Mixed production planning in the pharmaceutical supply chain

Konter, W.W.H.

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Mixed Production Planning in the Pharmaceutical Supply Chain

By: W.W.H. Konter

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Student identity number: 0650655

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Supervisors:

dr.ir. N.P. (Nico) Dellaert, TU/e, OPAC

dr. A. (Arun) Chockalingam, TU/e, OPAC

Ing. L. van Velzen, Company X

Abstract
This master thesis is about mixed integrated production planning on both a tactical and detailed level in the pharmaceutical compounding company named Company X. On a tactical level a deterministic algorithm is proposed to set product specific order rules and the performance of this algorithm is compared to a pre-determined general rule set by PFCX. On a detailed level a stochastic method is proposed for a mixed detailed planning of incoming orders and vendor managed inventory. By simulating orders under the new rules set by the tactical level, the influence of orders on capacity is measured. With this capacity a scheduling model for the VMI items is proposed under multiple scenarios. By comparing the performance measurements the final conclusions and recommendations can be made.

Management summary

Company X has a leading position in the pharmaceutical compounding industry and owns a large part of this supply chain. The master thesis project is conducted at Production Facility Company X (PFCX), one of the production sites of the Company X. Company X is focused on providing the industry with high-quality raw materials and semi-finished products to make individual specific solutions possible. It hopes to keep its leading position by providing innovative solutions to the market.

Figure 1: The Supply Chain of Company X

The master thesis subject is about optimizing production order planning considering the supply chain as a whole. Currently production planning is done by employees of the planning department, which base their decisions mainly on experience. Some important decisions made by the members of the planning department concern the combination of orders, the machine usage and VMI production. These decisions are mainly influenced by capacity, stock keeping cost, perishability of raw materials, raw material setup cost and order specific setup cost.

Production planning at PFCX is separated into three levels: the tactical, detailed and operational level. The tactical planning level concerns the external order parameters, such as the order quantity and order frequency. The detailed level is focused on the incoming orders and concerns the combination of orders and employee capacity. The operational level considers the employee, machine and cleanroom selection.

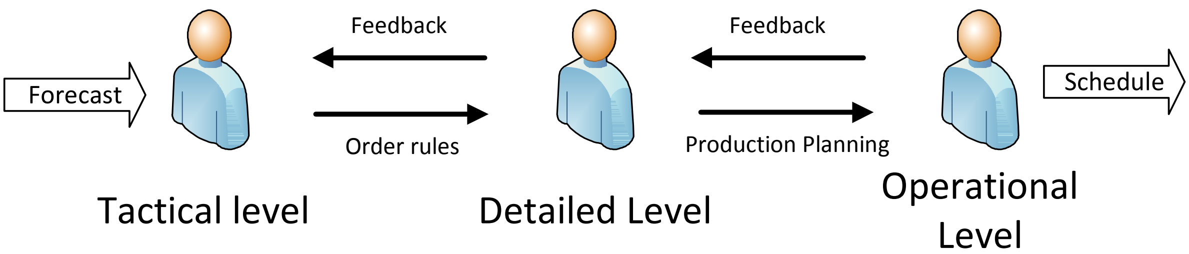

Figure 2: Planning levels

Within these levels three problem areas are defined, respectively one on each level. The problem definition is given by three main problem areas:

Problem 1: The predetermined rules, as they are currently used, are not argued for on a theoretical level. Therefor the optimality of these rules is questionable.

On a detailed level, problems are defined concerning the heuristic proposed in the planning process described in chapter one.

Problem 2: Many significant variables and the relation between them are estimated and therefore not data driven. For example, the relation between raw material specific setup cost, order specific setup cost and presentation specific stock keeping costs.
Problem 2.1: The failure in good variable determination results in limited insights in upcoming capacity shortages. In this case a decreasing amount of combined orders is spotted, which has a downhill effect on capacity.

While the operational level is out of scope, some of the decision making in this process is pulled towards the detailed level. As mentioned in the motivation the machine decision is a major objective of this research project.

Problem 3: Capacity limitations are only provided with a three day horizon, so no long-term capacity shortage can be spotted. Further on, cleanroom and machine capacity constraints have always been neglected.

Considering these problems, it leads to the following main research question:
"To what extend can we reduce the total supply chain cost using a data-driven Lot Sizing Problem based model at PFCX and how can we transform this into an easy-to-use, compatible tool?"

In order to answer this research question, first a process description was made to map and analyse the company's internal processes. There after the data was collected out of the ERP system to determine the values of the necessary variables in the tactical and detailed model. This process was very time consuming while the data was not particularly easy to link.

First the current set of rules on a tactical level was analyzed and an optimization method was proposed. The current set of rules is given in the table below and is poorly substantiated by PFCX. Based on gut feeling there was a logical trade-off made between setup costs and inventory holding cost.

Forecast/year	**Order size**
FC < 100	Year forecast
100 < FC < 400	100
FC > 400	¼ FC

Table 1: Current set of Rules

The proposed method on the tactical level was an algorithmic solution method proposed in the book of Silver, Pyke and Peterson. The proposed solution method led to optimal order quantities and order frequencies. Next, the influence of perishability, VMI and special orders on the proposed solution was investigated. Finally six scenarios were proposed as represented in the table below.

	Best Solution	**Similar SKC**	**Less SKC**
Benelux VMI	Scenario 1	Scenario 3	Scenario 5

100% VMI	Scenario 2	Scenario 4	Scenario 6

Table 2: Scenario's

In conclusion scenario 6 was used as implementation in the detailed model. Further on an implementation method and a cost analysis is discussed for the scenarios concerning the more realistic Benelux VMI situation. The final results for scenario 6 are represented below and can be considered highly beneficial.

TOTAL Direct Clean Cost	-€15.732,36
TOTAL Bulk Picking Cost	-€2.082,82
TOTAL Order Cost PFCX	-€164.840,07
TOTAL Order Arrival Cost Partner	-€9.116,00
TOTAL Stock Keeping Cost	€76,28
TOTAL (SAVING)	**-€191.694,97**

Table 3: Results Scenario 6

The optimal order quantities were used as input to the detailed model, which was split into a made-to-order processing part and a made-to-stock (VMI) production selection part. This means the incoming orders are subject to a multiple orders per job theory and the VMI selections concerns a batch scheduling problem. A serial solution method was proposed, where the output of the made-to-order part of the production is a production proposal of raw materials and its influence on capacity.

