MASTER

Synchronization of supply chain planning processes
design of a production wheel at an outsourched company

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Synchronization of supply chain planning processes: Design of a production wheel at an outsourced company

by

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Abstract
The division of COMPANY faces high and uncontrollable stocks of widgets. To solve this problem, this Master’s thesis project proposes a redesign of the production strategy at CONTRACTOR. For each of the packaging lines a production wheel is developed to align the order plan of COMPANY with the production plan of CONTRACTOR. These wheels can be used as a communication tool between both companies about the sequence and timing of production. In addition the new production strategy is based on carefully chosen lot sizes, which result in significant cost savings for COMPANY on cycle and safety stocks. Due to the synchronization of the supply chain planning processes, the material consumption of widgets becomes more predictable and therefore the stocks more controlled. Finally, some organizational challenges remain to successfully implement the production wheel.
Management Summary

The main goal of this thesis is to design an operational planning and control policy that synchronizes the supply chain planning processes of CONTRACTOR and COMPANY. CONTRACTOR is a contract packager of COMPANY. Currently, the planning processes of both companies are not aligned. This study concludes that the production wheel concept can be used as a tool to communicate the sequence and timing of production in order to align the supply chain planning processes of both companies. In addition, this study shows that adjusted lot sizes can result in significant inventory savings on cycle and safety stocks of finished goods. This management summary briefly explains what is studied in this thesis.

Problem description

COMPANY orders both medical devices and widgets at SUPPLIER and after production these are shipped to CONTRACTOR, which is a contract packager of COMPANY. At CONTRACTOR both widgets and medical devices are packaged in boxes with country specific labels for the market. The packaging lines are fully dedicated to the packaging process of the widgets. Finally, the products are shipped to sales affiliates in the countries. All supply chain planning activities are organized by COMPANY, except for the packaging process, which is scheduled by CONTRACTOR. As a result, the packaging process of CONTRACTOR is not aligned with the ordering process of COMPANY. The lack of alignment between the supply chain planning activities of CONTRACTOR and COMPANY results in unbalanced inventories of widgets. The new operational planning and control policy should align the supply chain planning processes of both companies and have to make them more dependent. The following research question is developed:

What is the impact of the production wheel concept on the inventory levels of widgets and on decisions about how to steer CONTRACTOR?

Problem analysis

An analysis has been conducted to get insights in the current scheduling strategy of CONTRACTOR. Each month COMPANY sends a list of Purchase Orders (POs) for the next month to CONTRACTOR. These requested POs are used to schedule the packaging lines. However the requested delivery dates of POs are not equally distributed across the month, what would be relevant for CONTRACTOR to balance the production capacity and to avoid downtime. Currently, the production capacity is balanced by preproduction which results in high and unbalanced inventories. Since there is a high demand peak of POs at the beginning of the month, CONTRACTOR uses free capacity at the end of the month to start production for POs of the next month. It is found that the POs are finished approximately 6 days before the requested delivery date. Furthermore, the data analysis shows that the arrival process of widgets has fluctuations and is not smoothed over time. This uncontrolled arrival process impacts the unbalanced inventory levels of widgets at CONTRACTOR.

Design

During the project for each of the three packaging lines a production wheel has been designed. A production wheel is characterized by a fixed setup minimizing production sequence and a fixed cycle length. The cycle contains free time to deal with uncertainties in the demand and production environment. An advantage of the production wheel concept is that it improves the communication between CONTRACTOR and COMPANY about the timing and sequence of production. Moreover, the
fixed production sequence gives CONTRACTOR the opportunity to improve the setups since these become repetitive for the operators.

The redesign problem is decomposed in three levels: strategic, tactical and operational. At the strategic level decisions about the capacity are made. During the analysis it is found that CONTRACTOR has to increase the number of crews to fulfill future demand, since the demand exceeds the current available production capacity. Furthermore, the characteristics of the demand and production environment are determined.

Three tactical parameters are used to design the production wheels, namely lot sizes, allocation and sequence. The Economic Production Quantity is used to determine the optimal lot sizes for all products which have to be produced for next year. Afterwards, the optimal lot sizes are adjusted to supply frequencies and full pallet sizes. These adjustments are made based on interviews with CONTRACTOR and COMPANY. This has resulted in a list with replenishment frequencies which can be used in the production wheels. Next to that, allocation rules are developed to come up with a setup minimizing production sequence. Since there are three packaging lines and also three types of product families, each product family is dedicated to a specific packaging line. During the allocation process, blocks with doubles (i.e. boxes with two vials of 50 widgets) are created since setup times of those products are significantly higher compared to other setups. Afterwards, the third tactical parameter of the production is determined: the production sequence. A local search heuristic is developed to create a feasible production sequence. During the steps of the local search heuristic the production capacity (i.e. number of POs produced per week and number of vials produced per week) is balanced over time. Based on new lot sizes and therefore new replenishment frequencies, safety stock levels are adapted. The calculations for the demand during lead time are based on forecast errors and variability of the lead time. Both elements are not present in current safety stock calculations.

At an operational level, rules have to be created to deal with exceptions of the of the production sequence given by the wheel. These rules are related to changes in demand and production sequence. Finally, the production wheel can only work if both companies stick to the made agreements. This means that the fixed production sequence of the wheel has to be accepted. Free time is included in the production wheel to deal with small changes in the order quantities. However, it is not allowed to exceed the predefined cycle length and therefore changes in the order quantities have to be discussed with both parties. Since not all products have a replenishment frequency of one cycle length, it is always possible to skip production if there is no demand.

Results
The developed production wheels are used to assess the impact of the new proposed lot sizes on three types of inventories, namely widgets, work in process and finished goods. One of the goals of the redesign is to level the production capacity of CONTRACTOR. Two indicators are used to measure this leveled production: the number of POs produced per week and the number of vials produced per week. The results show that both indicators are balanced across the month. Furthermore, the consumptions of the largest bulk components, which are vials with 50 widgets, are leveled over time. As a result the material outflow of CONTRACTOR is smoothed across the month. In addition, the results show that all packaging lines have sufficient free capacity during the cycle to deal with uncertainties in demand or
production environment. This free capacity is necessary since the proposed lot sizes are based on deterministic demand. The production wheel also proposes that preproduction can be avoided in the future, since the order plan of COMPANY is aligned with the production plan of CONTRACTOR. This means that the delivery date of POs is closer to the production date. The impact of the new production wheels on the finished goods inventory levels is compared with the old replenishment strategy, showing that COMPANY could save significant costs on cycle and safety stocks. This inventory reduction is achieved by decreasing lot sizes and higher replenishment frequencies, resulting in the potential benefits for COMPANY.

Finally, rules and concepts are defined to steer the production wheel. Since lot sizes are a tactical parameter, adjustments should take place with a normative level. Both parties have to stick to the predefined sequence. Revision of the production wheel takes place every three months, based on new information from the market and production environment. Furthermore, CONTRACTOR and COMPANY should have contact on a weekly basis in order to discuss issues regarding the production wheel.

**Conclusion and recommendations**

In general, it is found that new lot sizes can lead to significant savings on cycle and safety stocks of finished goods. Furthermore, the production wheel gives transparency in the production strategy of CONTRACTOR, which is important for an improvement in the communication between COMPANY and CONTRACTOR. Communication is essential to ensure that both companies benefit from the production wheel. Due to the production wheel, the supply chain planning activities of CONTRACTOR and COMPANY become more dependent and it is assumed that inventory levels of widgets become more balanced. Implementing the production wheel has to be performed step by step. First, it is essential that both companies understand the concept and that both companies are convinced that implementation is beneficial. Only with their support the implementation becomes a success.

The most important recommendation for COMPANY is to use the $P_2$ service measure in the future. Currently, the $P_1$ service measure is used to make the safety stock calculations and this measure is doubtful in situations with large order quantities. Besides, it is necessary to have a common understanding between the service which is calculated and what is measured. Furthermore, it is recommended to do further research in the synchronization of all other supply chain planning activities. The arrival frequencies of widgets and transportation frequencies of finished goods have to be aligned in order to benefit optimally of the new proposed lot sizes.
Preface
This report is the result of my Master’s thesis project which I conducted in partial fulfillment for the degree of Master in Operations Management and Logistics at Eindhoven University of Technology in the Netherlands. The past six months I have been working fulltime on this project at COMPANY. It was really a great experience for me. I would like to make use of this page to express my gratitude to a few people.

First of all, I would like to thank Ton de Kok for giving me the opportunity to do this project under his supervision. During my project you provided me with valuable insights about the topic. Despite having an extreme busy agenda, you always found the time to support me. As my second supervisor, I want to thank Nico Dellaert for his time and critical review of my work.

Secondly, I would like to express my sincere gratitude to my supervisors Achim Siegert-Wilcke and Frank Brokmann. Both provided me with constructive and valuable feedback and I learnt a lot from your experience in the field of logistics. Furthermore, I would like to thank all colleagues of the GSCM department for having me there.

By reaching the end of this project I have reached the end of my life as student too. I would like to thank my family and friends for their support and trust in me. Special thanks to my parents who always were there when I needed them. Furthermore, I want to thank my family and friends who took the time to visit me in Berlin. However, I did the sightseeing more than twenty times, those weekends were really great. Also thanks to ‘Naomi’ who always took the time to listen to my stories, complaints or jokes. You all made my student time a fantastic period.

Wilbert Schouten

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1 Introduction
This Master’s thesis is conducted at COMPANY and is the result of the Master Operations Management and Logistics at Eindhoven University of Technology (TU/e). It investigates the synchronization of supply chain planning processes of two independent companies.

The core businesses of COMPANY are medical device and associated widgets. Both products are packaged at a contract packager. Currently, the supply chain planning processes of both companies are not aligned. Both companies operate independent and as a result the inventory levels of widgets are not balanced. This study provides a redesign of the current packaging strategy in order to synchronize both supply chain planning processes.

Since this Master’s thesis project is conducted at the COMPANY, first a short introduction about the business is given. Next, a brief project description is provided and the business problem which is solved in this project is given. Finally, the structure of this report is given.

1.1 Context
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1.2 Project description
The market of medical care has moderately expanded since the beginning of this century, especially caused by the increasing United States of America market and demand for medical equipment. Depending on the type of health insurance and regulations of the local governments, patients receive reimbursements on certain types of medical device. Patients can substitute to another product if they don’t receive any type of reimbursement. If health insurance companies give no (or partial) reimbursements for the widgets, patients might decide to switch to another product.

The related division has the goal to reduce inventories and lead times in the supply chain processes in order to reduce working capital in the complete supply chain. So, from their perspective, inventories are too high and lead times are too long. Furthermore, the supply chain planning systems and processes of CONTRACTOR and COMPANY are not synchronized which results in unbalanced inventory levels of widgets. The following problem definition is developed based on above described project description:

Inventory levels of widgets supplied by SUPPLIER are unbalanced

In 2011 the average total inventory in the complete supply chain was on average XXX Days On Hand (DOH), where DOH is the ratio between the average numbers of days an item is held as inventory. An overview of the supply chain inventory levels of widgets is given in Figure 1.
This figure shows that the total supply chain inventory is approximately XXX weeks, which is equal to the target level of XXX DOH. The widgets are shipped from SUPPLIER to CONTRACTOR and this takes XXX weeks. Next, the widgets are on average XXX weeks in stock at CONTRACTOR. The widgets are packaged at CONTRACTOR and afterwards the Finished Goods (FG) are shipped to the local and/or regional Warehouses (WH) of COMPANY in the countries. The goal of the division is to bring the average total inventory of 2012 below XXX DOH by synchronizing the supply chain planning processes of CONTRACTOR and COMPANY.

1.3 Report structure

This chapter gave a general introduction about the problem. This information is important in order to understand the business where this project is conducted. The conducted research is based on the methodology of the regulative cycle (Aken, Berends, & van der Bij, 2007). This cycle gives the different research steps that are used during this project. The regulative cycle is also used to structure this report. Chapter 2 describes the current operational processes and the business processes that manage them and provides the problem definition. Next, the problem analysis and diagnosis step is described in Chapter 3. Thereafter, a theoretical framework is created in Chapter 4 which is used for the redesign. A redesign of the problem and the validation are shown in Chapter 5 and 6, respectively. The results of the case study are described in Chapter 7. Finally, the implementation and conclusions are given in Chapter 8 and 9.
2 Supply chain analysis

In this chapter the supply chain of the widgets is described. This analysis is based on the PCIO model of van Goor et al. (1996), which is an abbreviation for Process, Control, Information and Organization. Description of the current operational processes and the business processes that manage them is important to understand the business problem and the direction for the redesign. First, the basic structure and processes of the supply chain are described.

2.1 Process

Products of COMPANY consist of two different products: the medical device and the widgets. Both products are required.

2.1.1 Products

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2.1.2 Actors

A simplified version of the supply chain of the widgets is given in Figure 2. This figure gives an overview of the material flow for the widgets and the meters and shows the three parties involved in the supply chain, namely SUPPLIER, CONTRACTOR, COMPANY. Each of these actors has their own roles and responsibilities in the supply chain, which are explained in more detail in this section. As can be seen in Figure 2 the total throughput time from production at SUPPLIER to distribution to the local or/and regional Warehouses (WH) is on average XXX months. The total lead time from purchasing to consumption is approximately XXX months.

![Figure 2: The supply chain of widgets and related throughput times](image)

SUPPLIER

SUPPLIER is an Original Equipment Manufacturer (OEM) and produces the meters and widgets ordered by COMPANY. Other attributes of the medical device (e.g. lancets, wires and packaging materials) are produced by other manufacturers. The collaboration with SUPPLIER is an example of collaboration between COMPANY and a subcontractor in order to reduce costs, increase flexibility and delivery reliability, and meet the global demand in terms of quality, safety and environmental regulations (COMPANY, Annual report, 2012). SUPPLIER is the only SUPPLIER of meters and widgets of COMPANY and therefore it is important for COMPANY to maintain this collaboration.

CONTRACTOR

CONTRACTOR is a contract packager of COMPANY. Once widgets and devices are shipped from SUPPLIER to CONTRACTOR they are COMPANY’s ownership. This means that COMPANY is also responsible for the transportation between SUPPLIER and CONTRACTOR. At the packaging site two main activities take place: packaging of vials with widgets and kitting of medical device. The packaging process of vials is automated and the medical device kits are packaged manually.
Three packaging lines are fully dedicated to the packaging process of widgets of COMPANY. At the packaging lines, vials receive country specific labels and are packaged in country specific (shipper) boxes. All widgets, which are distributed for the market, are packaged at the site of CONTRACTOR and therefore all of these products are competing for the same capacity. After packaging, finished goods are immediately shipped (on average within XXX days) to a local or regional warehouse of COMPANY somewhere in the market. This is the third actor in the supply chain and is described in the section about the organization.

2.2 Control

In order to have a better understanding of the production planning process of CONTRACTOR, the current process is mapped. This process is shown in Figure 1 of Appendix A and gives all steps from receiving the net demand forecast until the final release step of finished goods. In general, the production planning process of CONTRACTOR consists of three parts: long term, intermediate and short term planning. First, the long term planning is discussed.

