries

Week	Week33	Week34	Week35	Week36	Week37	Week38	Week39	Week40	Week41	Week42	Week43	Week44	Week45	Week46	Week47	Week48	Week49	Week50	Week51	Week52	Week1	Week2	Week3	Week4
FLEX	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0
DS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Feasible Master Production Schedule

Week	Week33	Week34	Week35	Week36	Week37	Week38	Week39	Week40	Week41	Week42	Week43	Week44	Week45	Week46	Week47	Week48	Week49	Week50	Week51	Week52	Week1	Week2	Week3	Week4
FLEX	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0	0
DS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Feasible Product deliveries

Week	Week33	Week34	Week35	Week36	Week37	Week38	Week39	Week40	Week41	Week42	Week43	Week44	Week45	Week46	Week47	Week48	Week49	Week50	Week51	Week52	Week1	Week2	Week3	Week4
FLEX	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0
DS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

		FLEX	DS	Bomlvl	MOQ	EOQ	Leadti	Price	OH	Pipelin	SafetySt	SafetyTi	ArrivalW	ArrivalQua	Label
	FLEX	1	0	0	1		1		0		0	0			
	DS	0	1	0	1		1		0		0	0			
01916	Loctite 222 Nut Lock 50ml Flac	1	1	1	10	26	2	124,55	0	0	0	2	0	0	B
03032	Loctite 406 / 20 gr	1	1	1	5	36	1	113,10	0	0	0	2	0	0	B
08600	Loctite 638 - 50ml Flacon	1	1	1	10	27	1	123,02	0	0	0	2	0	0	B
21657	Lager 61902-2RS	1	0	1	50	85	2	12,20	79	50	10	2	32	50	B
21718	Bearing 628_9-2Z	7	0	1	175	125	2	17,31	161	250	0	2	36	250	B
23618	Door M5007 200x160x140	3	3	1	100	461	2	10,23	0	0	0	2	0	0	B
23622	Door M5043 700x500x400	1	1	1	60	71	2	13,23	0	0	0	2	0	0	B
24708	Label 38 X 12 Artnr. 53000316	20	20	1	5000	3123	3	10,05	4505	0	0	2	0	0	B
26240	EPOS controller	4	4	1	100	17	8	1245,35	124	80	0	2	40	80	A
26711	WAGO - 264-731_2_03 TERM	4	0	1	100	361	3	10,50	196	0	21	2	0	0	B
26714	WAGO - 2001-1402 - TERM ORANGE	2	2	1	100	269	3	10,45	116	0	0	2	0	0	B
26722	WAGO - 264-368 - endplate	1	0	1	25	482	3	10,07	49	25	21	2	40	25	B
26723	WAGO - 2001-1403 - TERM RED	13	11	1	400	686	3	10,45	528	0	21	0	0	0	B
26724	WAGO - 2001-1405 - TERM BLACK	14	13	1	400	712	3	10,45	402	400	21	2	40	400	B
26725	WAGO - 249-116 - EINDKLEM	12	10	1	300	867	3	10,26	235	300	21	2	33	300	B
26726	Wago 2001-402 jumper bar	13	12	1	400	1275	3	10,13	258	400	21	2	36	400	B
26727	Wago - 2002-1492 - endplate	6	5	1	200	699	3	10,20	146	200	21	2	37	200	B
26731	Molded Bearing - 70shore A	4	4	1	125	99	3	16,69	144	0	0	2	0	0	B
26732	CM idler pulley	2	2	1	50	46	3	115,89	48	0	0	2	0	0	B
26734	Urethane Molded Bearing - Flat	10	0	1	250	190	3	14,53	263	0	0	2	0	0	B
26735	Linear bushing PTFE	9	9	1	250	244	3	12,46	263	0	21	2	0	0	B
26736	Misumi Toggle Clamp	1	1	1	25	46	3	17,90	45	0	21	2	0	0	B
26737	Threaded Rotort Shaft 10	4	4	1	100	92	3	17,71	0	0	0	2	0	0	B
26740	Magnet countersink	12	12	1	300	241	3	13,37	281	0	0	2	0	0	B
26741	Rubber Bumper - Counterbored	1	1	1	75	46	3	17,04	110	0	21	2	0	0	B
26743	MISUMI TWSSS16-10-5	6	6	1	150	188	3	12,78	105	0	21	2	0	0	B
26744	MISUMI furik-d10-v4-5-t3	2	2	1	50	144	3	11,58	68	0	21	2	0	0	B
26747	MISUMI MBRF23-2-P8	2	2	1	50	58	3	19,88	48	0	0	2	0	0	B
26748	MISUMI T5 bolt 1465 mm	1	1	1	25	21	3	137,75	23	0	0	2	0	0	B
26749	MISUMI MBFN23-2-1	4	4	1	100	81	3	110,13	94	0	0	2	0	0	B
26750	Linear guide	2	2	1	25	16	6	1143,86	58	0	0	2	0	0	A
26752	Spur gear	8	8	1	200	123	3	18,66	184	0	0	2	0	0	B
26753	Linear shaft	1	1	1	25	57	3	15,09	24	0	0	2	0	0	B
26755	Misumi pulley	2	2	1	50	56	3	110,57	48	0	0	2	0	0	B
26757	MISUMI MBT4 bolt 725mm length	2	2	1	50	86	3	14,46	46	0	0	2	0	0	B
26758	MBT3-115 Round Bolt	2	2	1	50	128	3	12,00	46	0	0	2	0	0	B
26760	FHBLT20-0.53 Bolt	2	2	1	50	47	3	114,98	94	0	0	2	0	0	B
26761	NTBG9-5 Bearing	2	2	1	50	84	3	14,64	53	0	0	2	0	0	B
26763	Misumi AZEXH15-15-M3-5	1	1	1	25	59	3	14,79	49	0	21	2	0	0	B
26764	Misumi UMFNS100 handle	1	1	1	25	56	3	15,25	49	0	21	2	0	0	B
26766	Misumi UMBGRM4-16	2	2	1	50	62	3	10,46	65	0	21	2	0	0	B
26767	Misumi UM13-25	1	1	1	25	164	3	10,61	49	0	21	2	0	0	B
26768	Misumi SOSP6-8	1	1	1	25	69	3	13,42	49	0	21	2	0	0	B
26769	Misumi FRNOS5-5-10	3	3	1	75	87	3	16,53	97	0	21	2	0	0	B
26771	Misumi BCHJJ7 slide bearing	3	3	1	75	137	3	12,62	96	0	21	2	0	0	B