In the made-to-order section of the research project, there was no data which represents the arrival of regular orders under the new set of rules. This order demand was simulated assuming a compound Poisson distribution with uniformly distributed order sizes. The other made-to-order demand, the special orders, is similar to the real data in 2013. For the combined regular and special orders the combination decision is made, so a multiple orders per job solution was proposed. Secondly, the machine production decision is considered.

The order production proposal and its influence on capacity were used as input into the made-to-stock VMI product selection process. The weekly demand at the sales partners is similar to the actual demand in 2013, so no simulation is needed. In this part a similar combination and machine decision is proposed. In each period T items are produced if the inventory positions drops below the re-order level. In case of leftover capacity, the potential savings in cleaning cost are compared to the increasing stock keeping cost. A Linear Programming model is proposed to find the most cost efficient set of production items in each period T. This LP-model proposed the following objective function with some employee and cleanroom capacity constraints.

Objective function:

$$\sum_{i=1,t=1}^{i=3438,t=52} C_{it}$$

$$= \sum_{i=1,t=1}^{i=3438,t=52} B_{it} * A_i * P_{ijt}\left(IP_{it} < O_i \ in \ X_j\right) - \left(IP_{it} - O_i\right) * v_i * \frac{\left(IP_{it} - O_i\right)}{DY_i} * r$$

Restrictions:

$$\sum_{i=1,t=1}^{i=3438,t=52} d_{it} \geq \sum_{i=1,t=1}^{i=3438,t=52} MIN\ d_{it}$$

$$\sum_{i=1,t=1}^{i=3438,t=52} d_{it} \leq \sum_{i=1,t=1}^{i=3438,t=52} MAX\ d_{it}$$

$$\sum_{i=1,t=1}^{i=3438,t=52} PT_{it} + CT_{it} = EC_t$$

$$\sum_{i=1,t=1}^{i=3438,t=52} HR_i * (PT_{it} + CT_{it}) < HRC_t, where\ HR_i = 1\ for\ HR\ items$$

$$\sum_{i=1,t=1}^{i=3438,t=52} HR_i * (PT_{it} + CT_{it}) < HRC_t, where\ HR_i = 1\ for\ no\ HR\ items$$

For this model six scenarios are presented which differ in the order policy and employee capacity constraints. Tow order policies are proposed, an R,Q-policy with a fixed order position and an s,Q-policy with a fixed production quantity. The capacity constraints consider three scenarios, the first with the original workforce capacity, second with a restriction of similar production amounts and third a variable workforce capacity of max 10% of average.

	100% Utilization rate	Similar Production Amount	Variable workforce (10%)
R,Q-policy	Scenario 1	Scenario 2	Scenario 3
s,Q-policy	Scenario 4	Scenario 5	Scenario 6

Table 4: Simulation scenarios

The average results for all scenarios are given in the table below, however in appendix V the extended results for each scenario are given (including the standard deviation and the confidence interval of each performance measurement).

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Scenario 1	866.959	8.465	146.123	99%	€ 200.938,53	36%
Scenario 2	765.964	7.231	113.127	97%	€ 177.553,16	36%

Scenario 3	895.713	8.994	154.366	99%	€ 176.480,70	36%
Scenario 4	796.945	3.658	68.468	99%	€ 191.892,95	42%
Scenario 5	757.954	3.559	60.984	98%	€ 180.135,92	42%
Scenario 6	798.362	3.667	66.866	99%	€ 188.789,68	42%

Table 5: Scenario Results

Due to the minimal amount of orders and slightly more beneficial results scenario 6 was chosen over scenario 4, while scenario 5 was computed to make a fair comparison possible between the results of the detailed model and the actual and tactical results. The total results of the detailed model are given in the table below and it confirms an improved situation. However, stochastic demand and capacity constraints do have a negative effect on the expected outcomes in the tactical model.

	Amount Produced	**Amount of Orders**	**Total Cleaning time (min)**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	26%
Simulation Average	**1.148.757**	**7.920**	**134.236**	**99%**	**€ 271.122,12**	**36%**
Standard Deviation	10.143	70	5.161	0%	€ 5.451,23	1%
Upper bound (95%)	1.169.693	8.065	144.889	99%	€ 282.373,47	38%
Lower bound (95%)	1.127.821	7.775	123.583	99%	€ 259.870,77	35%

Table 6: Results Scenario 6

In conclusion, an s,Q order policy was choses with a variable workforce. This showed negative effects in comparison to the tactical level, but still a cost reduction of €142.500,-. The data-driven tactical and detailed model was converted into easy-to-use compatible tools, of which the tactical tool is already globally implemented.

Preface

This report is conducted as a result of my master thesis project in order to fulfil my master degree in Operation Management and Logistics at the Eindhoven University of Technology. This project toke place at one of the production facilities of the world leading company in the pharmaceutical compounding industry, Company X, located in Uitgeest.

The journey towards this final project, is one with many ups and downs of which the ups where luckily in the vast majority. While the main focus of the bachelor is on the theoretical aspect of Industrial Engineering, my masters provided the opportunity to frame this theory on more practical cases. Therefor I must admit that my master and definitely this final project caused a higher level of satisfaction as my bachelor did. The numerous cases, in which a combined effort led to a practically sufficient solution to huge problems, motivated me during my masters in OM&L.

First, I would like to show my gratitude to my first university supervisor and mentor Nico Dellaert, for his dedication to guiding this master thesis project to a great end. In particular, I admire the moments when he showed me the way to a solution which not yet occurred to me, by asking the right questions at the right time. The suggestions of further research and the constant feedback on how to improve my research are much appreciated. Besides, I would like to thank my second university supervisor Arun Chockalingam for challenging my way of thinking and constantly reflecting the research project.

Furthermore, I would like to thank my first company supervisor Linda van Velzen for her guidance on the practical issues involved in this master thesis project. Especially the way how she kept me focused in moments I lost sight of the original goals of this research project. Further on, I would like to thank the entire Project Team at PFCX for their contribution to a positive result. And lastly I would like to thank the Steering Committee and especially Mia Remken for challenging me on a daily basis and Luc Polaris for more thorough theoretical discussions. Overall I enjoyed my time at PFCX and found it a very educative period in my life.

Last but not least, I would like to thank my family and friends, for their support during my studies at Eindhoven University of Technology. I would like to thank them for their interest in my time at the TU/e, National Taiwan University and Company X.