2.2.1 Long term planning (strategic)

The long term planning activities are triggered by two types of information, namely (1) the net demand forecast for the upcoming 12 months and (2) the final list with POs. This information is provided by COMPANY on a monthly basis. First, the net demand forecast is used to manage the inventory of packaging materials (e.g. cartons, labels and literatures). The packaging materials are ordered XXX months in advance. The replenishment lead time of the packaging materials is XXX months. Furthermore, CONTRACTOR has XXX months of stock available in the shelf to be prepared for unexpected demand changes in the final quantities of POs. Second, the net demand forecast is used as input for the rough capacity planning. The goal of this capacity plan is to generate an overview of the workload distribution for the next months.

The second input for the long term planning is a list with final POs. This list is used as input for the rough production capacity plan and the MRP calculations. Currently, COMPANY has no insights in the production strategy of CONTRACTOR and therefore the requested delivery date can change from the promised delivery date. This means that there is always a negotiation process between CONTRACTOR and COMPANY about the final delivery dates of POs. This negotiation process is based on the two internal goals of CONTRACTOR:

1. Fulfill customer demand at the requested date.
2. Balance production capacity in order to avoid downtime.

After the MRP is calculated, a list is created with materials which still need to be ordered. CONTRACTOR also receives a file with the Expected Time of Arrivals (ETA) of the products ordered by COMPANY. These products are produced at SUPPLIER. Finally, a draft of the production plan is created. After confirmation of final delivery dates by both parties, the draft plan is released as final production plan. In general, this takes place XXX weeks before the first PO is requested. After the long term planning activities, the intermediate planning activities start, as described in the next section.
2.2.2 Intermediate planning (tactical)

The final production plan, which is released XXX times per month, is used as input for the intermediate planning activities. Those activities start with the detailed scheduling of the packaging lines. This detailed scheduling is translated in a daily plan. CONTRACTOR has the ability with this daily plan to monitor and control the production process (the short term planning). After the products are packaged, the quality of the POs is checked and POs are released as finished goods in the COMPANY system. Finally, the products are ready for shipment to the local or regional warehouses.

COMPANY owns the packaging lines at CONTRACTOR, which are solely used for packaging of products with widgets. The detailed scheduling decisions of the lines are analyzed based on three parameters: lot sizes, allocation and sequence.

Lot sizes

The first parameter is lot sizing. Lot sizes of work orders are determined by the size of the PO. Since there are countries with low demand, lot sizes can differ between production runs. Furthermore, the lot size is always less than the quantity that is ordered. During a production run not all vials pass the quality control and therefore the requested quantity is less compared to the final delivered quantity. CONTRACTOR aims to have large batch sizes, because in this way the total setup time can be reduced. Figure 3 shows the lot sizes of work orders on each working day in October 2012 at line 1. There is a large variability in the lot sizes of different production runs. Due to quality and healthcare regulations, CONTRACTOR is not allowed to use multiple bulk batches for production of a single work order. Therefore CONTRACTOR requires, intermittently, multiple work orders for one PO.

![Figure 3: Production quantities line 1 in October 2012](image)

Allocation

The second parameter is the allocation of work orders. Figure 4 shows the allocation of both production lines. The first packaging line is solely used for packaging of single vials. This means that this line only produces boxes containing one single vial. As you can see Figure 3 almost 92% of the produced quantities are made of the Product A 50 and the Product B 50 widgets. Only a few batches of other products are packaged on this line. These products are intermediates for the Product A and Product B product family.

The second packaging line is designed for the packaging process of both single and double vials. The double vials are boxes which contain two vials of 50 widgets. More than 55% of the quantities produced
on this line are from the Product C family (see Figure 4). Besides, almost 25% of the finished goods products are produced of Product A vials. Most of these finished goods are doubles.

![Total produced quantities on line 1 in percentage](image1)

![Total produced quantities on line 2 in percentage](image2)

*Figure 4: Total produced quantities on both lines in October 2012*

**Sequence**

The sequence of the production process is the last decision in the detailed scheduling process. The production sequence is important to minimize the setup times. During a setup, the packaging line is prepared for the next work order (e.g. changing packaging materials). Furthermore, all rejected products from the previous production run are checked and documented.

Line number 1 is solely used for packaging of single vials. In the current production strategy, the production sequence is not fixed and meaning that products are not always produced in the same order. The sequence is based on the requested delivery date of the PO and material availability.

Production line 2 is used for the packaging process of Product C and all doubles. A change-over from singles to doubles takes approximately two hours and this is mainly affected by the production settings of the machine that needs to be changed. Therefore, the production planners try to schedule these products in a block in order to avoid unnecessary setup time. The sequences of these blocks are not fixed, which means that the interval between the double and single vials is not the same for each period. Also the sequence within a block of doubles is not fixed. In the next section the short term planning activities are discussed.

**2.2.3 Short-term planning (control)**

The last level of planning is the short-term planning. Main goal of this level of planning is to directly control the operational activities, which is important to keep track of the real-time flow of materials through the packaging process compared to the daily plan. Furthermore, control of the packaging process is important to provide the tactical level of planning of feedback information about potential improvements for tactical decisions in the future (Hopp & Spearman, 2008). Other activities of the short-term planning are the quality check of finished goods and finally the goods receipt release step. After this step, finished goods are ready for transportation to the local or regional warehouses of COMPANY.

**2.3 Information**

Since all widgets, medical devices and production equipment at CONTRACTOR belong to COMPANY, COMPANY provides all the required data (e.g. ETA of bulk products, requirements Purchase Orders, SKU
changes) to give CONTRACTOR the opportunity to schedule their packaging process. The information sharing process between the different actors in the supply chain is discussed in this section.

**SUPPLIER**

COMPANY gives a Purchase Order (PO) to SUPPLIER every four weeks. This PO is based on the aggregated net demand forecasts of all finished goods and is a multiple of full pallets. Due to the long lead time, the final PO is placed eight weeks in advance. Once an order is placed, COMPANY has no opportunity to change it and has to accept the ordered quantities. Figure 2 shows that production of widgets take on average XXX weeks. Finally, finished goods are shipped to CONTRACTOR, which takes approximately 6 weeks. This is the next location in the supply chain.

**CONTRACTOR**

Each month CONTRACTOR receives the 12 months rolling horizon net demand forecast and a list with POs for the next month. The final list with POs is delivered XXX weeks before the first requested due date of an order. This means that CONTRACTOR has XXX weeks to react on unexpected changes in the final PO size. During the XXX weeks of the packaging process there is frequently contact between CONTRACTOR and COMPANY to ensure that the promised delivery date of POs is met.

**COMPANY**

Figure 5 shows the different steps that are performed from creating the demand forecast to the final shipment to the customer. The boxes represent the information activities and the arrows indicate the direction of the information flow. The three actors of the supply chain are also involved in this process. The local and regional warehouses of COMPANY are replenished according to the Vendor Managed Inventory (VMI) principle. This means that COMPANY manages the inventories of the corresponding warehouses. The local warehouses (most upper lane) provide a 24 months rolling horizon demand forecast to the regional COMPANY Supply Chain Management (SCM) on the first Friday of the month (COMPANY, COMPANY executive version steering model v6, 2009).

![Figure 5: Simplified overview of information flows of widgets](image-url)
The most important step of Figure 5 is that COMPANY informs CONTRACTOR monthly about the final list with POs and about forecasted of the next 12 months. This information is shared in the XXX week of the month and CONTRACTOR schedules their production activities based on the delivery dates of these POs. Due to changes in the demand it occurs that the final PO differs from the initial forecasted demand. The information sharing process is important in the supply chain in order to synchronize the different supply chain planning processes.

2.4 Organization
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3 Problem analysis and diagnosis

This chapter gives a more detailed analysis of the problem definition based on quantitative and qualitative analysis. Furthermore, a cause and effect diagram is developed and analyzed to find the main cause of the defined problem. Next, the goal of the redesign is defined in order to find a solution for the main cause. Finally, a set of research questions is given. First, the problem is analyzed which are the unbalanced inventory levels of widgets.

3.1 Inventory levels

In general there are two different types of end products, namely intermediates and finished goods. Intermediates are produced from vials with 5, 10 or 25 widgets and used for medical device kits. The finished goods are produced from vials which contain 25 or 50 widgets. As mentioned before, all SKUs of widgets are produced from three different product families: Product A, Product C and Product B. The vials with 50 widgets are responsible for XXX% of all the inventory value of widgets. This means that the inventory of vials with 5, 10 and 25 widgets are only responsible for XXX% of the total inventory value at CONTRACTOR.

Figure 6 shows the total monthly inventory value of all products stored at CONTRACTOR, which are owned by COMPANY. The inventories of bulk widgets are on average responsible for XXX% of the monthly inventory value at CONTRACTOR. Next, Figure 6 shows that the average monthly inventory value of finished goods is only XXX% of the total value, since finished goods are, after release, shipped within XXX days to the local or regional warehouses. The last XXX% of the monthly inventory value at CONTRACTOR is caused by other products which are owned by COMPANY. The high inventory value in May 2012 is a result of the disappointing market launch of the Product B meters in the beginning of this year.

![Monthly inventory at CONTRACTOR in Euro's](image)

Figure 6: Monthly inventory at CONTRACTOR

Figure 7 gives the cumulative total bulk consumption and the cumulative total bulk arrivals. The red line represents the cumulative amount of widgets (in equivalent units (EQU) of 100) from the beginning of this year. The first value of this cumulative amount of widgets is the amount of widgets that was in the shelf at the beginning of 2012. The blue line gives the cumulative amount of widgets that is consumed for production at a specific point in time. This line is equal to the cumulative demand of POs since the
beginning of 2012. Based on this figure, inventories and lead times of all widgets are determined. The horizontal difference between both lines represents the lead time of widgets and the vertical difference is the inventory level. In general, both lines are more or less parallel and therefore inflow is assumed to be equal to the outflow of the inventory. Since the planning processes of CONTRACTOR and COMPANY are not aligned, there is variability in the inventory levels and lead times. This variability becomes larger on a SKU level. For instance, Figure 3 in Appendix B shows that the inventory level of Product B widgets with vials of 50 widgets is increasing during the summer of 2012.

![Figure 7: Cumulative arrivals and cumulative consumption of bulk widgets](image)

The inventory positions of the widgets are given in Figure 8. This figure shows that the shape of the line ‘Inventories Total’ is determined by the line ‘Inventories Product A’, which is equal to Product A vials with 50 widgets. So, most of the inventory at CONTRACTOR is driven by this product. Furthermore, the line of ‘Inventories Total’ shows that the inventories of widgets are changing over time and are, therefore, unbalanced. The line of ‘Inventories Others’ shows that these products have very low inventory values compared to the Product A 50’s vials. This is caused by the fact that demand of these three products (Product A 5, 10 and 25 widgets) is also less.

![Figure 8: Inventory levels of bulk widgets](image)
The characteristics of the inventories of the individual widgets are given in Table 1. This table shows that the average total inventory of bulk products in the first 8 months of this year is around 1.85 million widgets (in EQU 100) per day. More than 58% of this inventory is caused by Product A vials with 50 widgets. Furthermore, the table shows the Coefficient of Variation (CV) of the inventory levels, which represents the standard deviation divided by the average inventory level. Therefore, this coefficient gives the degree of variation of the inventories of widgets. By aggregating the inventory levels, the variability in stock levels decreases. The CV of all widgets is around XXX, which means low variability of the inventories. However, if you look at a more detailed level, there is more variability in the inventory levels. For instance, the inventory of Product B vials with 50 widgets has a CV of almost XXX, indicating that the inventory of this product is not balanced.

<table>
<thead>
<tr>
<th>Inventories</th>
<th>Product A 50’s</th>
<th>Product B 50’s</th>
<th>Product C 50’s</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>Standard deviation</strong></td>
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<tr>
<td><strong>Coefficient of Variation</strong></td>
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</tbody>
</table>

Now, the lead times of the widgets are discussed, which is the horizontal distance between the cumulative bulk arrivals and the cumulative bulk consumption in Figure 7.

### 3.1.1 Lead times
Based on the horizontal differences of the cumulative bulk arrivals and bulk consumption of widgets, the lead times are determined. The results are given in Table 2. This table shows that the average total lead time of all widgets is around XXX days, which means that widgets are on average XXX days in the inventory before consumed. The lead times (average en standard deviation) of Product A 50 widgets and Product C 50 widgets are almost similar. The CV value of the Total lead times is around XXX, which indicates that lead times are quite stable over time and show less fluctuation. However, if the CV is determined on the SKU level, there is more variation. For instance, the CV of Product B vials with 50 widgets is XXX, which is almost three times the CV of the Total lead times. The reason for this is that the inventories of this specific SKU are increasing the last analyzed months.

<table>
<thead>
<tr>
<th>Lead times</th>
<th>Product A 50’s</th>
<th>Product B 50’s</th>
<th>Product C 50’s</th>
<th>Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
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<td><strong>Standard deviation</strong></td>
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<tr>
<td><strong>Coefficient of Variation</strong></td>
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</tr>
</tbody>
</table>

In this section the inventory levels of widgets are analyzed. The target inventory levels of all components are two weeks of cycle stocks and two weeks of safety stocks. As is shown in Table 2 the current lead times are on average XXX days, which is XXX days above the target inventory levels. Currently, the supply chain planning processes of CONTRACTOR and COMPANY are not aligned and this results in unbalanced inventory levels of widgets.
3.2 Forecast of Purchase Orders

The final quantity of the POs differs from the forecasted quantity. Each month CONTRACTOR receives an update of the net demand forecast for the upcoming 12 months. In 2012 the division is over forecasting on average XXX% (see Figure 9), i.e. that the final quantities of POs are XXX% lower compared to the net demand forecasts of the same period. Over forecasting results in increasing inventory levels of widgets and all related packaging materials. However, the forecasting process is improved in the last three months on 2013, mainly based on different forecasting projects within COMPANY which have a focus on statistical forecasting. The over forecasting is reduced to 9% during these last three months.

Confidential

Figure 9: Forecast vs. Purchase Order (PO) of vials

Since ordering decisions of widgets are taken XXX months (i.e. XXX weeks production time and XXX weeks transportation time) before the final POs of finished goods are given, this over forecasting process is a cause for the unbalanced inventory levels of widgets. This structural over forecasting is out of scope of this project and the focus of this project is on the other main root cause: the arrival process of bulk is not in line with the packaging process, which is analyzed in the next section.

3.3 Arrival of widgets

The arrival pattern of widgets is given in Figure 10 and shows that the arrival process of widgets differs over time. For instance, almost 1 million widgets (in EQU 100) arrived at the packaging site of CONTRACTOR in week 19. However, the week before and the week after only a few widgets are delivered. The replenishment frequency of widgets is based on the monthly shipments from SUPPLIER to CONTRACTOR. The figure shows variability in the arrival of widgets, which is a cause for unbalanced inventory levels of widgets.