Figure 28 Screenshot of interface of DS tool

Appendix H

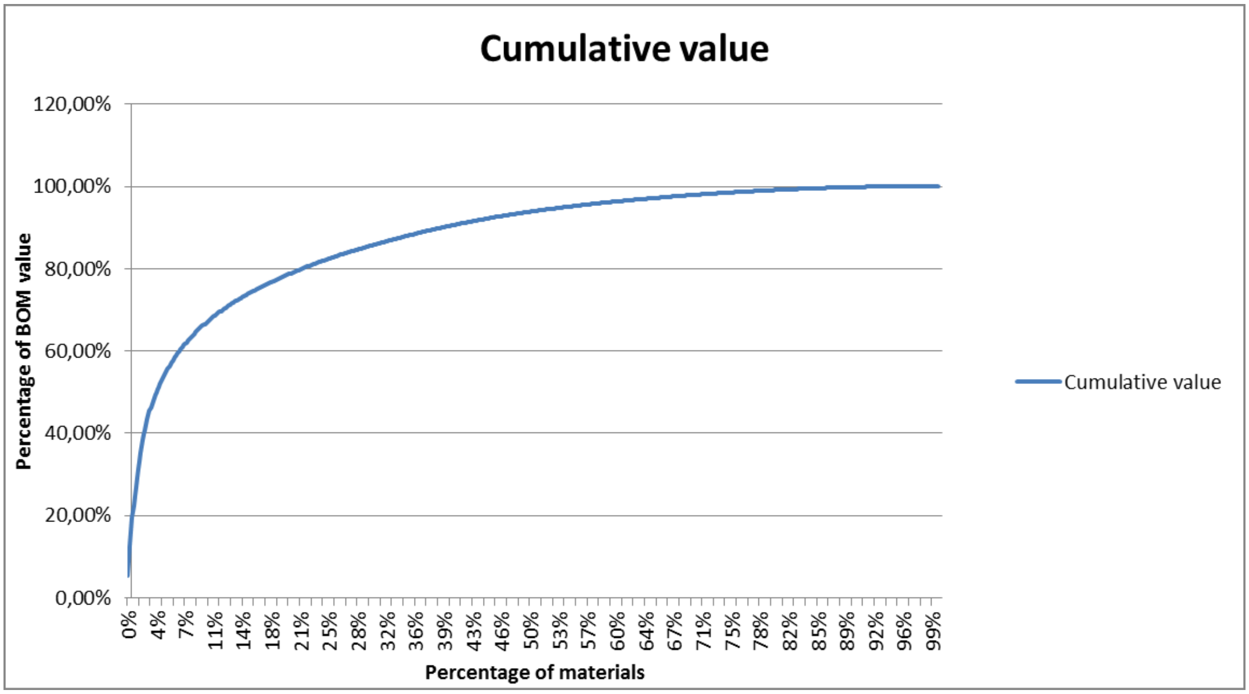


Figure 29 Cumulative BOM value as percentage of included materials