Wiebe Konter

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List of Abbreviations

BPP	Bin-packing problem
B&B	Branch and Bound method
DP	Dynamic Programming
EDD	Earliest due-date
EJL	ERIM Journal List
ELSP	Economic Lot Sizing Problem
CLSP	Capacitated Lot Sizing Problem
MICLSP	Multiple Item Capacitated Lot Sizing Problem
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MIQP	Mixed Integer Quadratic Programming
MOJ	Multiple Orders per Job
MP	Mathematical Programming
PFCX	Production Facility Company X
R&D	Research and Development
SCM	Supply Chain Management
SCPM	Supply Chain Planning Matrix
SELSP	Stochastic Economic Lot Sizing Problems
VMI	Vendor Managed Inventory
VNS	Variable Neighbourhood Search
WEDD	Weighted Earliest due-date
WACC	Working Average Cost of Capital

1. *Project Context*

This master thesis is executed in completion of the master Operation Management & Logistics at the Industrial Engineering & Innovation Sciences department of Eindhoven University of Technology. It serves the purpose of developing a relevant addition to the existing literature and investigates the practicality of this addition.

This chapter contains background information on the company at which this master thesis is conducted and the thesis topic. The origin, structure and supply chain of the research company, Company X, are briefly discussed. A more in-depth approach is proposed towards the production planning process and its relevant parameters.

1.1 Company Description

1.1.1 Company X

The Company X's core business relies on the innovation of pharmaceutical compounding goods and preserving an efficient supply chain. Company X sustains multiple sales channels of which pharmacies, hospitals, wholesalers and patients are its most successful channels. To pharmacies, hospitals and wholesalers Company X supplies semi-finished products for further compounding. The actual patient is offered a tailor-made pharmaceutical solution to improve the experience of the initial treatment. Company X's strategy is focused on innovation, respectively 10% of each year's turnover is R&D related, with the objective to keep a leading position in the international market.

In just 7 years it obtained a leading position in the national pharmaceutical compounding market. By focusing on innovation and operational optimization they fulfilled the worldwide growing need for tailor-made medication. Nowadays, Company X is the global market leader and active in 30 countries in Europe, North America, South America and Asia. Company X's sales market stretches even further, while products are sold to over 200.000 customers in over 60 countries. Since 2007 it is listed on Euronext Brussels and Euronext Amsterdam.

1.1.2 Production Facility Company X

In Europe the Company X facilitates multiple production facilities, of which the most sophisticated is located in the Netherlands. This location is internally labelled as Production Facility Company X (PFCX) and it employs around 150 people divided over production and back-office. Their core activities consist of repackaging and labelling raw materials to supply the sales companies of the Company X. PFCX offers an assortment of over 10.000 different presentations of 1500 different bulk materials. These presentations differ in weight or volume and/or product label. PFCX owns three different labels, to apparent market diversification. The total production amount in 2013 was over 1.100.000 packages, which were distributed to ten different sales partners. The majority of their production quantity is purchased by the sales companies located in the Netherlands, Belgium and Germany.

1.1.3 Company X's Supply Chain

Globally the pressure on an efficient Supply Chain Management (SCM) increases, due to increasing variability in customer demand and the necessity of overall shorter lead-times. With Company X's Buy-and-Build strategy they obtained an extensive supply chain. It stretches from the procurement of raw materials to offering a tailor-made pharmaceutical solution to the end-customer. It offers the opportunity of global procurement, continental production, national distribution and sales through multiple channels.

Figure 3: The Supply Chain of Company X

To give an idea of the content of Company X's supply chain, it is visually represented in the figure above. This figure depicts the place of each of the members in the supply chain and below a descriptive summary is made for the specific purpose of each of these members.

1. The starting link of Company X's supply chain considers the procurement of raw materials. In general Company X procures its raw materials directly at the source, however occasionally an intermediate wholesaler is inevitable. The global procurement department is responsible for selecting suppliers, while the production facilities are responsible for the actual procurement.
2. The production facility is responsible for the production of semi-finished goods by repackaging the bulk raw materials. PFCX is an example of the link between global procurement and the sales companies. The presence of these sales companies results in a limited amount of business relations for the production facilities.
3. The sales companies are the link between the production facilities and the pharmacies, hospitals and wholesalers. Obviously their main objective is increasing sales, but on an operational level they are also accountable for procurement of semi-finished goods and forecasting.
4. The sales companies generally supply pharmacies, hospitals and wholesalers. Hospitals and wholesalers are always considered end-customers; pharmacies can be internal customers or end-customers. These internal pharmacies produce tailor-made pharmaceutical solutions and simultaneously play a crucial role in product innovation.
5. In case of these internal pharmacies, the end-customer is the user of the product. In this case the tailor-made drug for each particular patient.

1.2 Company X Production Planning

In this paragraph the production planning process at PFCX is presented with the intent to clarify the current situation. First, the general structure of the planning department is discussed to explore the different levels in this department. Further on, the production planning process and its place within the organization is given.

1.2.1 Production Planning Levels

By analysing the different levels of the planning process, the line of responsibility is visualized. The planning process at PFCX can be separated into three levels: the tactical, detailed and operational level. The tactical level concerns the external order parameters, generally the order quantity and order frequency. The detailed level is focused on processing incoming orders and employee capacity. The operational level considers the employee, machine and cleanroom selection.

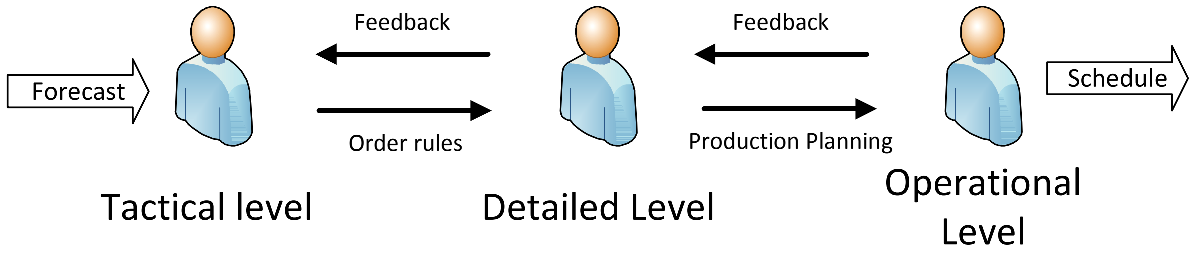


Figure 4: Planning levels

Forecasting is considered an input variable of the tactical planning level within the organization, but considered out of scope. The responsibility over the tactical level is with the senior management of each production facility and with the global operation department. The senior operational management department at PFCX consists of three employees: the general manager, operational manager and logistic manager. On a global basis the Chief of Operations and the Supply Chain Manager are involved in the decision process. The output of the tactical level is an order policy and corresponding order rules.