Figure 10: Arrivals of widgets

The order process of bulk widgets is managed by COMPANY and the production process is managed by CONTRACTOR. Since the production process of CONTRACTOR is unknown to COMPANY, the arrival process of widgets is not synchronized with the supply chain planning processes of CONTRACTOR. In order to avoid that widgets are a bottleneck in the supply chain, COMPANY always wants XXX weeks of both safety stock and cycle stock at CONTRACTOR. As a result all widgets are planned to be XXX months before the start of the production process available. The next section describes the problems which are identified during the production planning process of CONTRACTOR.
3.4 Unknown production strategy

The production planning process as described in Chapter 2 is used to identify potential problems during each step of the mapped planning process. In order to identify the most important problems during the planning process, a Failure Mode and Effect Analysis (FMEA) is used. The goal of this FMEA is to quantify the impact of the identified problems based on three criteria: severity, occurrence and detection. The FMEA is created in cooperation with both involved parties: COMPANY and CONTRACTOR. After several discussion sessions all identified problems are quantified. Interesting to see is that the three highest ranked problems are related to the long term planning process of CONTRACTOR. This means that the problems occur in an early stage of the complete planning process and therefore they have effect on all other activities. The impacts of the problems differ and are used to perform the problem analysis step. The three highest ranked failure modes of the production planning process of CONTRACTOR are:

1. Insufficient detailed information about delivery of specific bulk batches (400).
2. Bulk material ordered by COMPANY not available for weekly production run (252).
3. Delivery date of POs not equal distributed across the month (140).

The number between the brackets is the product of the three quantification criteria: severity, occurrence and detection. Each of these criteria has a range from 1 to 10 and therefore the maximum score is 1000. The scale of the criteria is determined in cooperation with the involved actors. Now the potential causes and effects of these three problems are discussed.

Bulk batch size information

The highest ranked failure mode is that CONTRACTOR receives insufficient detailed information about the delivery of specific bulk batches. CONTRACTOR receives at least once per month an ETA update of products which are ordered by COMPANY. Most of the products arrive at XXX and shipped to CONTRACTOR. Since the batch sizes of widgets are not the same, CONTRACTOR is not aware of the volume distribution across the bulk batches. Only when the products are arrived at CONTRACTOR, the exact batch distribution is known. This especially causes a problem for the scheduling process of low count vials. These low count vials are used as intermediates for the medical device kits. Therefore, the production scheduling process of intermediates is related to the production plan of medical device kits. In order to avoid that the availability of intermediates is a bottleneck for the meter kitting process, CONTRACTOR always wants to plan the production of these vials as soon as they have the required information (i.e. due date and quantity). By having more detailed information about the batch sizes of widgets, CONTRACTOR is able to make in an earlier stage the detailed scheduling for intermediates.

Bulk batch availability

The second identified problem is that bulk material ordered by COMPANY is not available at the right point in time for the scheduled production run. Although COMPANY keeps a safety stock of XXX months, CONTRACTOR is still complaining that not the right bulk is available for production. As a result of this unavailability, CONTRACTOR needs to reschedule the packaging lines to deal with these unexpected changes in the plan. As is shown in Figure 10, the arrival process of widgets is not balanced and shows variability in the arrival process. Currently, COMPANY is not aware of the current production strategy of CONTRACTOR and therefore the arrival plan of bulk widgets is not in line with the packaging process.
**Delivery date of Purchase Orders**

During the planning process there is always a negotiation between CONTRACTOR and COMPANY about the requested delivery date of the final PO. Figure 11 shows the two different plans of both companies. The blue bars are the requested delivery dates from COMPANY and the red bars represents the promised date by CONTRACTOR after the negotiation process. The figure shows that almost 40% of the quantities are requested in the first week of the month (week 36 and 40). As mentioned before, on the one hand CONTRACTOR always wants to fulfill customer demand and on the other hand CONTRACTOR wants to avoid downtime. Both internal goals are important during this negotiation process of the delivery dates of POs. The requested delivery dates are generated by the planning system of COMPANY. As a result, the requested delivery dates are not equally distributed across the month since the system aims to replenish in the beginning of the month.

![Plan of COMPANY and CONTRACTOR in vials per week](image)

*Figure 11: Requested and promised delivery date of POs*

Due to the negotiation process, the POs are more equally distributed across the month. However, in order to avoid any downtime of the production facility, CONTRACTOR produces POs ahead. Figure 12 gives the throughput times of the production process at CONTRACTOR.

This figure shows that the average time between the real production and the POs are booked as completed is on average XXX days. Only if the POs are completed they are physically ready to be shipped. However, the POs are on average more than XXX days in the inventory of CONTRACTOR before they are booked into the SAP system of COMPANY. This is caused by the fact that CONTRACTOR waits with this release step until the promised delivery date is achieved. During the steps ‘Completed’ and ‘Sent from JDE to SAP’ no value is added and therefore it is assumed that this time is wasted. So, a result of this preproduction of POs is that the finished goods are waiting in the warehouse of CONTRACTOR for the last release step.

![Throughput time of production process at CONTRACTOR](image)

*Figure 12: Throughput time of production process at CONTRACTOR*

### 3.5 Cause and effect analysis

In order to find the main cause of the identified problem, a cause and effect diagram is developed (see Figure 13, which is based on the above described problem analysis. The problem of unbalanced inventory levels of widgets is caused by inventories which are too high or either too low. Inventory levels are a trade-off between service and costs. Both scenarios are undesired since too high inventories decrease the cash flow position and too low inventories have a negative impact on the service levels.
The first root cause of the identified problem is the overforecasting process of the demand of finished goods. The bad forecast knowledge of the forecast managers is the only cause which is completely controlled by COMPANY. Since the complete supply chain is based on make to forecast principles, a good performance of the forecast is important for the balanced inventory levels of widgets. The second root cause is related to the unaligned arrival process of widgets with the packaging process of CONTRACTOR. The diagram shows that the main cause for this effect is the unknown production strategy of CONTRACTOR. Based on interviews with CONTRACTOR it is stated that bulk batches are not always at the right point of time available at CONTRACTOR and therefore the inventory levels of bulk products are unbalanced.

### 3.6 Problem diagnosis

The results of the problem analysis step are used to determine potential improvements for balancing the inventories of widgets at CONTRACTOR, which are described in this section. In general there could be stated that the listed problems are related to the fact that production plans of CONTRACTOR and the ordering plans of COMPANY are not aligned at the moment. This means that the main cause for the unbalanced inventory levels of widgets is that the supply chain planning processes of CONTRACTOR and COMPANY are not synchronized.

Although, the highest ranked problem is not caused by this missing alignment between CONTRACTOR and COMPANY, it gives an indication that the information sharing process of both companies can be improved. Since CONTRACTOR has no information available about the specific lot sizes of bulk batches, the distribution of bulk batches is unknown until the bulk arrives at their plant. However, CONTRACTOR never requested this information and therefore COMPANY was also not able to deliver this. This means that COMPANY has the requested information available and therefore information sharing of the specific bulk batch sizes is a simple improvement and can be immediately implemented.

In Figure 6 is shown that the inventory of widgets is high compared to all other components at CONTRACTOR. Since COMPANY wants to avoid that unavailability of widgets is a bottleneck for the packaging process, COMPANY keeps at least XXX months of widgets in stock at CONTRACTOR. Nevertheless, the second identified problem indicates that not always the right bulk is available at the
required point in time. This is caused by the fact that the arrival process of bulk widgets is not in line with the packaging process of CONTRACTOR. So, this is the first indication that the supply chain planning processes of both companies are not synchronized.

The second indication of a missing alignment between the planning process of CONTRACTOR and COMPANY is found in the third identified problem. The problem analysis showed that 40% of the requested quantity needs to be delivered in the first week of the month. Therefore, CONTRACTOR starts to negotiate with COMPANY about the final delivery date. The two internal goals of CONTRACTOR influence this negotiation process. After the negotiation process the POs are more equally distributed across the month. CONTRACTOR produces POs ahead (approximately XXX days) in order to avoid downtime. This preproduction results in waiting time of finished goods before they are released into the COMPANY system and ready for transportation. Better alignment between the planning processes of CONTRACTOR and COMPANY can avoid this preproduction.

The main cause for the unbalanced inventory levels of widgets is the unknown production strategy of CONTRACTOR. The goal of the redesign is to make the production strategy clear for both companies and it must find an optimal balance between customer service and costs (setup- and holding costs). The new production strategy gives both companies the opportunity to synchronize the supply chain planning processes and make these processes dependent. As a result the inventory levels of widgets become balanced over time. The problem diagnosis results in the following redesign goal:

*Redesign the production strategy of CONTRACTOR according to the production wheel concept in order to synchronize the supply chain planning processes of CONTRACTOR and COMPANY. Determine the optimal production lot sizes and replenishment frequencies and show what the relating impact is on safety and cycle stocks of finished goods. Furthermore, the redesign has to be reproducible and should describe the impact on the communication between CONTRACTOR and COMPANY.*

*Research questions*

Based on the problem diagnosis and the redesign goal the following central research question is derived:

*What is the impact of the production wheel concept on the inventory levels of widgets and on decisions about how to steer CONTRACTOR?*

The following sub questions are determined to answer the central research question:

1. *What are the consequences of the production wheel concept for the optimal production lot sizes, production frequencies and safety stock settings of finished goods?*
2. *What is the impact of the production wheel concept on the inventory levels of finished goods?*
3. *How does this new production strategy influence the communication between CONTRACTOR and COMPANY?*

The next chapter gives a literature overview of production scheduling problems and the production wheel concept.
4 Literature overview

This part of the report contains an overview of the literature study conducted by Schouten (2012). The literature study focuses on multi-product single-machine scheduling problems with setup costs. According to Winands et al. (2011) this type of scheduling problems depends on three characteristics: customized and standardized products, the presence or absence of setup times and/or costs, and the predictability of the production environment. Each of these characteristics is discussed briefly in this chapter. Finally, cyclical production is explained. First, an introduction in the field of production scheduling is given.

4.1 Production scheduling problems

Nowadays, virtually all production managers want on-time delivery, minimal work in process, shorter lead times, and maximal utilization of resources (Hopp & Spearman, 2008). The goal of production scheduling is to make trade-offs between those conflicting targets. Production scheduling problems can be solved with the help of mathematics and they provide the optimal production order and it projects the start time of each job. Now, the first characteristic is explained.

Van Foreest, Wijngaard, & van der Vaart (2010) discussed the Stochastic Economic Lot Scheduling Problem (SELSP) for products which are produced in a make-to-order environment. This article described that lot scheduling problems becomes more complicated compared to the make-to-stock environment, because not only the utilization must be at an acceptable level, but also customer due dates should be met. They concluded that intelligently adding slack in the production schedule is a good strategy to achieve a good balance between high utilization and customer order acceptance.

The second characteristic is the presence or absence of setup times. Reduction of time spent on setups can be achieved by combining individual orders with the same characteristics into production runs of single product families. The formation of the batch size of these individual orders is a part of the decision making process and therefore it is a tactical production parameter (Allahverdi, Ng, Cheng, & Kovalyov, 2008). Production efficiency increases by spreading the inter-family setup time over the orders within one production run (Foreest, Wijngaard, & Vaart, 2010). Furthermore, the sequence of the production orders must be determined in order to make a feasible production schedule. Batch setups are sequence dependent if the time between two setups differs among different product families.

The third characteristic is the predictability of the production environment with two types of lot scheduling problems: deterministic and stochastic. First, the deterministic version is described.

4.2 Deterministic problems

The most famous deterministic lot sizing problem is the Economic Order Quantity (EOQ) model, which assumes a continuous time scale, constant deterministic demand and an infinite time horizon. This model is the basics for the Economic Lot Scheduling Problem (ELSP) and is a trade-off between inventory holding and setup costs. According to Silver et al. (1998) there are two factors which make the ELSP difficult: (1) the need to satisfy a production capacity constraint and (2) the need to have only one single product in production at a time. The ELSP deals with the problem to determine the sequence, lot sizes and cycles for the production of single products in order to minimize the costs. According to Moon,
Silver, & Choi (2002) there are three types of approaches to solve the ELSP, namely (1) the common cycle approach, (2) the basic period approach and (3) the extended basic period approach.

The focus of the common cycle approach is finding the re-order interval instead of finding the best batch size, because it is often easier to think in terms of frequency of production than in terms of numbers of units that need to be produced (Silver, Pyke, & Peterson, 1998). Therefore, an advantage of this approach is that it is a simple procedure which always finds a feasible production schedule since each product is produced only once in a cycle. A disadvantage is that the solutions for the common cycles are in some cases far above the lower bound (Moon, Silver, & Choi, 2002). According to Lopez & Kingsman (1991) the common cycle approach does in general not provide the optimal solution to the original lot scheduling problem due to imbalanced demand rates and production rates of the individual products.

The basic period approach is an extension of the common cycle approach, only it allows different cycle times for different products. However, the different cycle times must be an integer multiple \( n_t \) of the so-called basic period \( W \). The general idea of the basic period approach is to determine a common order interval, which is a multiple of the basic period of the cycle where all the products are produced within one rotation cycle.

The extended basic period approach is developed according the so-called time varying lot sizes approach and relaxes the restriction of equally spaced production runs. This means that this approach allows different lot sizes for any given product during a cycle. Due to the fact that the capacity restriction of this approach is more precise in terms of minimizing the total costs per unit time, the extended basic period approach performs better compared to the basic period approach (Moon, Silver, & Choi, 2002).

### 4.3 Stochastic problems

Winands et al. (2011) identified two major differences among production plans for the deterministic and the stochastic version of the lot scheduling problem. First, the rigid cycle production plan will not fit anymore in a stochastic environment. Second, inventories of all individual products are more important in a stochastic environment since inventories reduce the number of setups and also guaranty a certain service level. According to Sox et al. (1999) the Stochastic Lot Scheduling Problem (SLSP) can be divided into two different problems: the Stochastic Economic Lot Scheduling Problem (SELS) and the Stochastic Capacitated Lot Scheduling Problem (SCLSP). The stochastic nature of demand adds a great deal of complexity, since all products are competing for the same capacity. As a result, stock levels and safety stock settings have to be taken into account in the decision making process for production.

The SELSP is characterized by the fact that a production plan is developed which defines for each possible state of the system to whether continue production of the current product or whether to switch to production of another product or to idle the machine. According to Winands et al. (2011) the presence of setup times in combination with the stochastic environment are most complicated elements of the problem. On the one hand, one seeks for short cycle lengths in order to be able to react to any variability in the system. On the other hand, short cycles increase the amount of setups and therefore decrease the available capacity for production. Trade-offs has to be made to determine whether the focus is on setup times or whether on setup costs. Sox et al. (1999) emphasized that the SELSP is NP-hard, which makes it unlikely that the optimal solution can be found within a reasonable amount of time.
4.4 Production Wheel

The production wheel concept is based on the principles of the common cycle approach, which is described in section 3.2. One characteristic of this approach is that each product is produced exactly once per cycle. In order to deal with uncertainties in demand and the production environment, only the flexible variant of the production wheel is discussed.

In Günther et al. (2006) the principles of the production wheel or block planning are described. The block planning concept is based on Mixed Integer Linear Programming (MILP) models. Goal of the MILP models is to minimize total holding- and setup costs. Constraints are based on the production capacity and fulfillment of the demand. A block is a predefined sequence of production orders with a variable size, where each production order matches with a unique product type. In Packowski et al. (2010) it is recommended to create a sequence which is based on a setup time reduction and therefore is optimal for all products within the production wheel. The unique period-block assignment is one of the important assumptions in block planning. The general block planning concept is shown in Figure 14.