The detailed level is performed by the planning department, which contains two full-time employees. This department is responsible for processing incoming orders into a three day planning; this process is further described in the next paragraph. On an irregular basis they provide feedback about the order policy and rules towards the tactical level.

The operational level is focused on scheduling orders to employees, machines and cleanrooms. While the decision processes is considered micromanaged there is expected to be no significant impact on the performance measurements. Therefore it is considered out of scope.

1.2.2 Planning Process

On a tactical level the planning process contains the set of order rules as given in the table below. Depending on the yearly forecast a presentation's order frequency is between minimum one and maximum four. Order quantities therefor also differ greatly between different presentations due to the variety in forecasted demand. In example, a presentation with a demand forecast of 265 is ordered three times a year with an order quantity of 100.

Forecast/year	**Order size**
FC < 100	Year forecast
100 < FC < 400	100
FC > 400	¼ FC

Table 7: Set order rules

Special orders are not subjected to these rules; they can have any order size and have no particular frequency.

Before presenting the detailed planning process, its place within the organization is briefly discussed. Because of the high interdependency between these processes, a figure is proposed which shows the flow of physical goods and information. The figure below depicts that the detailed planning process is a singularly informative process. As a centrally located process it provides critical information to most other core processes within the organization. PFCX's vision is that a more productive and effective detailed planning process should beneficially influence the organization as a whole.

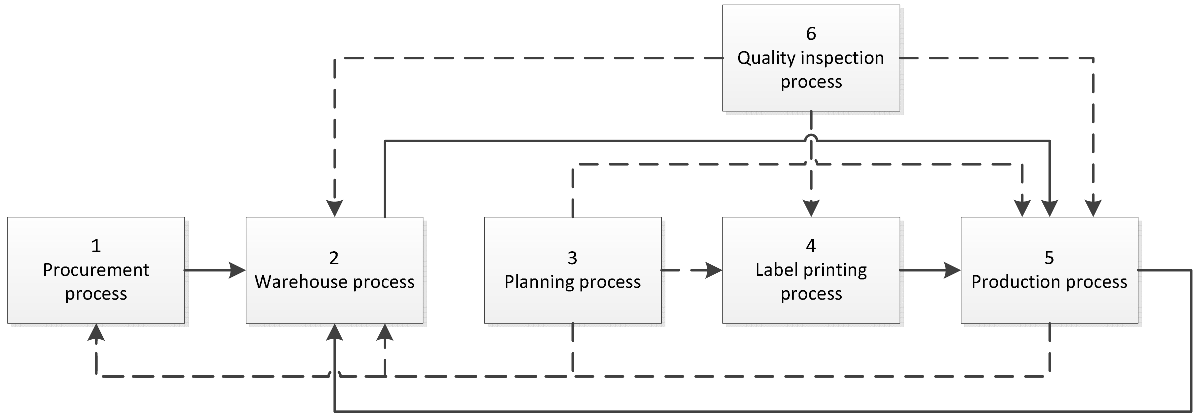


Figure 5: Process Overview

A more in-depth description should provide insights in possible shortcomings and show opportunities for optimization. In the figure below a flow-chart is provided, which contains the core operations.

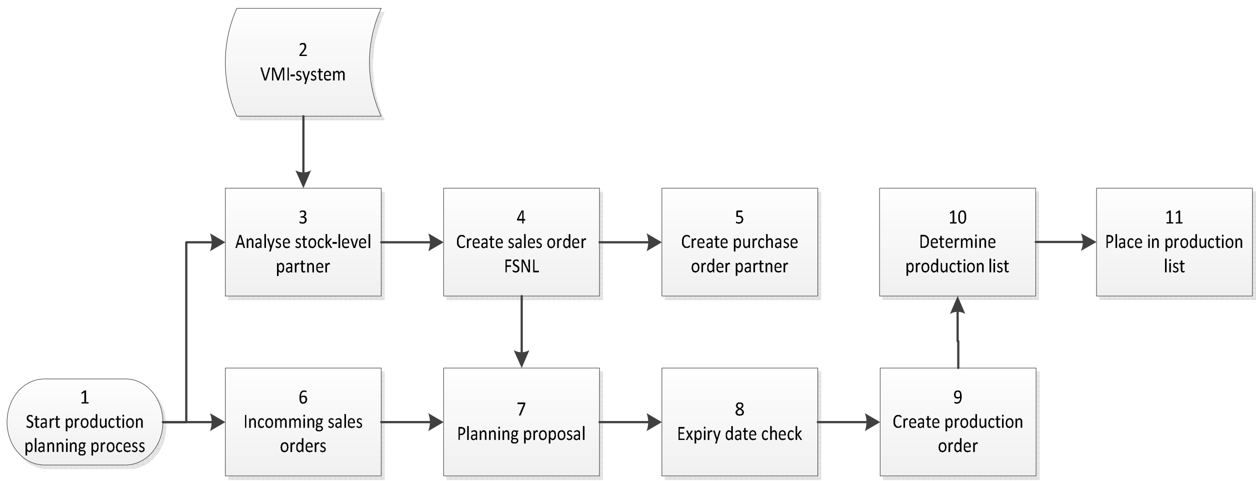


Figure 6: Planning Process

1. The start of the planning process gives two parallel processes: the arrival of orders and an analysis of the Vendor Managed Inventory (VMI).
2. The VMI-system provides the planning department with insights considering the stock-levels at the sales partners. This data is retrieved from the ERP-system and exported into Microsoft Excel.
3. With the exported data a comparison between the stock-levels and re-order points of each presentation is made. If a production decision is positive, other presentations of a similar family are considered for production, even if the stock-level is above the re-order point. After the production decisions are made a VMI order is treated in a similar way as an incoming sales order.

4. For each VMI production decision two different orders are created: a purchase order at the partner and an internal sales order.
5. Through the creation of a purchase order for the sales partner, the sales partner is informed about the estimated order arrival time and the order quantity.
6. General sales orders are incoming orders directly placed by PFCXs partners, therefor there are not as variable as VMI orders. These sales orders have a fixed production amount and a standard delivery time of six weeks. VMI production decisions are translated into similar sales orders, with a similar lead-time and variable production amounts. Special orders are an exception, these are mostly small urgent sales orders, which have a lead-time of two weeks.
7. In the planning proposal VMI orders and incoming sales orders are implemented and planned according an Earliest Due Date sequence.
8. There main reasons for checking the expiry date for each raw material concerns the potential shelf life of the presentations and therefor raw materials. PFCX estimates if it is likely for the sales partner to sell the production quantity before the expiration date of the raw material. Depending on this estimation the production quantity can be adjusted. In other cases the shelf life influences the minimal order frequency, which can influences the outcome of the tactical level.
9. If the expiration date is checked and the availability of raw materials is sufficient a production order is created.
10. The production orders are exported from the ERP system into Microsoft Excel. These are placed into their appropriate list, which differ in high risk presentations and normal presentations. While there are considerably more normal presentations the amount of normal cleanrooms is in similar proportions. A new, very capacity demanding, high risk presentation is in the process of implementation. For this research is considered out of scope, but this can have minor influence on some results in the detailed level.

Type of cleanroom	**Number of available cleanrooms**
Normal Cleanroom	9
HR Cleanroom	2

Table 8: Clean Rooms

11. The core activity of the planning department is combining different orders into one job to reduce the total cleaning time. Cleaning takes place after each raw material, not in between orders of a similar family. This decision process depends on the employees experience and instincts, but it is based on the following heuristic:
    - Estimate variables: The planning employees estimate a cleaning cost by their knowledge of the specifications of a raw material. For the stock keeping cost the quantity of the order is used.
    - Estimate threshold: The balance between production quantity and cleaning cost is analysed, note that there are no calculations involved in this process.
    - Check available capacity: In case of a shortage of capacity, orders are less likely to be combined and orders can even be split into multiple orders.

- Combination decision: With the information collected out of the previous steps a final combination decision is made. This decision making process is a constantly evolving environment and is not permanent up to a week before production.

With the final production list a three day production capacity planning is proposed, which includes an advice on the machine decision. In this process the major cost are involved in the setup of each order, the cleaning after each raw material, or so called presentation family, and the stock keeping at the partner.

1.2.3 Supply Chain Planning

By exploring Company X's core business, discussing its supply chain and zooming in on the planning process of PFCX a clear view of current activities is provided. In this paragraph we discuss the relation between the planning process at PFCX and its supply chain partners.

One step back in the supply chain, we can conclude that procurement is rarely a bottleneck for production. However, the relation between these links is considered out of scope. Therefor we assume a perpetual availability of raw materials.

The forward step in the supply chain is more involved in the planning process. As mentioned earlier, the sales partners provide the production facilities with information like forecasting and sales orders. In principle, PFCX produces solely on a made-to-order basis while production is pulled by orders. In reality, VMI causes PFCX to produce partly to-stock and partly to-order. However, internally the process stays totally made-to-order.

2. Project Description

In the project description the boundaries of this master thesis are explored. It contains the internal motivation for executing this project, a general problem description, the project's scope and finally the research questions.

2.1 Motivation

In November 2012 the findings of Jeroen Draak, fellow student at IE&IS department of the TU/e, lead to an increasing attention towards the importance of the supply chain planning process. The most valuable conclusion concerned the customer order decoupling point (CODP) which showed the production of semi-finished products was highly unproductive because of the low forecast reliability.

Since a new COO started at Company X, the planning process has been an important subject. The introduction of VMI was one of the first steps towards an improved supply chain. With the implementation large cost savings were expected, but this was never confirmed by the results. This lack was the core motivation to search for further optimality in the supply chain planning. The objective was to fulfil delivery requirements against the lowest possible costs for the entire supply chain.

At PFCX the need for developing a tool to support the planning of the production activities was growing. This tool should communicate with the current ERP system (Navision Dynamics) and should replace the current stand-alone excel files. The goal is to lead to a more efficient and generalizable planning. Ideally it will serve a shell for further implementation at other production sites.

The main issues to be taken into account are:

- choice between manual production vs. automated production
- storage limitations (space, holding costs, time - perishable products)
- set-up times
- technical batch size restrictions
- combination of customer orders

2.2 Problem Description

In this problem description a top-down approach is proposed. The problems in the rules and order policy of the tactical level are discussed first, after the problems at the detailed level are mentioned.

Problem 1: The predetermined rules, as they are currently used, are not argued for on a theoretical level. Therefor the optimality of these rules is questionable.

On a detailed level, problems are defined concerning the heuristic proposed in the planning process described in chapter one.

Problem 2: Many significant variables and the relation between them are estimated and therefore not data driven. For example, the relation between raw material specific setup cost, order specific setup cost and presentation specific stock keeping costs.
Problem 2.1: The failure in good variable determination results in limited insights in upcoming capacity shortages. In this case a decreasing amount of combined orders is spotted, which has a downhill effect on capacity.

While the operational level is out of scope, some of the decision making in this process is pulled towards the detailed level. As mentioned in the motivation the machine decision is a major objective of this research project.

Problem 3: Capacity limitations are only provided with a three day horizon, so no long-term capacity shortage can be spotted. Further on, cleanroom and machine capacity constraints have always been neglected.

These three problem descriptions represent the majority of the problem area discovered after analyzing the planning process. Smaller problems are not mentioned in this problem description but can part of the lower levels proposed in the research questions paragraph.

2.3 Project Scope

While some of the boundaries are already mentioned in the previous chapters, this paragraph is proposing a clear overview on what the scope is of this research project. The general scope of this research considers the planning process on a tactical and detailed level while simultaneously taking the supply chain as a whole into account. In specific, the boundaries are formed by the neighboured links in the supply chain and the different levels in the planning process.

2.3.1 Forecasting

While the sales companies are responsible for forecasting, this input is considered out of scope in this research project. This is reassured by the restrictions given by the operational management at PFCX. Forecasting is considered accurate if the actual demand deviates not more than 20% of the forecasted demand, total forecasting has an estimated 20% accuracy. Although this limited forecasting is considered a given, it should be mentioned that it has a negative influence on the results of this research project.

2.3.2 Tactical Level

On a tactical level, the demand forecast received from the sales partners is considered. In the process of optimizing the supply chain, the focus is on PFCX and its neighbourly links. The proposed solution methods in this research project are suitable for ordinary presentations. Presentations like mix-products (two mixed bulk materials) and Syrspend kits (a variety of products in one box) are considered out of scope. This will slightly influence the outcomes of this research project, while it is only 1% of the demand over 2013. Perishability of raw materials and the influence of special orders are within scope, as this has an influence on an order frequency and quantity.