![Figure 14: The block planning concept (Günther, Grunow, & Neuhaus, 2006)](image)

The flexible block planning concept has no time restrictions, which means that the start and finish time is not linked to time boundaries. Hence, a block is allowed to start as soon as the predecessor block is finished. However, the execution of a block must be finished before the end of the assigned period (Bilgen & Günther, 2010). This is another important assumption of the general block planning concept. Furthermore, the total length of a so-called macro-period is always the same (e.g. week or month). A major advantage of the block planning concept is that it is easy to implement and therefore the complexity of the scheduling problem is reduced (Günther, Grunow, & Neuhaus, 2006). Bilgen & Günther (2010) mentioned that the developed flexible block planning framework provides considerable flexibility in the production schedule. Furthermore, the block planning concept represents a practical and efficient way to support decision makers in practice.

4.4 Service levels

The inventory levels are always a trade-off between costs and customer service. Customer service is measured with a service level. There are two service measures which are most widely discussed in the inventory literature, namely $P_1$ and $P_2$. The $P_1$ service level is defined as the probability of not being out-of-stock just before a replenishment order arrives and the $P_2$ is defined as the long-run fraction of total demand, which is being delivered from stock on hand (fill rate) (Silver et al., 1998). The formulas of both service levels for an $(s, Q)$ inventory policy are the following:

$$P_1 = P[D(t_1, t_1 + L_1) + U_1 \leq s]$$
The $P_1$ service measure is most prominent in standard inventory text books, since expressions of this service measure are easily derived. The $P_2$ measure is the most used in practice. Both formulas contain terms of the expected demand during an interval $D(t_1, t_1 + L_1)$, the undershoot of a specific replenishment $(U_1)$ and the reorder point $(s)$. The only term which is present in the $P_2$ and not in the $P_1$ is the order quantity $Q$. The order quantity $Q$ is an important term, especially in cases where $Q$ is very large. The $P_1$ measure is independent of this term and therefore not influenced by order quantity. In practice it is common that there is no direct link between the inventory level and the required service level. Furthermore, professionals use ERP systems that compute inventory control parameters based on expressions for the $P_1$, while the actual measurement is often based on the $P_2$ measure (Kok, 2005).

4.5 Conclusion
In this literature review the general principles of lot scheduling problems are discussed. The production wheel or block planning concept is described in detail since this concept is used for the redesign of the production strategy of CONTRACTOR. The two major characteristics of the production wheel: fixed sequence and fixed cycle length are important for the redesign because this provides a clear communication between both parties about the timing of production. Based on this production wheel concept the supply chain planning activities of COMPANY can be aligned with the production strategy of CONTRACTOR.
5 Redesign
This chapter provides the redesign of the current production strategy. The goal of this redesign is to build a production wheel for each packaging line based on feasible lot sizes. In section 5.1 the problem is decomposed in different levels. Afterwards the decision making process at each level is discussed in more detail. First the conceptual design is described.

5.1 Conceptual design
Supply chains are characterized by material and information flows. According to de Kok & Fransoo (2003), there are three different levels of hierarchical control in planning: strategic, tactical and operational. The redesign problem is decomposed based on these three levels. Decisions about how materials and information flows go through the production environment are made on the strategic level. Strategic decisions result in a set of requirements and those are input for the next level, which is the tactical level. At this level the parameters of the production wheel are determined (e.g. lot sizes and safety stocks). Finally, at the operational level decisions of the tactical level are controlled and coordinated. The decomposition of the problem is shown in Figure 15.

5.2 Strategic level
The overall goal of the redesign is to improve the alignment of the supply chain planning processes between CONTRACTOR and COMPANY. During the redesign the two current goals of CONTRACTOR are taken into account, namely (1) fulfill customer demands and (2) balance production capacity to avoid downtime. Furthermore, the production input (bulk consumption) and production output (number of POs) should be leveled over time.

The first internal goal of CONTRACTOR is to fulfill customer demand. This goal can easily be met since the order pattern of COMPANY is based on the new production strategy of CONTRACTOR. The requested delivery dates of POs are determined by the sequence of the production wheel. Only if COMPANY sticks to this fixed sequence the production wheel can work. The second internal goal of CONTRACTOR is to balance production capacity and avoid downtime. Avoiding downtime can be achieved by making full use of the production capacity. However, when all the production capacity is used there is no buffer to deal with any variability in the demand or production environment. Since both are not deterministic in this project, there should always be enough capacity in the production strategy to deal with these uncertainties. This has to be taken into account at the tactical level.
Furthermore, both production input and production output should be leveled over time. Production input is characterized by the consumption of widgets. Since 85% of the finished goods quantities are produced from vials with 50 widgets, the bulk consumption of those products must be leveled over time. As a result, the bulk arrival process of these vials should be leveled too. Moreover, the output of the number of POs and the produced vials per week must be leveled over time. Currently one of the major problems is that the requested amount of vials is not equally distributed across the month. This order behavior is given in Figure 11 and shows that 40% of the monthly quantity is requested in the first week of the month. In order to compensate this demand peak in the beginning of the month, CONTRACTOR needs to produce orders ahead to meet the requested date. A leveled production output is achieved if during each week approximately 25% of the requested amount of vials per month is produced. The new order pattern of COMPANY is adjusted based on the production output of CONTRACTOR.

First two prerequisites of the production wheel have to be checked: the demand forecast and the production environment.

5.2.1 Demand forecast
The first prerequisite of the production wheel is that the demand forecast is stable over time. The demand forecast of 2013 on bulk level is shown in Figure 4 of Appendix C. The following two steps are required to come to the total demand forecast for the next 12 months: (1) determine set of SKUs and (2) calculate demand forecast.

**Step 1: Determine set of SKUs**
The first step is to analyze which SKUs need to be produced at CONTRACTOR. The SKU mix is changing all the time due to new product launches. Only if the total set of products is changed, the set of SKUs has to be updated. The total set of SKUs consists of \( k \) products.

**Step 2: Calculate demand forecast**
The second step is to calculate the total yearly demand forecast \( D_t \) for all \( k \) products. The total demand forecast for all \( k \) products in 2013 is XXX million vials, which is around XXX million vials per month. The CV of the aggregate demand is equal to 0.1, which indicates that the variability in aggregate demand is low compared to the average aggregate demand (Hopp & Spearman, 2008). The forecast bias of the total demand volume is decreased to less than XXX% in the last three months of 2012 (see Figure 9). Currently, COMPANY is working on several programs to increase the performance of the demand forecast. Based on these improvement programs and the decreasing forecast bias it is assumed that the forecast bias is negligible, which results in the assumption that the demand forecast is equal to the real demand.

5.2.2 Production environment
The second precondition of the production wheel is that the production environment is stable over time. Table 3 shows the average and standard deviation of the setup times during September, October and November 2012. Different types of setups are identified, depending on the type of vial and the packaging line. The setup times for packaging line are stochastic, since only Product A and Product B products are packaged on this line. These products are identical and therefore the setup times on this line are product independent. However, the setup times on packaging line 2 are product dependent. Since different type
of bulk products are packaged on this packaging line, it is difficult to determine if the variability in setup times is caused by a stochastic process or by product dependency. Nevertheless, in order to deal with the variability there should be sufficient free time at each packaging line.

Table 3: Production characteristics of different product groups

<table>
<thead>
<tr>
<th>Type of setup</th>
<th>Setup times (min)</th>
<th>Production rate (vials/hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Single-Single line 1</td>
<td>55</td>
<td>20</td>
</tr>
<tr>
<td>Single-Single line 2</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>Single-Double line 2</td>
<td>128</td>
<td>55</td>
</tr>
<tr>
<td>Double-Double line 2</td>
<td>65</td>
<td>25</td>
</tr>
<tr>
<td>Double-Single line 2</td>
<td>78</td>
<td>35</td>
</tr>
</tbody>
</table>

Furthermore, the average production rates for each line are shown in Table 3. The CVs show that the variability depends on the product group. Especially, products that are produced on line 2 show more variation compared to products produced on line 1. This is caused by the fact that line 2 needs technical setups, when there is a switch from single to double or the other way around. These technical setups influence the performance of the packaging line. The yield of the packaging process is on average 99.53%, which means that only one or two shipper boxes of 24 vials are not included in the final PO.

5.2.3 Capacity planning

The production capacity for 2013 is given in Figure 16. The graph shows that the capacity is increased in January 2013. To check the production capacity, the absolute lower bound is calculated. This lower bound assumes that each product is produced only once per year. The capacity is checked with the following constraint:

\[ \sum_{i=1}^{k} D_i PT_i + ST_i \leq C \]

Where,

- \( D_i \) = demand of product \( i \), in units/year
- \( PT_i \) = production time of one unit of product \( i \), in year
- \( ST_i \) = setup time of one batch of product \( i \), in year
- \( C \) = maximum yearly production capacity, in year

The maximum yearly production capacity \( C \) is calculated based on the actual production capacity of CONTRACTOR. Currently, CONTRACTOR works with 6 crews and each crew works 8 hours/day during 5 days/week. This gives a weekly production capacity of 240 hours \((6 \times 8 \times 5)\). This means that always 2 packaging lines are simultaneously in production. Furthermore, it is assumed that a year has 50 weeks. Therefore, the total yearly production capacity \( C \) is 12,000 hours \((50 \times 240)\). All packaging lines are identical and have therefore the same production characteristics.

For each individual product \( i \) the average production time \( (PT_i) \) and average setup time \( (ST_i) \) are calculated. The average production time of one vial is based on the production rate as for example is shown in Table 3. The production rate is defined as the amount of vials which is produced per hour for a
specific product \( i \). The average setup times and production rates are based on production data of September, October and November 2012. If each product is produced only once per year, which is the absolute lower bound of the capacity, then the required capacity is 12,597 hours.

Since \( \sum_{i=1}^{K} D_i PT_i + ST_i \geq C \) the current production capacity of 6 crews is not sufficient to fulfill customer demand of 2013. CONTRACTOR has to increase the number of crews to fulfill customer demand. These calculations are based on the assumption that the real demand is equal to the forecasted demand. Since the maximum number of crews who can work at CONTRACTOR is equal to 9, the maximum production capacity \( C \) is equal to 18,000 hours \( (50 \times 360) \). This number of crews is chosen because it is expected that due to the new lot sizes the setup times increase. Not all capacity can be used for production, since there must always be some free time to deal with uncertainties in the production environment. It is assumed that maximum 90% of the total capacity is available for production, which is 16,200 hour. The assumed production capacity and total demand is shown in Figure 16 and indicates that the maximum capacity is sufficient to fulfill future demand.

![Production capacity (in vials per month)](image)

**Figure 16: Total demand and production capacity**

### 5.3 Tactical level

In the previous section the decisions at the strategic level are described. As is shown in Figure 15 the output of this strategic level is a capacity plan and this is the input for decisions at the tactical level. Decisions that have to be made at a tactical level are: (1) lot sizes, (2) allocation, (3) sequencing and (4) safety stocks. These tactical parameters are discussed in this section.

#### 5.3.1 Lot sizes

The first parameter that has to be determined is the lot size of each individual SKU. In the current situation the production frequencies, and therefore the lot sizes, are not based on any formulas. Only the real high runners are produced on a weekly level, but all other products are produced on a monthly level independent whether or not this cost optimal. The first step is to calculate the optimal lot sizes of each individual SKU.

**Step 1: Determine optimal lot sizes**

The Economic Production Quantity (EPQ) is an extended version of the Economic Order Quantity (EOQ). Therefore, also the assumptions of the EOQ hold. According to Silver et al. (1998) the following assumptions are made:
1. The demand rate is constant and deterministic.
2. The order quantity is an integral number of units, with no minimum or maximum restrictions.
3. The unit variable cost does not depend on the replenishment quantity.
4. The cost factors do not change appreciable with time; inflation is at a low level.
5. The products are analyzed individually, without interactions.
6. The replenishment lead time is of zero duration.
7. No shortages are allowed.
8. The entire order quantity is delivered at the same time.
9. The planning horizon is very long and therefore all parameters will continue at the same values.

As described in Silver et al. (1998) one of the assumptions inherent in the derivation of the EOQ is that the complete replenishment quantity arrives at the same time (assumption 8). However, if this quantity becomes available with a certain type of production rate, then the formula of the Total Relevant Costs (TRC) for all $k$ products is given by:

$$TRC = \sum_{i=1}^{k} A_i \left(\frac{D_i}{Q_i}\right) + \frac{v_i r Q_i}{2} \left(1 - \frac{D_i}{P_i}\right)$$

Where,

- $TRC$ = Total Relevant Cost, in euro’s/year
- $A_i$ = fixed setup costs of product $i$, in euro’s
- $D_i$ = forecasted demand of product $i$, in units/year
- $Q_i$ = the replenishment order quantity, in units
- $v_i$ = unit variable costs of product $i$, in euro's/unit
- $r$ = interest rate, in percentage
- $P_i$ = production rate of product $i$, in units/year

Furthermore, the total production and setup time must fulfill the capacity constraint as is shown below. If the capacity constraint is violated, the solution is not feasible. The capacity constraint is as follows:

$$\sum_{i=1}^{k} D_i P_i T_i + \frac{D_i}{Q_i} S T_i \leq C$$

Based on this cost formula, the optimal value of $Q_i$ can be calculated by taking the derivative of this costs formula to $Q_i$. In order to avoid that the capacity constraint is exceeded the Lagrange multiplier ($\lambda$) is introduced. A Lagrangian problem is created in which the capacity constraint is replaced with a penalty term in the objective function involving the amount of violation of the constraint. The following problem is created:

$$TRC = \sum_{i=1}^{k} A_i \left(\frac{D_i}{Q_i}\right) + \frac{v_i r Q_i}{2} \left(1 - \frac{D_i}{P_i}\right) - \lambda \left(\sum_{i=1}^{k} \left(\frac{D_i}{Q_i} P_i T_i + \frac{D_i}{Q_i} S T_i - C\right)\right)$$

The formula for the optimal $Q_i$ is the following:
\[ EPQ = Q_i = \frac{2(A_i + \lambda ST_i)D_i}{v_i r \left( 1 - \frac{D_i}{P_i} \right)} \]

Note that if \( P_i = \infty \) (i.e. replenishment is infinitely fast) then this formula for the best value of \( Q_i \) is equal to the formula of the EOQ. The outcome of this step is a set with optimal lot sizes \( Q_i \) for each individual SKU. The next step is to come up with the number of replenishment orders placed per year.

**Step 2: Determine optimal replenishment frequencies**

After the optimal lot sizes are determined, the related Replenishment Frequencies (\( RF_i \)) for each SKU \( i \) need to be calculated. This is done with the following formula:

\[ RF_i = \frac{Q_i}{D_i} \times W \]

As mentioned in section 5.2.3, a year has 50 weeks and therefore the variable \( W \), which gives the number of weeks per year, can be replaced by the value 50. The next step is to adjust the best replenishment frequencies.