Considering the tool, the scope was originally to develop one suitable for the current ERP system or in Excel. However, the Chief Information Officer suggested this scope could widen to the procurement of a capable software system. While it is not desirable for highly fluctuating rules on a tactical level, the tool should be developed for monthly application.

2.3.3 Detailed Level

The detailed level is focused on the combination of orders, machine decisions and allocation of capacity. Similar to the tactical level the irregular presentations are considered out of scope. This mainly influenced the capacity constraints, which were adjusted accordingly. The procurement process was out of scope, so the availability of raw materials was assumed. The selection of cleanrooms in this level, was limited to a selection between normal and high-risk presentations.

The decision of machine or manual production was considered out of scope in the tactical level, but is considered within scope for the detailed level. Originally this decision was on an operational level, now this decision shifts to the detailed level.

Originally employee capacity is considered out of scope. The variability in the workforce is very limited because of the large break in period of about four weeks. In later scenario's this scope restriction will be stretched a little. Cleanroom capacity was within scope for both normal cleanrooms and HR-cleanrooms. Machine capacity was also considered within scope.

2.3.4 Operational Level

The scheduling of the actual orders to different employees, cleanrooms and machines is considered out of scope. The influence of this on the results of this research project is considered nihil.

2.4 Research Questions

In this section of the research proposal a research question will be derived. By using the Management Research Question Hierarchy (MRQH) of Blumberg et. al (2008), six hierarchical levels are proposed. In the figure below the consecutive question, that concerns each different level, is given.

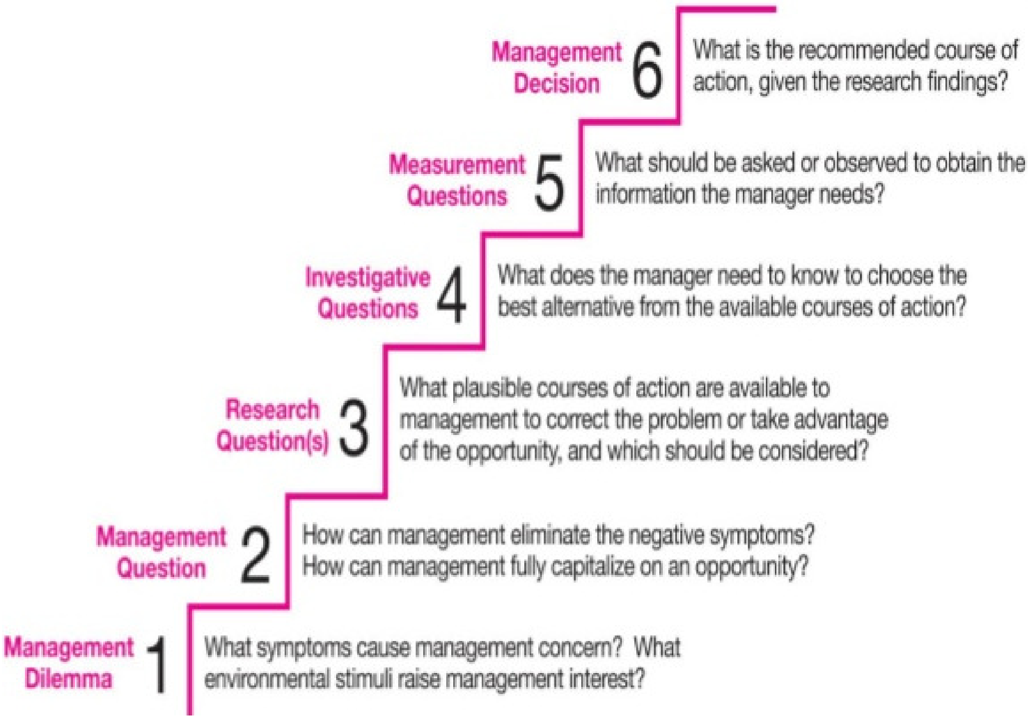


Figure 7: Management Research Question Hierarchy

Management Dilemma

As mentioned earlier the motivation for this research was the lack of results from implementing VMI. On an operational level it is proven to be difficult to adjust capacity to fluctuating demand. And while the planning decisions are not tangible, the necessity for investigation was confirmed.

Management Question
How can we provide a more automated, data-driven optimized planning process to reduce overall cost in the supply chain?

Research Question
To what extend can we reduce the total supply chain cost, by using a data-driven tactical and detailed model, and how can we transform this into an easy-to-use, compatible tool(s)?

Investigative Questions

a. How can we define the order process flow regarding the four influence factors given and at the same time cope with capacity?
b. Which data is available and how does a data-driven order process flow differ from the current method, used in practice now?
c. Up to what level can we adjust the set of order rules and what is the influence of this adjustment on the performance of the supply chain?
d. To what extent will the proposed tactical and detailed model provide an optimal solution and how do they cope with stochastic demand?

Measurement Questions

a. Planning process:
   - What are the variables on which the selection of cleanrooms depends?
   - What are the variables on which the combination decision depends on and what value restrictions does this decision encounter?
   - What are the variables on which the machine decision depends on and what value restrictions are proposed?
   - What is the influence of capacity and perishability on a detailed level and which decisions are encountered?
b. Available data:
   - How many presentation families are there and how can they be distinguished?
   - How can we determine the production speed of handmade production and machine production?
   - How can we determine the cleaning times and how does this variable differ with machine production? Is this similar for production speed?
   - What are the capacity constraints considering cleaning rooms, machines and employees?
c. Tactical level:
   - What are the current order rules and are these applicable for adjustment?
   - What is the result of the changing set of rules on the order process and the supply chain as a whole?
   - What is the gap between the current and perceived situation caused by the adjusted set of rules?
   - What seems to be the bottleneck in the order process taken the capacity and perishability constraint into account?

d. Performance of the Tactical and Detailed model:
   - How do the tactical a detailed model cope with capacity under stochastic demand?
   - What is the result of the model on the total cost of the supply chain?
   - What is the result of the model on the P_1-servicelevel?
   - How can this be translated in an easy-to-use, compatible tool?
e. Development of the tool
   - Should the tool be facility specific or companywide?
   - Is the current ERP system capable of delivering such a tool?
   - Is there a tool available on the market as it is?
   - What are the costs and benefits of the tool?