**Step 3: Determine optimal cycle length**

The cycle length of the Production Wheel (\( PW \)) is a result of the EPQ and the related capacity constraint. Only if the optimal cycle length of the production wheel is shorter than the chosen cycle length, the capacity is sufficient. Each product is produced only once in the optimal cycle, which is calculated for the complete set of SKUs. This results in a production wheel with replenishment frequencies which are deviating from the optimal replenishment frequencies as calculated in the previous step. The number of batches produced per year is changed from \( \frac{D_i}{P_i} \) to \( \frac{W}{PW} \), where \( PW \) is the length of the production wheel in weeks. The \( TRC \) of step 1 must be adjusted and this results in the following formula:

\[ \min TRC = \sum_{i=1}^{k} \frac{A_i \times W}{PW} + \frac{v_i r D_i PW}{2W} \left( 1 - \frac{D_i}{P_i} \right) \]

Subject to

\[ \sum_{i=1}^{k} D_i P_i + \frac{W}{PW} ST_i \leq C \]

The Lagrange multiplier (\( \lambda \)) is introduced to include the capacity constraint in the minimization problem. The following problem has to be minimized:

\[ \min TRC = \sum_{i=1}^{k} \frac{A_i \times W}{PW} + \frac{v_i r D_i PW}{2W} \left( 1 - \frac{D_i}{P_i} \right) - \lambda \left( \sum_{i=1}^{k} D_i P_i + \frac{W}{PW} ST_i - C \right) \]
The result of this step is the optimal cycle length of the production wheel \((PW)\) in weeks. The length of the production wheel \((PW)\) is set to one month, which is only possible if the optimal cycle length is less.

**Step 4: Adjust for supply frequency**

The optimal replenishment frequencies of step 2 need to be adjusted on three parts: a lower bound, an upper bound and aligned with the total cycle length. First, a lower bound for these frequencies needs to be determined. From transportation perspective it makes no sense to produce products on a higher frequency than once a week. Therefore, the lower bound of the replenishment frequencies is set to 1 week. The upper bound is set to 13 weeks due to shelf life restrictions of the widgets. Finally, the replenishment frequencies are rounded to the nearest power of two \((2^0, 2^1, 2^2, 2^3 \text{ and } 2^4)\). In the end the result of this step is to come up with a list of replenishment frequencies of all SKUs which are 1, 2, 4, 8 or 13 weeks. These replenishment frequencies are a multiple of a cycle length of one month.

Finally, this adjusted list needs to be revised by the Supply Chain Team (SCT) of COMPANY to avoid SKUs are produced on a higher frequency compared to the agreed replenishment frequency with the final customer. This is of course senseless, because then the products are waiting at the warehouse for the next shipment to the final customer. Products with a frequency of 8 weeks are produced bimonthly and products with a frequency of 13 weeks are produced only once every three months. The new adjusted lot size \(Q_i\) can be easily calculated by the following formula:

\[
Q_i = \frac{D_i}{RF_i}
\]

These new revised lot sizes are input for the next step.

**Step 5: Adjust for full pallet size**

Next, the lot sizes need to be adjusted for full Pallet Size \((PS_i)\) of each product \(i\). In order to avoid shipments of partial pallets, CONTRACTOR only produces full pallets. This means that the new lot size is a multiple of the pallet size. Moreover, in order to deal with the Minimum Order Quantity of CONTRACTOR it is recommended to always round up the lot size to the nearest multiple of the pallet size. Now, the new lot sizes are determined with the following formula:

\[
\text{Final } Q_i = \text{round up} \left( \frac{Q_i}{PS_i} \right)
\]

The result of step five is to create the final lot sizes which can be used for the production wheel.

**Step 6: Calculate costs and capacity**

The last step of the lot sizing procedure is to calculate the annual Total Relevant Costs with the adjusted lot sizes. The formula of the annual Total Relevant Costs is the same as in step 1. Furthermore, the capacity constraint must still be met. The total required capacity is calculated with the following formula:

\[
\sum_{i=1}^{k} \frac{W}{RF_i} TT_i \leq C
\]
Where, $TT_i (Q_i P T_i + S T_i)$ is the total time (in hours) to produce one batch of product $i$. If this capacity constraint is not met, the adjusted lot sizes need to be increased to reduce the number of replenishment frequencies and therefore the required capacity.

**Conclusion**

In above described steps the Economic Production Quantities are calculated and adjusted due to shelf life, Minimum Order Quantities and full pallet size restrictions. As a result, a final list with new lot sizes and related replenishment frequencies is determined. Furthermore, the optimal cycle length is determined and must be shorter than one month in order to ensure that the capacity of the wheel is sufficient. With this information, the products can be allocated to the different packaging resources.

5.3.2 **Allocation**

The allocation procedure is the next step of the redesign. All identified SKUs that need to be produced at CONTRACTOR are dedicated to specific lines. Currently one specific packaging line is dedicated for production of doubles and Product C products. Overall goal of the allocation and sequencing decisions is to minimize the setup times and to level the production load at CONTRACTOR. In order to achieve the best allocation, it is recommended to make the allocation decisions in cooperation with operational managers of CONTRACTOR who have adequate knowledge about which product(s) can be dedicated to the lines. The first step is to cluster different product types.

**Step 1: Cluster product types**

Table 3 shows that the setup times between single and doubles are significantly higher than setups between single and single vials. Setups from single to doubles require technical changes of the packaging lines. Based on interviews with the operational manager of CONTRACTOR it is stated that these technical changes reduces the productivity of the line. To avoid unnecessary setups between singles and doubles, the following rule is created:

*RuLe 1:* Cluster all doubles in blocks and allocate them on the same line in order to minimize the sum of the setup times and the time due to technical interventions of the packaging lines.

**Step 2: Cluster product groups**

The next step is to allocate the different product groups to the three packaging lines. Table 4 shows the different setup times between different product groups. The table shows that the average setup time between Product C - Product A (B) (A – C) and vice versa is 15 minutes longer compared to the average setup time between the product groups Product C – Product C (C – C) and Product A (B) – Product A (B) (C – C). The difference in setups is independent of the amount of widgets in the vial.

The difference between those setups can be found in the fact that the vials of Product C products have not the same design as the vials of Product A (B) products. Setups for products with not the same design require on average more time (see Table 3 and Table 4). Therefore, it is recommended to allocate the blocks with doubles and Product C products on the same line.
Table 4: Setup times of different product groups

<table>
<thead>
<tr>
<th>Setup product groups</th>
<th>Setup times (min)</th>
<th>Average</th>
<th>Standard deviation</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>C – AB/C – AB</td>
<td></td>
<td>72</td>
<td>24</td>
<td>0.3</td>
</tr>
<tr>
<td>C – C/AB – AB</td>
<td></td>
<td>57</td>
<td>25</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Currently there are three product groups: Product C, Product A and Product B. So, it is easy to allocate each product group to a specific line. Based on above description the following rule is made:

**Rule 2:** Allocate all Product C and doubles to packaging line 1, Product B products to packaging line 2 and Product A products to packaging line 3.

However, the total production and setup time of all products at one packaging line may not exceed the total cycle time of one month. This capacity restriction is checked during the last step of the allocation procedure.

**Step 3: Check capacity restriction**

Finally, for all the packaging lines the total production and setup times are calculated. Due to the fact that the demand and the production environment are not totally deterministic, there must be enough free time in each production wheel to deal with these uncertainties. Therefore, it is not allowed to fill the production wheels of the packaging lines up to a utilization of more than 90%. If this capacity is exceeded, then SKUs need to be reassigned until the required level of utilization is achieved for all the packaging lines. It is recommended to keep packaging line 1 untouched since reallocation of these products can have a significant impact on the setup times. This procedure of reallocation is a manual and iterative process and continues until all SKUs are allocated.

**Conclusion**

During the allocation procedure, all SKUs are dedicated to a specific packaging line. The goal of this allocation procedure is to achieve a balanced work load of all three packaging lines based on product characteristics and therefore also on setup time minimizing sequence of the SKUs. Result of this step is a list with which products need to be produced on which line. The frequency of production is important for the sequencing process which is described in the next section.

**5.3.3 Sequencing**

The goal of the sequencing step is to create a fixed optimized sequence. The current sequencing process is based on the delivery date of the PO, which means that there is no fixed sequence of production since the delivery dates of POs change from month to month. A fixed predefined production sequence provides visibility and predictability in the used production strategy. The total cycle length of the production wheels is one month, which is approximately equal to 4 weeks. This decision is based on the fact that all planning activities within the supply chain are designed for a monthly cycle. Moreover, this design decision is supported because the optimal cycle length (as calculated in step 2 of the lot sizing procedure) is equal to 2.17 weeks and therefore shorter than 4 weeks. Based on the monthly cycle, the production wheel is divided into four spokes with all a length of one week. Only the last spoke of the wheel has one or two working days extra depending on the length of the month. The following local search algorithm is developed to come with a feasible solution:
1) Make two clusters: single and doubles (only for line number 1)
2) Sort all SKUs within the cluster based on the same bulk component
3) Sort all SKUs within the cluster in ascending order of replenishment frequency
4) Sort all SKUs within the cluster in descending order of lot size
5) Dedicate SKUs with a replenishment frequency of 1 week to the beginning of each spoke
6) Dedicate SKUs with a replenishment frequency of 2 weeks to two spokes in a biweekly pattern
7) Calculate remaining time of each spoke by taking the difference of the available time per spoke (in hours) and the time that is consumed so far by production (in hours) \( \sum_{i=1}^{n} TT_i \), for all \( n \) products which are in the spoke so far

If remaining capacity is > 8 hours then go to 8), else go to next spoke and go to 8)

8) Select the first product, with the same bulk component as last dedicated product in the spoke, and with a \( TT_i \) smaller than the remaining time
9) Dedicate this product to the spoke
10) If all products are dedicated then go to 11) else go to 7)
11) Check number of POs produced per week
12) Check bulk consumption of vials with 50 widgets per week
13) If 11) and 12) are leveled then stop else reallocate SKUs to get both output indicators balanced.

Step 13) is a manual and iterative process and this process is performed until a good balance between the input and output of production is found. The leveled production is measured with the average bulk consumption per week and the number of POs per week. Since changes in the sequence have influence on both numbers, the last three steps of the procedure have to be performed manually. Result of the sequencing procedure is a setup minimizing fixed production sequence. Note that the sequencing procedure is only applicable for a cycle length of one month, since the used replenishment frequencies are based on this cycle length. This is a disadvantage of the designed procedure.

Conclusion
The predefined fixed sequence is optimized for setup time and leveled production process perspective. For each of the packaging lines a production wheel is determined based on the aforementioned decisions. Furthermore, it is important to emphasize that it is always possible to decide whether or not to produce a product. Products with a lower production frequency of once per month can be skipped for production. However, this means that CONTRACTOR always needs to be prepared to produce this product. A manual about how to build a production wheel is given in Appendix D.

5.3.4 Safety stocks
The last decision that is taken at the tactical level is related to the safety stocks. The level of safety stock is a tactical parameter since it is based on the lot sizes of the different SKUs (Sox et al., 1999). Nowadays, decisions about safety stocks are made at the operational level and are country specific at COMPANY. Each sales affiliate has its own rules regarding safety stocks. Safety stock decisions are made manually into the SAP® system of COMPANY. There is a target safety stock level of XXX DOH, but this level is for each country the same independent of the replenishment strategy.
Inventory policy

In order to calculate the safety stock levels the \((R, s, Q)\) inventory policy is used. The new calculated replenishment frequencies are equal to the review period \((R)\). Furthermore, the new calculated lot sizes are equal to \(Q\) in this inventory model. If the inventory is reviewed and below the re-order level \((s)\), a new replenishment of size \(Q\) is placed. According to Silver et al. (1998) the safety stock is defined as the average level of the net stock just before a replenishment arrives and can be calculated with the following formula:

\[
SS = k\sigma_L
\]

Where,
- \(SS\) = safety stock
- \(k\) = safety factor
- \(\sigma_L\) = standard deviation of forecast errors of demand over the lead time \((L)\)

The safety factor \(k\) depends on the measured customer service level and the demand distribution during the replenishment lead time. COMPANY measures the \(P_1\) service level, which is defined as the probability of not being out-of-stock just before a replenishment order arrives (Silver et al., 1998). COMPANY has a target service level of 98%. Moreover, the factor \(k\) depends on the demand distribution during the replenishment lead time. In order to check if it is beneficial to use the standard deviation of forecast errors instead of the standard deviation of the actual sales, both values are compared. For 69% of the in total 58 SKUs, the standard deviation of the forecast error is higher than the standard deviation of the actual sales. However, COMPANY is currently working on projects to increase the forecast accuracy and therefore it is recommended to use the standard deviation of the forecast errors for future safety stock calculations. Furthermore, COMPANY assumes that the demand during the lead time is normal distributed. The Mean Squared Error (MSE) is directly related to the standard deviation of errors of forecast of demand made for a unit period \((\sigma_1)\) and is calculated with the following formula (Silver et al., 1998):

\[
\sigma_1 = \sqrt{MSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(x_t - \hat{x}_{t-1,t})^2}
\]

Where,
- \(MSE\) = Mean Squared Error (MSE)
- \(x_t\) = actual demand of period \(t\)
- \(\hat{x}_{t-1,t}\) = forecasted demand of period \(t\), made in period \(t - 1\)
- \(n\) = number of time periods

Since the replenishment lead time is not equal to the forecast update interval, \(\sigma_1\) need to be converted to \(\sigma_L\). The exact relationship between \(\sigma_L\) and \(\sigma_1\) depends in a complicated fashion on the specific underlying demand model, the forecast updating procedure, and the value of the smoothing constants.
used (Silver et al., 1998). Moreover, the lead time ($L$) itself can also be variable and is dimensionless and equals an integer number of periods. The standard deviation of demand during lead time ($\sigma_L$) is calculated with the following formula (Silver et al., 1998):

$$\sigma_L = \sigma(D(0,L)) = \sqrt{E(L)\sigma_1^2 + [E(D)]^2\sigma^2(L)}$$

Where,

- $\sigma(D(0,L))$ = standard deviation of demand in a replenishment lead time
- $E(L)$ = expected length of lead time ($L$ is the number of unit time periods and dimensionless)
- $\sigma^2(L)$ = variance of length of lead time
- $E(D)$ = expected demand forecast in units, in a unit time period
- $\sigma_1^2$ = variance of forecast errors (=MSE)

Based on this formula of the standard deviation of the demand during lead time, the safety stock levels can be calculated. A goodness of fit test is used to test the distribution of the forecast errors. The gamma and the normal distribution are tested and it showed that the normal distribution fits in 61% of the selected SKUs. This means that the gamma distribution fits in 39% of the cases. Based on this statistical test it is assumed that demand is normal distributed. Furthermore, the $P_1$ service level is equal to 98%. This assumption is based on the current service level calculations of COMPANY. The $P_1$ measure is used by SAP and therefore COMPANY uses this measure also for safety stock calculations. However, as explained in Chapter 4, the $P_2$ measure performs better in cases with a large order quantity ($Q$) and therefore it is recommended to use the $P_2$ measure in the future. Now, all new re-order levels ($s$) can be calculated with the following formula (Silver et al., 1998):

$$s = E[D(0,L)] + k\sigma(D(0,L))$$

The first part of this formula ($E[D(0,L)]$) is the forecasted demand during lead time and the second part of this formula is equal to the safety stock level. Now, all variables of the ($R, s, Q$) inventory model are calculated and also the last tactical parameter is determined.

5.4 Operational level

After all tactical parameters are determined the production wheel has to be controlled at the operational level (see Figure 15). As is described in Günther et al. (2006) the block planning concept or production wheel is easy to understand. However, it is important that both parties keep stick to the designed production wheel. This section gives the rules in order to ensure that the established production wheel works at an operational level. First, the rules for COMPANY are discussed.

5.4.1 Rules COMPANY

The different production slots of each SKU are based on lot sizes which are near the optimal lot sizes. This means that with these lot sizes the total yearly demand is covered. Of course the demand of SKUs is not deterministic and therefore the requested quantities can differ from wheel to wheel. However, these changes in lot sizes have to be respected over a longer time period. So, COMPANY is not allowed to do substantially changes each period in the lot sizes. Lot sizes are tactical parameters and therefore these parameters do not have to be changed at the operational level.
Furthermore, the order pattern from COMPANY needs to be adapted to the sequence of the production wheel. An advantage is that the requested delivery date of the POs is closer to the production date of the POs since for COMPANY it becomes visible when each product is produced. A disadvantage of the fixed sequence is that COMPANY sometimes has to wait for a new replenishment until the next production slot of that SKU. However, the new determined safety stock levels should avoid out of stocks. Furthermore, there must be sufficient free capacity in each production wheel to react on demand changes.

Finally, COMPANY has to keep track of the inventory settings. The inventories have to be tracked in order to ensure that the parameters (e.g. safety stocks) are set at the right level. Control of the stock points is really important since COMPANY always wants to avoid any stock outs. That is also one of the reasons why safety stock decisions are adjusted at the moment at this level.

5.4.2 Rules CONTRACTOR
The rules for CONTRACTOR at the operational level become easier with the implementation of the production wheel. Since there is a fixed production sequence for all of the lines, CONTRACTOR does not have to take care anymore about the detailed scheduling process of the vial lines. After each production run, COMPANY must decide whether to start production or whether to skip production of the next product. However, this implies that CONTRACTOR must always be prepared to produce all products within the production wheel and therefore also the related packaging materials should be available. This means that the probability whether a SKU has to be produced or not can differ.

The overall main goal of the operational level is to control the production and planning process (Hopp & Spearman, 2008). This control results in a feedback loop to both strategic and tactical decisions (See Figure 15). The control process of CONTRACTOR influences decisions on a strategic level about the capacity plan for the future. Due to the fixed production sequence, CONTRACTOR can improve the setups and therefore the productivity of the production lines is expected to increase in the future. This information is required for new strategic decisions about the production capacity.

5.4.3 Exception Management
Due to demand changes or disruptions in the production environment it can occur that exceptions are required. For instance, if one of the packaging lines break down then this line has to be rescheduled to meet the order due dates. Therefore, there must be always sufficient free time to deal with these uncertainties in the production environment. Furthermore, the designed production wheels must have sufficient free time to deal with small changes in the demand. A small increase or decrease of the proposed lot size has also impact on other tactical decisions and therefore these changes always have to be taken with respect to the proposed lot sizes. These small changes must be at a normative level.

In general, it is not allowed to adjust the sequence or lot sizes of the production wheel. The production wheel is beneficial if both parties follow the rules of the wheel. In any case of exceptions, it is recommended to discuss with both parties whether changes in sequence or quantity are really necessary and what the impact is of this exception on the remaining part of the production wheel. Therefore, one of the disadvantages of the production wheel is that the production flexibility of CONTRACTOR is reduced.
5.5 Conclusion
In this chapter the redesign of the new production strategy is given by decomposing the problem into three planning levels: strategic, tactical and operational (Kok & Fransoo, 2003). Decisions at a strategic level are used to check the prerequisites of the production wheel. The decisions at the tactical level are most important for the design of the production wheel. Those decisions are related to: lot sizes, allocation, sequence and safety stocks. In order to ensure that the production wheel provides any benefits it is crucial that both parties follow the rules of the designed wheel.
6 Case study

In the previous chapters a framework is designed to build a production wheel for each of the packaging lines at CONTRACTOR. The purpose of this chapter is to provide a production wheel for each packaging line and this is used for a proof of concept of the developed redesign. The first step in the redesign is to determine the most optimal lot sizes according to the formula of the Economic Production Quantity. In order to determine these lot sizes some assumptions are made about the used variables.

6.1 Lot sizes

6.1.1 Assumptions

First, the fixed setup costs of product $i$ ($A_i$) are assumed to be €XXX per hour and based on a reference packaging line located in Leverkusen. This fixed setup costs per hour is multiplied by the individual setup times of a product ($ST_i$). Therefore, the setup costs are SKU specific. Second, the interest rate ($r$) is assumed to have a value of XXX%, which is equal to the interest rate in SAP®. Next, the setup time ($ST_i$) and production time ($PT_i$) of product $i$ are calculated based on production data from September-November 2012. Finally, the production rate ($P_i$) is defined as the amount of vials which could be produced if the full production capacity is used for product $i$. As mentioned in section 5.2, the total production capacity ($C$) is assumed to be 18,000 hours.

6.1.2 Replenishment Frequencies

Based on these assumptions the optimal lot sizes and replenishment frequencies are calculated for each product $i$. The results of these optimal replenishment frequencies are given in Figure 17. The figure shows that 57% of the SKUs have to be replenished within 4 weeks, which is approximately equal to one cycle of the production wheel. Due to the shelf life of the widgets, the maximum replenishment frequency is set to 13 weeks for 8% of the SKUs. The adjusted lot sizes and replenishment frequencies are shown in Table 1-3 of Appendix E.

6.1.3 Cycle length

After the adjustments of supply frequency and pallet size, 74% of the SKUs are produced at least once per month. This also means that 26% of the products have a replenishment frequency which is larger than one month. Figure 5, 6 and 7 of Appendix E give an overview of the probability distribution of the different cycle lengths. The figures show that there are four different cycle lengths for each production wheel and that the cycle lengths also differ between the three production wheels. Based on these three figures the average cycle length is determined.
6.2 Production wheels
The adjusted replenishment frequencies are used to determine the production frequency of each product in each wheel. For each of the packaging lines a production wheel is designed based on the allocation and the sequencing procedures as is explained in section 5.3.2 and 5.3.3 respectively. All packaging lines produce at full capacity, which means that each line operates 24 hours/day. At the end of each spoke free time is implemented in order to give CONTRACTOR flexibility within the production wheel to deal with uncertainties of the production and setup times. Moreover, this free time ensures that the required replenishment frequencies are always established.

6.2.1 Packaging line 1
The first packaging line is completely dedicated to all doubles and Product C products. Figure 18 shows the sequence of production at an aggregated bulk level. Most of the SKUs are produced from Product C vials with 50 widgets. Furthermore, the production wheel has two blocks with the production of doubles, which start both with a production run of Product B vials with 50 widgets. Intermediates and finished goods are differentiated to inform CONTRACTOR about the timing of production of these products. Table 1 of Appendix D gives the production sequence at a more detailed level.

6.2.2 Packaging line 2
The second packaging line is used to produce Product B products. Since there are no setup time restrictions for this type of products, it is assumed that the proposed sequence is always setup time optimized. Again, first the products which need weekly production are placed at the beginning of each spoke. Afterwards, all spokes are filled according to the sequence procedure as is described in section 5.3.3. Most of the products produced on this line are vials with 50 widgets. The final production wheel of this line is shown in Figure 19. The sequence at a SKU level is shown in Table 2 of Appendix D.

6.2.3 Packaging line 3
The third packaging line is dedicated to Product A and Product A Plus bulk products. Figure 20 shows the design of the production wheel at bulk component level. Product A Plus is a new product and launched during this year. The detailed production sequence is shown in Table 3 of Appendix D. Approximately XXX% of the products are produced from Product A vials with 50 widgets. Consumption of this bulk product is balanced during the sequencing procedure.
6.2.4 Block planning

The designed production wheels can be rolled out over the total cycle length of one month, which is assumed to be 21 working days. Figure 21 gives the results of the designed production wheel of packaging line 2 and shows four green blocks for the production of Product B vials with 50 widgets. The orange blocks represent free time at the end of the week. The goal of this free time is to provide flexibility within the weeks to deal with changes in the demand and in the production environment. It is important that the total cycle length of one month is not exceeded (Günter et al., 2006). Furthermore, this additional free time gives CONTRACTOR the opportunity to ensure that production of the next spoke can always start at the beginning of the next week. This is to ensure that the proposed replenishment frequencies of SKUs are in line with the production frequencies of these products. Due to the fixed production sequence, the timing and quantity of production is also fixed. The production wheel provides more predictability in the production strategy. Moreover, the fixed production sequence gives CONTRACTOR the opportunity to improve the setups and achieve a higher productivity of the packaging lines.

![Production wheel line 2 with production blocks](image)

Figure 21: Production wheel line 2 with production blocks

The designed blocks of widgets can be used in the implementation phase of the redesign. This is explained in Chapter 8. The other two production wheels are shown in Figure 8 and 9 of Appendix D.

6.3 Safety stocks

Decisions of the safety stocks are based on the proposed lot sizes and on the new replenishment frequencies and therefore on the safety stock settings.

6.3.1 Variables

The expected length of the lead time \( E(L) \) and the variance of the lead time \( \sigma^2(L) \) are based on data from the TM3 system, which stores all transportation data of COMPANY. This transportation time contains: (1) the waiting time at CONTRACTOR, (2) the transportation time from CONTRACTOR to the hub (3) the waiting time at the hub and (4) the transportation time from the hub to the sales affiliate. The length of the lead time is product and country specific. Furthermore, the forecast errors are calculated based on the difference between the forecast and the actual sales of 2012. The forecast errors are statistically tested and show a good fit with the normal distribution.

6.3.2 Validation

According to Sox et al. (1999) decisions about safety stocks should be part of the tactical decision making process. In the current situation this is not the case and moreover these decisions are not for each SKU based on any formula. Each country can change the safety stock settings manually in SAP® and often the safety stock level is a result of a negotiation between the countries and Basel. In general COMPANY has a
target $P_1$ service level of 98%, but the target safety stock setting is XXX DOH independent of the standard deviation of demand during lead time. The new safety stocks are calculated based on the formulas from section 5.3.4. The results of these calculations are validated with the Excel spreadsheet “Classical Inventory Models” of de Kok (2002). The new safety stocks are based on a service level and not on a number of safety days. As a result not all safety stocks are equal to XXX DOH. For instance Product A in Country A has a safety stock of XXX DOH, which gives a significant inventory reduction.

6.4 **Proof of concept**
The next step is to discuss the modeling errors and how to deal with these errors. These modeling errors are based on assumptions that are made. This section provides a proof of concept of the redesign.

6.4.1 **Demand changes**
One of the assumptions of calculating the optimal lot sizes is that demand is deterministic and constant over time. Hence, one of the assumptions is that the demand forecast is equal to the real demand. As is shown in section 4.2, the final PO quantities are over forecasted at an aggregated level with XXX% and at a SKU level the forecast bias can be even bigger. Moreover, the demand forecast becomes less reliable if the forecast horizon increases (Silver et al., 1998). This indicates that the assumed demand is too high compared to the real actual demand and this results in a lower reorder level $s$ and order quantity $Q$.

6.4.2 **Production environment**
In order to ensure future demand is fulfilled in the most optimal lot sizes, the production capacity is increased from 6 to 9 crews. However, production managers at CONTRACTOR do not expect that this is really necessary in the future since demand is not sufficient. Moreover, CONTRACTOR does not have sufficient warehouse capacity at the moment to increase the number of crews. This is a managerial decision which has to be made among CONTRACTOR and COMPANY. However, if the production capacity not increases to 9 crews, the proposed lot sizes are not implementable.

Furthermore, it is assumed that each batch is produced from one work order. Currently CONTRACTOR has to create multiple work orders from one PO, especially for large orders. As a result, in real life more setups are required to produce one single PO. Due to the fact that the lot sizes are decreased, it is assumed that CONTRACTOR can dedicate one single work order to one PO. The model assumes that the setup- and production times are deterministic. As is shown in Table 3, there is variability in both parameters. Currently, COMPANY is working on several projects to decrease the setup times at CONTRACTOR, which means that the setup times are decreasing. Therefore, the setup times which are used for the case study, are not up to date anymore.

Moreover, the production wheel concept assumes that all required products (i.e. packaging materials and widgets) are always available for production. However, as is shown in the problem analysis this is not always the case. If products are not available for production then CONTRACTOR and COMPANY must skip the SKU and start with production of the next product. So, this is an important assumption of the concept.

6.4.3 **Cycle length**
The cycle length is a decision which is made on a strategic level since all supply chain planning activities of COMPANY are taken on a monthly level. The optimal cycle length is equal to 2.17 weeks, which is less
than one month and therefore allowed. If the length of the production wheel differs from one month, than the replenishment frequencies and sequencing steps must be adapted to the new cycle length.
7 Results

The impact of the designed production wheel consists of two parts. First, the current production strategy of CONTRACTOR will change. Decisions related to the lot sizes, allocation and sequence have impact on (1) the utilization of the three packaging lines and on (2) the number of POs produced per week. Second, there is an impact on the three types of inventories, which are discussed in section 7.2.

7.1 Impact production CONTRACTOR

7.1.1 Utilization

Since the production wheels are designed with a deterministic model, there should be sufficient free time at each packaging line to deal with uncertainties in the demand and/or production environment. Table 5 shows the capacity utilization of the three packaging lines. It is assumed that all available production capacity is used. At packaging line 1 the blocks with doubles are produced and therefore the average percentage setup time is higher at this line compared to the other two lines (see Table 3). Furthermore, Table 5 shows that the overall utilization of this packaging line is approximately 66% and therefore the free time is almost 34%. Reduction of the numbers of crews at this packaging line from 3 to 2 gives a very tight schedule, with absolutely no free time anymore. It is important that the total cycle length of the production wheel is not exceeded. Therefore, additional free capacity is required do deal with changes in lot sizes and production disruptions. During the remaining free time the crews can be trained to improve the setups.

7.1.2 Production output

The production wheel is able to level the production load of CONTRACTOR. One of the steps in the sequencing algorithm is to balance the number of orders per week. This step ensures that the workload after production is also leveled over time and therefore the production output is leveled too. Figure 22 and Figure 23 show the minimum and maximum number of POs per week. The minimum number of POs is equal to the number of POs which have a replenishment cycle shorter than 1 month. In order to keep this output balanced over time, CONTRACTOR has to follow the rules of the blocks which are built within the production wheel. The total minimum and maximum number of POs is 69 and 84 respectively. Due to the new lot sizes, the number of POs increased from 46 to at least 75. This means an increase of 50% and therefore also the workload of quality control and administration is doubled in the new situation.

<table>
<thead>
<tr>
<th>Table 5: Capacity utilization of the three packaging lines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Setup time</td>
</tr>
<tr>
<td>Processing time</td>
</tr>
<tr>
<td>Free time</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Figure 22: Minimum number of POs per cycle

Figure 23: Maximum number of POs per cycle
7.2 Impact inventories

The new designed production wheels also have an impact on the inventories of widgets. Three types of inventories are discussed in this section: 1) widgets, 2) work in process and 3) finished goods.