Management Decision
Considering the answers to the measurement questions, we should be able to make the major management decisions. Four possible scenarios are examined, which are given in the table below.

	Current Tactical Model	New Tactical Model
Current Detailed Model	If the answers to all the measurement questions are negative, preserving the current situation could be the best option.	If the perceived method does not perform, but the adjusted rules influencing the input of the process do, this could be ideal.
New Detailed Model	If the perceived method shows better performance, but the current set of rules is not in need of adjustment this is preferable.	If the tactical model shows a better performance with the new rules and the detailed model increases this performance this should be preferable.

Table 9: Possible Management Decision Scenarios

Depending on the performance of the detailed model, a decision regarding the development of the tool can be made. If the benefits of this tool exceed the costs, the development of the tool is certain. The generalization of the situation experienced in this research project should determine the outcome of the procurement of a stand-alone tool.

3. Literature Review

A literature review serves the purpose of summarizing all significant literature published in the research area of this master thesis. To propose a scientific model that fits the problem instance on both levels, an in-depth research towards possible solution areas is necessary.

3.1 Research Area

Three different areas of expertise are discussed, where the research area is narrowed down by each consecutive level. The final overlap of these topics is the research area in which this research project is executed. In conclusion, the research area of this master thesis is the production planning and control in consideration of the total supply chain in the pharmaceutical industry.

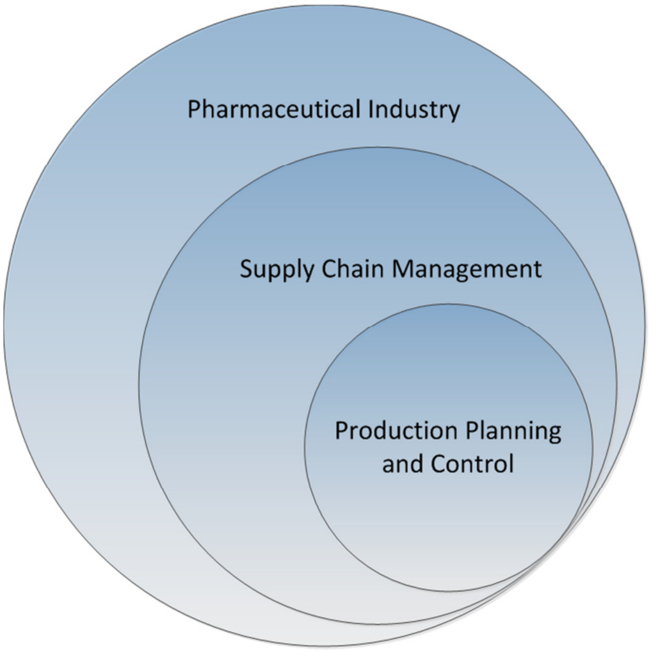


Figure 8: Research Area

The pharmaceutical industry is a complex, diverse industry which is subjected to strict regulations which results in strongly restricted solution methods. Shah (2004) describes in his literature review how the pharmaceutical industry is constructed in relation to the supply chain. He concludes a major part of this industry develops drugs through clinical trials. This comes with high levels of uncertainty and huge cycle times of the supply chain.

Considering supply chain management (SCM) many different definitions are found in different scientific books and research papers. Mentzer et al. (2001) develop a single, encompassing definition of SCM. ''A systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole.''

Considering the "Production Planning and Control", Pei et al. (2014) present a supply chain scheduling problem including non-identical job sizes, release times and processing times with the objective to minimize makespan. They consider a quite small supply chain of a supplier and a manufacturer. Staudacher and Bush (2014) introduce the Lean Approach in the pharmaceutical supply chain. The main effects of the lean approach are setup-time and batch sizes reduction, as they are looking at smoothing the flow.

Because of the different levels in this research project of which each level needs an appropriate solution method, three major research areas are selected:

1. Lot Sizing Problem
2. Multiple Orders per Job (MOJ)
3. Scheduling

3.2 Lot Sizing Problem

The incapacitated lot sizing problem is also referred to as the ELSP and it is researched for over 50 years. It was first introduced by Jack D. Rodgers of Berkeley in 1958. The paper of Kayvanfar and Zandieh (2012) addresses an ELSP for manufacturing environments with special attention to slack cost and deterioration items. The objective is to determine the optimal batch size by minimizing the total related cost.

The last literature review on the subject of Stochastic Economic Lot Sizing Problem (SELSP) found in the literature is the paper of Winands et al. (2011). This literature survey is focused on stochastic economic lot sizing problems. It targets papers which propose a fixed production sequence and a dynamic cycle length where the lot sizing decisions depend on the complete state of the system, including other stock-levels. They conclude there is some research done in this area, but this is significantly older work.

The second, more thoroughly investigated part of the lot sizing problem is the capacitated lot sizing problem (CLSP). The following key characteristics where described in the paper by Karimi et al. (2003):

- Planning horizon: may be finite or infinite, finite horizons are characterized by stationary demand and infinite horizons by dynamic demand.
- Number of levels: depends on the amount of operations that are considered in production.
- Number of products: single-item production planning assumes one final product, where multi-item planning takes multiple final products into account.
- Capacity: the level of capacity constraints
- Deterioration: is a restriction on inventory holding time
- Demand: is either deterministic or stochastic
- Setup structure: is either a simple sequence independent structure or a complex sequence depending structure
- Inventory shortage: makes backlogging and lost sales possible

A paper which is focused on parallel machines is the paper by Marinelli et al. (2007). They discuss a CLSP and scheduling real problem with parallel machines and shared buffers.
Roughly a year later, Buschkühl et al. (2008) presents a literature review of the past four decades of research. They discuss modelling approaches and algorithmic solution approaches. The focus of the modelling approaches is mainly on multi-level capacitated lot-sizing problems (MLCLSP) that separate the lot-sizing problem from the scheduling problem.

Pahl and Voß (Advanced Manufacturing and Sustainable Logistics, 2010) study in their paper the influence of deterioration and perishability constraints on discrete lot sizing and scheduling problems. Finally, some reviews of works considering CLSP are given in the papers by Quadt and Kuhn (2008) and Jans and Degraeve (2008).

The stochastic capacitated lot sizing problem, differentiates most from the deterministic CLSP in the demand variable. The situation of stochastic demand in combination with unrelated parallel machines described as a multiple-item CLSP is given in the paper of Toledo and Armentano (2006). The objective function is to minimize the sum of production, setup and inventory costs.