7.2.1 Bulk widgets

During the design of the production wheel the consumption of widgets is leveled. One of the major problems in the current production planning process is that the production quantities are not equally distributed over the weeks. Therefore, CONTRACTOR has to produce POs ahead and this has to be avoided with the new production strategy. The maximum, average and minimum of produced vials per week are shown in Figure 25. Since most of the SKUs are produced at least once per cycle, the difference between the minimum and maximum produced vials per cycle is small. This means that if all SKUs have to be produced the output of vials is also leveled over time.

Since 85% of the SKUs are produced from vials with 50 widgets, also the consumption of these specific bulk products is leveled during the sequencing process. Figure 24 shows that the maximum, minimum and average bulk consumption per week for Product B vials with 50 widgets is the same since SKUs of this bulk component are always produced. This bulk product is used for 33% of the total produced vials. In order to balance the inventory capacity and the arrival process of this bulk product, it is important that the consumption is leveled over time. This leveling is also part of the developed sequencing heuristic in the redesign.

Moreover, the total inventory of widgets can be reduced due to the implementation of the production wheel. Since the sequence of production is always fixed, the arrival process of widgets can be aligned with this wheel. This means that COMPANY knows exactly at which point in time the bulk components are required for production. In the current replenishment strategy of widgets, there is always one month of stock available at CONTRACTOR. Due to the synchronization it is expected that these stocks can be reduced to XXX weeks, which is already a reduction of approximately XXX% and equal to XXX DOH. Note that this reduction is not quantified in this study and therefore this is an approximation.

7.2.2 Work in process

In Figure 12 it is shown that the average time between orders completed from production and released as finished goods was on average XXX days. This is caused by the preproduction of CONTRACTOR which is necessary to fulfill the high peaks of demand in the beginning of the month. Due to the production wheel it is assumed that this preproduction is not necessary anymore. The workload of CONTRACTOR is now
better distributed across the month. The delivery dates of POs are aligned with the production strategy of CONTRACTOR and therefore having the same sequence and timing. As a result, the waiting time of products between ‘completed’ and ‘sent from JDE’ is expected to reduce. As soon the step ‘sent from JDE’ is performed, orders are booked as finished goods.

![Graph: Savings for number of days produced ahead](image)

**Figure 26: Absolute inventory savings due to preproduction**

The average yearly savings due to the production wheel are shown in Figure 26. This figure shows that if for instance the maximum number of preproduction can be reduced to zero days, the annual saving for this type of inventory was €XXX in 2012. These products are still in the books as bulk components and have a value of €XXX. The interest that is missed with this preproduction in 2012 is equal to €XXX. This potential inventory reduction is based on the best case scenario and is only achieved if the ordering plan of COMPANY is exactly in the same pattern as the production plan of CONTRACTOR.

### 7.2.3 Finished goods

The inventory at finished good level, at the sales affiliates, is expected to reduce on two types of stocks: cycle stocks and safety stocks. This type of inventory reduction is not caused by the production wheel, but by the fact that for the design of the production wheel the most optimal lot sizes are used. Furthermore, it is assumed that orders are immediately shipped from CONTRACTOR to the countries. This means that orders have no waiting time at the hub, which disturbs the designed replenishment frequencies.

**Cycle stocks**

For most of the products the lot sizes are reduced with the designed production wheel. Due to this lot size reduction the replenishment frequencies are increased. An increase of the replenishment frequencies impacts the cycle stocks of the finished goods. The new replenishment frequencies are used to simulate the impact of the production wheel on the cycle stocks. Figure 27 shows an example of the improvements in cycle stock for one specific SKU. The figure shows that the average cycle stock reduces with the implementation of the production wheel. During the simulation the total produced volume of each product is kept the same and therefore the ending inventory is the same in both scenarios. The only two parameters that are changed are the lot size and the replenishment frequency.

For each SKU the new inventory level, with new production strategy, is compared with the old inventory level. Product B products are not included in the calculations for the annual savings, since these products were launched in 2012 and therefore the inventories of these products are not representative for the complete portfolio. This means that the impact of the new lot sizes is only tested on the Product A and Product C product line and afterwards adjusted for the complete portfolio of SKUs.
The new production strategy provides an inventory reduction on cycle stocks of €XXX in 2012. Note that this inventory reduction is only a one-time effect because the inventory can be reduced only one time due to the new proposed lot sizes. However, the inventory level is constantly on a lower level from then on which leads to annual savings compared to the old situation. Furthermore, the annual savings of 2012 are €XXX if the production wheel was implemented. These annual savings are the so-called opportunity costs and are cost reductions. In total COMPANY could have saved €XXX in 2012 if the new replenishment frequencies were used, which is on average equal to XXX DOH inventory reductions. This number is confirmed by the involved team of COMPANY.

Note that these savings are not a result of the production wheel, but of the new proposed lot sizes. The production wheel is only the tool to communicate the new production strategy between CONTRACTOR and COMPANY.

Safety stocks
The second type of inventory reduction is related to the safety stocks. Due to the new proposed lot sizes and replenishment frequencies the safety stocks of finished goods can be reduced. The current safety stock settings of finished goods are not based on formulas, since each sales affiliate can adjust the settings manually. In order to determine the impact of the production wheel on the safety stocks, the formulas from section 5.3.4 are used for both scenarios. The old replenishment frequencies are compared with the new proposed replenishment frequencies. This has an impact on the standard deviation of the demand during lead time \( \sigma(D(0,L)) \) since the time between two replenishments is changed for some products. Therefore, the only parameter that is changed in the comparison is the replenishment frequency.

Due to the new proposed replenishment frequencies COMPANY is able to reduce the safety stocks of the finished goods with €XXX which means an inventory reduction of 9%. Furthermore, the opportunity costs are equal to €XXX and are the annual cost savings due to the interest rate of XXX%. This means that the total savings on safety stocks are €XXX if the production wheel is implemented. Since the current safety stock calculations are manually changed and therefore the service levels for each country differ, it is difficult to calculate the real savings on safety stocks. From theoretical perspective the inventory reduction would be €XXX (XXX DOH), but in practice the savings could be different. Therefore, this saving is used as a theoretical indication of inventory reduction.
In order to determine the impact of the assumption that the demand has a normal distribution, the same calculations are made with a gamma distribution. All other parameter settings are kept the same. The results are calculated with the Excel spreadsheet “Classical Inventory Models” of de Kok (2002). When the same parameters are used, the $P_1$ service level of SKUs reduces. For one product the comparison is shown in Figure 10 of Appendix E. The average $P_1$ service level reduces from 98.00% to 96.30% when the gamma distribution is used instead of the normal distribution. This has an impact on your safety stocks, since more safety stock is needed to cover the same service level of 98%.

### 7.2.4 Total Relevant Costs

The Total Relevant Costs (TRC) of the lot sizing procedure are shown in Table 6 and shows that the TRC of the optimal lot sizes is equal to € XXX. Since these optimal lot sizes are a trade-off between setup and inventory holding costs, these costs are the same in the step 1. The TRC for the optimal cycle length are increased with XXX% compared to the optimal lot sizes, due to the fact that each product is produced once per cycle. After the optimal lot sizes are revised for supply frequency and adjusted for full pallet sizes, the TRC are almost doubled to € XXX compared to the scenario with the EPQ. This is caused by the fact that for some products weekly replenishments are increased to monthly replenishments due to supply contracts with third parties. As a result, the setup costs are reduced with XXX% to € XXX and the inventory holding costs are increased with XXX% to € XXX. This indicates that the inventory holding costs have a big impact on the total costs.

<table>
<thead>
<tr>
<th>Step</th>
<th>TRC (€)</th>
<th>Setup costs (€)</th>
<th>Holding costs (€)</th>
<th>Total time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1: Optimal lot sizes</td>
<td>€ XXX</td>
<td>€ XXX</td>
<td>€ XXX</td>
<td>13,690</td>
</tr>
<tr>
<td>Step 3: Optimal cycle length</td>
<td>€ XXX</td>
<td>€ XXX</td>
<td>€ XXX</td>
<td>14,047</td>
</tr>
<tr>
<td>Step 6: Adjusted lot sizes</td>
<td>€ XXX</td>
<td>€ XXX</td>
<td>€ XXX</td>
<td>14,428</td>
</tr>
</tbody>
</table>

Furthermore, Table 6 shows that due to the lot size adjustments the total time to produce all orders for 2013 increases with 5% to 14,428 hours. These adjustments are required to avoid partial shipments.

### 7.3 Conclusion

This chapter showed that the new production strategy has impact on both the production environment of CONTRACTOR and on inventory levels. The production strategy makes use of the full production capacity and each packaging line has free time to deal with disruptions in the production process. Furthermore, it is shown that the number of POs and the production quantity per cycle is better balanced across the month. This is one of the major problems in the current situation and can be solved with the implementation of the production wheel concept.

A leveled production output has also impact on the consumption of widgets. During the sequencing process of SKUs the bulk consumption of vials with 50 widgets is checked and is balanced across the weeks. Furthermore, the production wheel can eliminate the preproduction of POs, since the workload of CONTRACTOR is leveled in the new situation. As a result, POs are produced more close to the delivery date because the ordering plan of COMPANY is aligned with the production plan of CONTRACTOR. Finally, it is shown that the new proposed lot sizes and therefore the new replenishment frequencies save costs on cycle- and safety stocks. However, this cost reduction can only be achieved if the transportation frequencies are also synchronized with the production frequencies.
8 Implementation

The implementation of the redesign is an important step in order to ensure that both companies benefit from the new production strategy. In chapter 4 the problem analysis and diagnosis phase is performed. Most of the problems are related to the information sharing process between both companies. The order plan of COMPANY is not in line with the production plan of CONTRACTOR and it is shown that the production wheel is a good tool to give insight in the production strategy. The implementation process consists of two parts: the organizational and technical implementation. Both processes can be undertaken at the same time, however it is recommended to first have a common understanding about what the production wheel exactly is. Only if both companies are really convinced that the production wheel provides benefits for them, the implementation will work. The technical as the organizational implementation are described in this chapter.

8.1 Organizational implementation

Based on the indicated problems in chapter 4 a quick win is highlighted: provide detailed information about the bulk batch sizes. This information gives CONTRACTOR the opportunity to dedicate specific bulk batches to work orders and is already available at COMPANY. Furthermore, based on the problem analysis it is shown that most of the issues are related to the information sharing process between both companies. Therefore, the first step is to solve the current issues between both parties.

After these problems are solved the organizational implementation process of the production wheel can take place. The organization implementation is the most difficult process since it is important that both parties follow the rules of the wheel in order to gain the benefits from it. In general the implementation contains the following steps:

1. **Explain the concept**
   The production wheel can only work if both parties have a clear and common understanding about what the rules are. It is important that the rules are followed correctly. Furthermore, both companies have to be convinced that this new production strategy gains benefits for them.

2. **Design production wheel**
   The variables (e.g. demand forecast, setup times, COGS) have to be updated to ensure that the sequence is setup time minimized. The thesis provides the steps for lot sizing, allocation and sequencing in order to build the wheel. It is recommended to involve operational managers of CONTRACTOR in this decision making process. This will increase their support to implement the production wheel.

3. **Start pilot**
   In order to ensure that both parties get familiar with the rules and concepts, the first start is to implement a production wheel at only one packaging line. This means that for all other products, which are not produced on this line, the old replenishment frequencies are used.

4. **Communication with CONTRACTOR**
   As soon as the first production wheel is implemented, it is recommended to have frequently calls between CONTRACTOR and COMPANY. During the first month there should be daily calls to discuss any issues or problems related to the wheel. These discussions are important to keep control of the performance of the wheel. The second and third month there should be weekly calls.
5. **Update production wheel**

After 3 months the production wheels have to be updated and revised. Different parameters of the production wheel could have been changed (e.g. demand forecast, setup times) which have an influence on the performance of the wheel.

Furthermore, the following steps are related to the synchronization of all other supply chain planning activities of COMPANY. Since the production wheel is implemented in the middle of the supply chain, both upstream and downstream processes have to be aligned to gain from the benefits.

6. **Synchronize transportation process**

Based on the designed production wheel at CONTRACTOR, the transportation processes to the countries have to be aligned. This means that the production frequencies should be the same as the transportation frequencies.

7. **Synchronize bulk arrivals**

The replenishment pattern of bulk components have to be aligned with the production wheel.

8. **Adjust safety stock settings**

The current safety stock settings have to be adjusted based on the new replenishment frequencies. This can be performed if the transportation process is synchronized with the production process.

Finally, it is important that both companies are convinced that the production wheel is beneficial for them. Both parties have to collaborate and communicate to ensure that the wheel is correctly working.

**8.2 Technical implementation**

The planning systems of CONTRACTOR and COMPANY are not integrated and therefore the production wheel is a good tool to synchronize the supply chain planning activities of both companies. Implementation of the production wheel is relatively easy for COMPANY since a module called ‘block planning’\(^1\) is already available in SAP®. The general idea of the block planning concept is that demand is backward scheduled to the predefined blocks and this is shown in Figure 28.

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\(^1\) [http://help.sap.com/saphelp_scm50/helpdata/en/5f/6d9041e6edda009e10000000a155106/frameset.htm](http://help.sap.com/saphelp_scm50/helpdata/en/5f/6d9041e6edda009e10000000a155106/frameset.htm)
The block planning concept has influence on the MRP run. The planner has to perform the following steps:

1. Create virtual resources (one resource for each production wheel)
2. Define block definitions on these resources
3. Tell MRP to consider the block planning principles

After this, the system will place the planned orders in the right blocks. Figure 28 shows all demand is placed in a predefined block. The block definitions are a result from the production wheel. In order to reduce the number of block definitions it is recommended to define these blocks only for the big bulk components and not on a detailed SKU level. Finally, the planner has to redesign the blocks each time the production wheel is updated.

Since CONTRACTOR does not have the same planning system as COMPANY it is recommended to provide them a list with the fixed sequence of SKUs which have to be produced on each line. A simple and effective tool could be an Excel file with the fixed sequence for the upcoming three months (see for example Table 1 of Appendix E). This list is updated each time the production wheels are revised. Furthermore, CONTRACTOR should be involved during the decision making process about the design of the production wheels. This involvement will lead to a higher commitment to implement the production wheel.
9 Conclusion
This chapter presents the general conclusions based on the research questions (9.1) and provides some recommendations for COMPANY (9.2).

9.1 General conclusions
The main cause of the unbalanced inventory levels was the unknown current production strategy of CONTRACTOR. The planning process of CONTRACTOR is mapped and data analysis shows that the ordering plan of COMPANY is not in line with the production plan of CONTRACTOR. As a result, both companies have to negotiate about the final delivery dates of POs, since the POs are not equally distributed across the month. Furthermore, CONTRACTOR has to produce POs on forehand, in order to deal with the high demand peaks at the beginning of the month. The order plan of COMPANY is driven by the system and therefore COMPANY is not aware of these high demand peaks. Most of the identified problems are related to a lack of communication about the planning processes of CONTRACTOR and COMPANY. For instance, the highest ranked problem is that CONTRACTOR has no detailed information about how the bulk batch sizes are distributed in a new replenishment from SUPPLIER. However, CONTRACTOR never requested this information and therefore COMPANY was not aware that this information could be a quick win.

The inventory levels of widgets showed that the arrival process of widgets is not in line with the production process of CONTRACTOR and therefore the inventories are unbalanced. Both lead times and inventory levels are above COMPANY’s target levels. Furthermore, the arrival process of bulk components shows a high level of variability. This is another indicator that the inventories of widgets are not aligned, resulting in unbalanced inventories of widgets.

What are the consequences of the production wheel concept for the optimal production lot sizes, production frequencies and safety stock settings of finished goods?
The identified problems are used as a starting point for the first research question. For each of the packaging lines a production wheel is designed. The purpose of the production wheels is to level the production capacity at CONTRACTOR and to make the production strategy of CONTRACTOR visible and transparent. A procedure has been developed which determined the three tactical parameter settings of the production wheel: lot sizes, allocation and sequence. First, for all SKUs the optimal lot sizes are calculated based on the Economic Production Quantity. These lot sizes are adjusted for supply frequencies and full pallet quantities. One characteristic of the production wheel is that the production sequence is fixed and setup times are minimized. Furthermore, the production wheel gives the opportunity to skip production of a SKU if there is no demand. All products are dedicated to one of the three packaging lines and sequenced according to product characteristics which minimized the setup times. Moreover, the new lot sizes also influenced the safety stock levels since lot sizes become smaller and replenishment frequencies increased.

What is the impact of the production wheel concept on the inventory levels of finished goods?
The designed production wheels show improvements on the production output of CONTRACTOR (i.e. balanced amount of POs and vials across the month). Furthermore, the designed production wheels show sufficient free time to deal with uncertainties in the demand and the production environment. The
impact of the new production wheels on the finished goods inventory levels is compared with the old replenishment strategy. The comparison shows that COMPANY could save costs on cycle and safety stocks. Note that these savings can only be achieved when the transportation process to the sales affiliates is aligned with the packaging process of CONTRACTOR. If the designed production wheels would have been implemented at the beginning of 2012, the savings in 2012 on cycle and safety stock were approximately €XXX million and €XXX million, i.e. totaling €XXX million and equal to XXX DOH. This means that the total supply chain inventory is reduced from XXX DOH to XXX DOH and therefore the target inventory level is reached with implementation of the production wheel concept. This inventory reduction is achieved by decreasing lot sizes and higher replenishment frequencies. Besides, the inventory levels of bulk components can be reduced by the implementation of the production wheel. The production wheel shows that preproduction of POs is not necessary anymore since the ordering plan of COMPANY is aligned with the production plan of CONTRACTOR. Additional inventory improvements can be achieved by the synchronization of the arrival process of bulk components with the packaging process.

How does this new production strategy influence the communication between CONTRACTOR and COMPANY?

The last objective is to give rules and concept to communicate this production wheel in the future. Lot sizes are a tactical parameter, which means that significant changes in lot sizes at an operational level disturb the decision making process. Therefore, it is recommended to adjust lot sizes with a normative level. Both parties have to stick to the predefined sequence which means avoidance of exceptions in general. However, any exceptions have to be discussed and the free capacity at the end of each block can be used to setup production of rush orders. Furthermore, the fixed sequence gives reproducibility in the production and planning processes. Revision of the production wheel takes place every three months, based on new information from the market and production environment. Furthermore, CONTRACTOR and COMPANY should have contact on a weekly basis in order to discuss issues regarding the production wheel. Communication is essential to ensure that both companies benefit from the production wheel.

In general, it is found that new lot sizes lead to significant savings on cycle and safety stocks of finished goods. Furthermore, the production wheel gives transparency in the production strategy of CONTRACTOR, which is important for an improvement in the communication between COMPANY and CONTRACTOR. Due to the production wheel the supply chain planning activities of CONTRACTOR and CONTRACTORbecome more predictable and it is assumed the inventory levels of widgets become more balanced and the number of DOH can be reduced from XXX to XXX. Finally, both supply chain planning processes become more dependent and synchronized with the production wheel concept.

9.2 Recommendations for COMPANY

Besides the production wheel, there are some recommendations for COMPANY as a result from the analysis.

9.2.1 Business case

This report shows the potential savings on inventories of finished goods. In order to determine whether the new production strategy is really beneficial for both parties, all additional costs have to be
calculated. Due to smaller lot sizes, the number of POs increases and this means an increase in workload for warehouse, quality control and administrative activities. The proposed model assumes that the number of crews increases from 6 to 9 to fulfill forecasted demand with the proposed production wheel. It is important to take these extra labor costs into account. However, since the labor costs are relatively low, these extra costs are assumed to be relatively low compared to the additional savings on inventory levels. Furthermore, the additional cost savings on inventories of widgets have to be determined. These cost savings are a result of the synchronization process of the supply chain planning activities.

9.2.2 Forecast accuracy
The problem analysis shows that the low forecast accuracy is the other main root cause for the unbalanced inventories of widgets. In general, the sales affiliates are over forecasting the final POs with approximately XXX% in the last 3 months of 2012. However, on SKU level the forecast accuracy can deviate even more. Since ordering decisions for bulk components are binding for all other supply chain activities, it is recommended to improve the demand forecast. The demand forecast has impact on all supply chain activities, since the sales affiliates are replenished based on make-to-stock principles.

9.2.3 Service measure
During this project the impact of the new production strategy on safety stock levels is calculated. Safety stock calculations are based on the P₁ service level. This service level is defined as the probability of not being out-of-stock just before a replenishment order arrives. However, the P₁ measure is independent of the order quantity Q and therefore it is recommended to use the P₂ measure in the future. Especially, in cases with large order quantities the P₂ measure is a better service level. Furthermore, there must be a common understanding about what this service level exactly measures and what is measured as service.

9.2.4 Synchronize other supply chain activities
Based on the designed production wheel, COMPANY is able to synchronize all other supply chain activities. For the upstream synchronization of bulk components, COMPANY has to cooperate with SUPPLIER. The designed production wheel at CONTRACTOR determines at which point in time the replenishment of bulk components is required. This means that the arrival of bulk components can be synchronized with the packaging process. During the sequencing process of the SKUs, the bulk consumption is also taken into account. With the designed production wheels the bulk consumption of vials with 50 widgets is leveled. When the arrival process of widgets is aligned with the new production strategy, the material flow of bulk components is more smoothed over time. The service levels of the inventory levels of widgets have to be measured too. It is recommended to use the P₂ service measure.

Finally, the downstream supply chain activities also have to be aligned. The designed production wheels are based on lot sizing principles and therefore some products are produced more frequent compared to the current situation. To benefit from these new lot sizes, COMPANY has to synchronize the transportation frequencies to the sales affiliates with the designed replenishment frequencies. This synchronization is a challenge since orders are consolidated at a hub. Consolidation can disturb the most optimal replenishment frequencies.
Bibliography


COMPANY. (2012). Annual report. COMPANY.


## List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>ETA</td>
<td>Expected Time of Arrival</td>
</tr>
<tr>
<td>EOQ</td>
<td>Economic Order Quantity</td>
</tr>
<tr>
<td>EPQ</td>
<td>Economic Production Quantity</td>
</tr>
<tr>
<td>EQU100</td>
<td>Equivalent Units of 100</td>
</tr>
<tr>
<td>FG</td>
<td>Finished Goods</td>
</tr>
<tr>
<td>FMEA</td>
<td>Failure Mode and Effect Analysis</td>
</tr>
<tr>
<td>MOQ</td>
<td>Minimum Order Quantity</td>
</tr>
<tr>
<td>MRP</td>
<td>Material Requirements Planning</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>PO</td>
<td>Purchase Order</td>
</tr>
<tr>
<td>SCT</td>
<td>Supply Chain Team</td>
</tr>
<tr>
<td>SKU</td>
<td>Stock Keeping Unit</td>
</tr>
<tr>
<td>VMI</td>
<td>Vendor Managed Inventory</td>
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Appendix A – Chapter 2

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Figure 1: Planning process CONTRACTOR

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Figure 2: Corporate structure of COMPANY
Figure 3: Cumulative bulk arrivals and consumption of Product B
Appendix C – Chapter 5
Confidential

Figure 4: Demand forecast 2013
Manual: Build a production wheel

The goal of this manual is to provide a stepwise overview of all the steps that have to be performed to build a production wheel. It is important that both parties are involved in this process in order to ensure that there is a common understanding of the concept.

Lot sizes

**Step 1: Determine set of SKUs**

Select all intermediates and finished goods which need to be packaged at CONTRACTOR in the upcoming 12 months. This means that also launch products have to be selected. There are in total \( k \) SKUs.

**Step 2: Determine optimal lot sizes**

First, the Total Relevant Costs have to be calculated for all \( k \) SKUs:

\[
TRC = \sum_{i=1}^{k} A_i \left( \frac{D_i}{Q_i} \right) + \frac{v_i r Q_i}{2} \left( 1 - \frac{D_i}{P_i} \right)
\]

s.t.

\[
\sum_{i=1}^{k} D_i PT_i + \frac{D_i Q_i}{ST_i} \leq C
\]

If the capacity constraint is exceeded then the Lagrange multiplier \( \lambda \) is introduced. Taking the derivative to \( Q_i \) gives the following formula for the optimal lot sizes:

\[
EPQ = Q_i = \frac{2(A_i + \lambda ST_i)D_i}{v_i r \left( 1 - \frac{D_i}{P_i} \right)}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
</tr>
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<tbody>
<tr>
<td>( A_i )</td>
<td>( A_i = ST_i \times A ) Where ( ST_i ) is the setup time of product ( i ) in hours and ( A ) is the fixed setup costs of €XXX per hour based on a reference packaging line, in euro’s</td>
</tr>
<tr>
<td>( D_i )</td>
<td>( D_i ) is the sum of the demand forecast of product ( i ) for the next 12 months in units. This information is taken from the flatfile.</td>
</tr>
<tr>
<td>( v_i )</td>
<td>Costs Of Goods Sold (COGS) of product ( i ) after packaging, in euro’s/unit.</td>
</tr>
<tr>
<td>( r )</td>
<td>Interest rate as used in SAP®: XXX%</td>
</tr>
<tr>
<td>( P_i )</td>
<td>Total number of products ( i ) which can be produced if the full capacity is used for production of this product ( i )</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Lagrange Multiplier; only used if the production capacity is exceeded</td>
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</table>

**Step 3: Determine optimal replenishment frequencies**

The optimal Replenishment Frequencies \( (RF_i) \) of product \( i \) are calculated with:

\[
RF_i = \frac{Q_i}{D_i} \times W
\]
Where, \( W \) is the number of weeks per year.

**Step 4: Determine optimal cycle length**
The optimal cycle length is calculated with:

\[
\min TRC = \sum_{i=1}^{k} \frac{A_i \times W}{PW} + \frac{\nu_i r D_i PW}{2W} \left(1 - \frac{D_i}{P_i}\right) - \lambda \left(\sum_{i=1}^{k} D_i PT_i + \frac{W}{PW} ST_i - C\right)
\]

Where, \( PW \) is the length of the production wheel in weeks. This minimization problem can easily be solved with the solver add-in of MS Excel®. Only if the optimal cycle length is shorter than the chosen cycle length, the capacity is sufficient.

**Step 5: Adjust for supply frequencies**
Lower bound of Replenishment Frequency = 1 week
Upper bound of Replenishment Frequency = 13 weeks (due to shelf life restrictions)
Replenishment Frequencies from step 3 rounded to the nearest power of two (1, 2, 4, 8, 13 weeks)

Based on the agreed supply frequencies with the final customer the Replenishment Frequencies are revised and adjusted. The new adjusted lot sizes are calculated with:

\[ Q_i = \frac{D_i}{RF_i} \]

**Step 6: Adjust for full pallet size**
Only full Pallet Sizes of product \( i \) (\( PS_i \)) are ordered. The final \( Q_i \) is calculated with the following formula:

\[ \text{Final } Q_i = \text{round up} \left(\frac{Q_i}{PS_i}\right) \]

The final \( Q_i \) is rounded to deal with the Minimum Order Quantity of one pallet.

**Step 7: Calculate costs and capacity**
The \( TRC \) of step 2 have to be calculated again with the final \( Q_i \) from step 6 to determine the setup- and holding costs of the designed production wheel.

The capacity is calculated with:

\[ \sum_{i=1}^{k} \frac{W}{RF_i} TT_i \leq C \]

Where, \( TT_i \) (\( Q_i PT_i + ST_i \)) is the total time (in hours) to produce one batch of product \( i \) and \( PT_i \) is the time to produce one vial of product \( i \) in hours. If this capacity constraint is not met, the adjusted lot sizes need to be increased to reduce the number of replenishment frequencies and therefore the required capacity.
**Allocation**

The identified SKUs are dedicated to the packaging lines

*Rule 1*: Cluster all doubles in blocks and allocate them on the same line in order to minimize the sum of the setup times and the time due to technical interventions of the packaging lines.

*Rule 2*: Allocate all Product C and doubles to packaging line 1, Product B products to packaging line 2 and Product A products to packaging line 3.

**Sequencing**

Goal of the sequencing procedure is to find a leveled production load and a balance between production inflow and outflow. The sequencing procedure is the following:

1) Make two clusters: single and doubles
2) Sort all SKUs within the cluster based on the same bulk component
3) Sort all SKUs within the cluster in ascending order of replenishment frequency
4) Sort all SKUs within the cluster in descending order of lot size
5) Dedicate SKUs with a replenishment frequency of 1 week to the beginning of each spoke
6) Dedicate SKUs with a replenishment frequency of 2 weeks to two spokes in a biweekly pattern
7) Calculate remaining time of each spoke by taking the difference of the available time per spoke (in hours) and the time that is consumed so far by production (in hours) \( \sum_{i=1}^{n} TT_i \), for all \( n \) products which are in the spoke so far

If remaining capacity is > 8 hours then go to 8), else go to next spoke and go to 8)

8) Select the first product, with the same bulk component as last dedicated product in the spoke, and with a \( TT_i \) smaller than the remaining time
9) Dedicate this product to the spoke
10) If all products are dedicated then go to 11) else go to 7)
11) Check number of POs produced per week
12) Check bulk consumption of vials with 50 widgets per week
13) If 11) and 12) are leveled then stop else try to reallocate SKUs to get these output indicators more balanced.

**Conclusion**

Now, the production wheel is build based on carefully chosen lot sizes. Each production wheel should have some free time in order to ensure that the total cycle length of one month is not exceeded. The allocation and sequencing procedure are based on minimizing production setup times.
Appendix D – Chapter 6

Figure 5: Probability of cycle lengths line 1

Figure 6: Probability of cycle lengths line 2

Figure 7: Probability of cycle lengths line 3

Table 1: Production sequence Line 1
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Table 2: Production sequence Line 2
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Table 3: Production sequence line 3
Confidential
Figure 8: Production wheel line 1 with blocks

Figure 9: Production wheel line 3 with blocks
Appendix E – Chapter 7

Figure 10: Comparison of $P_1$ service level

Table 4: Parameter settings

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