3.3 Multiple Orders per Job

Most sophisticated research is done on the MOJ scheduling problem including product families and due dates. Erramilli and Mason (2006) investigate a problem where customer orders are grouped into jobs and jobs into batches which are then scheduled single batch processing machine. The following figure shows this process.

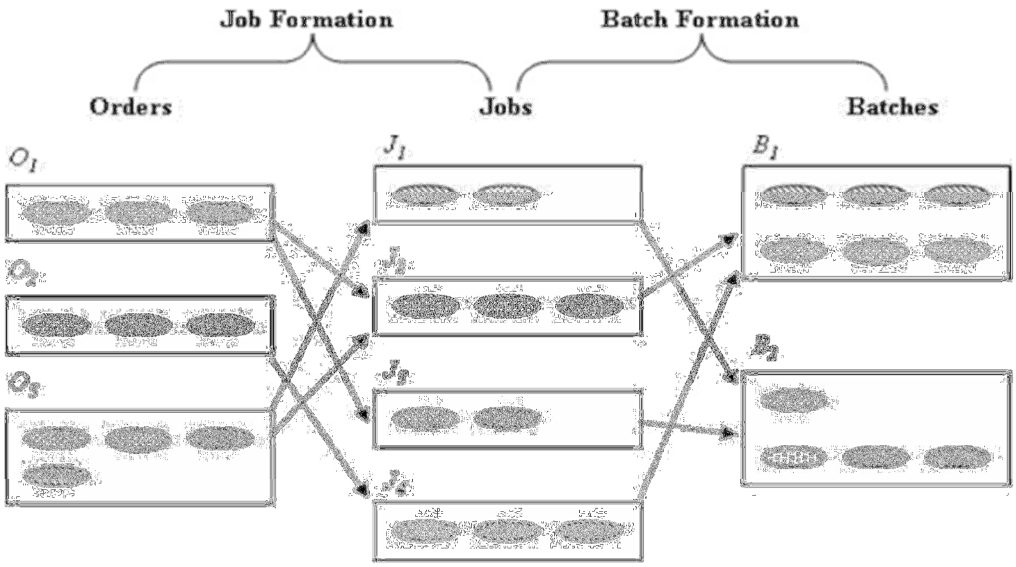


Figure 9: MOJ Batch Scheduling

The objective in this study is to minimize total weighted tardiness of orders. They assume no restrictions on combining orders of the same family into one job. They develop and test a mixed-integer program (MIP).

3.4 Batch and Scheduling Problem

A BSP without product families and due dates, but including parallel machines is described by Józefowska and Zimniak (2008). With a more practical approach on short-term production planning and scheduling they study a situation with a single operation routing on parallel machines with different possible production paths. The focus is on assigning product batches to different machines.

One of the first papers written on product families in BSP is the paper by Pekny et al. (1990). Especially unique for that time was the parallel algorithm that they describe which provides schedules based on two basic principles. The costs depend on the consecutive jobs passing through the production system (product families) and the profits are considered to be the sum of the benefits of each job. A later case study was done by Kondili et al. (1993). They create a general framework to cope with scheduling problems in multiproduct batch chemical plants. Due to the low reliability of demand forecast they choose a short-term order based scheduling solution containing a complex MILP. Shen et al. (2013) decided to put more effort in this area of expertise and describes a serial batching scheduling problem with multiple parallel machines under the influence of identical jobs in product families. Batches of jobs belonging to the same family can be formed to avoid setups.

The most expanded BSP on product families and due dates is discussed by Xiong et al. (2013). A single-operation serial batch scheduling problem, with multiple products which have a batch of predetermined size, a release time, a due date, an importance measurement and a product family is studied. They propose three decision problems: product batch splitting, sequencing and resource selection. They solve these three decision problems by introducing a hybrid algorithm combining the genetic algorithm for sequencing with the heuristic algorithm for resource selection. The figure below shows the framework they use for solving this scheduling problem.

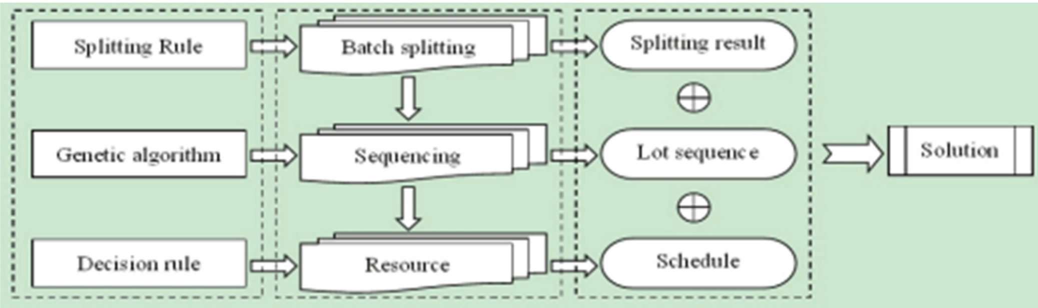


Figure 10: Used Framework

Their objective is to minimize the total weighted tardiness of all jobs. They first split batches into lots based on the amount of molds available for production, secondly they optimally sequence all lots and the last step is to select the optimal machine and mold.

3.5 Practical Conclusion

If we consider the current situation at PFCX a variety of solution methods could be reasoned for. Considering the problem in the tactical level, a CLSP should be solved to propose a rough cycle planning within the capacity constraints. On a detailed level the problem should be handled by an MOJ scheduling problem, which is solved in every time-step. This combination of two solving methods should lead to a more optimal scheduling result and lower overall cost.

4. Research Design and Methods

This chapter gives the structure on how the answers to the measurement questions and the research questions could be obtained. The research approach will describe the concept of structuring the project. Further on we will discuss the availability of data and how to handle this data. Subsequently this provided structure and the available data provide us with the right tools to develop a method to conduct answers to the research and measurement questions.

4.1 Research Approach

In this research proposal the structural approach of Mitroff et al. will be used as it depicts in the figure below. This research model describes the relation between the problem situation in reality and the ideal scientific model. A concept model is developed, which translates the problem situation into an environment which is suitable for modelling. By fitting the conceptualized problem into a proposed scientific model, a situation is created where the practical problem fits the scientific model. By comparing the proposed scientific model to the practical problem situation, the model is validated. After successful validation a solution is provided by solving the model for different scenarios. If this solution solves the conceptualized model, it is ready for implementation. In this way the quality of the implemented solution is ensured.

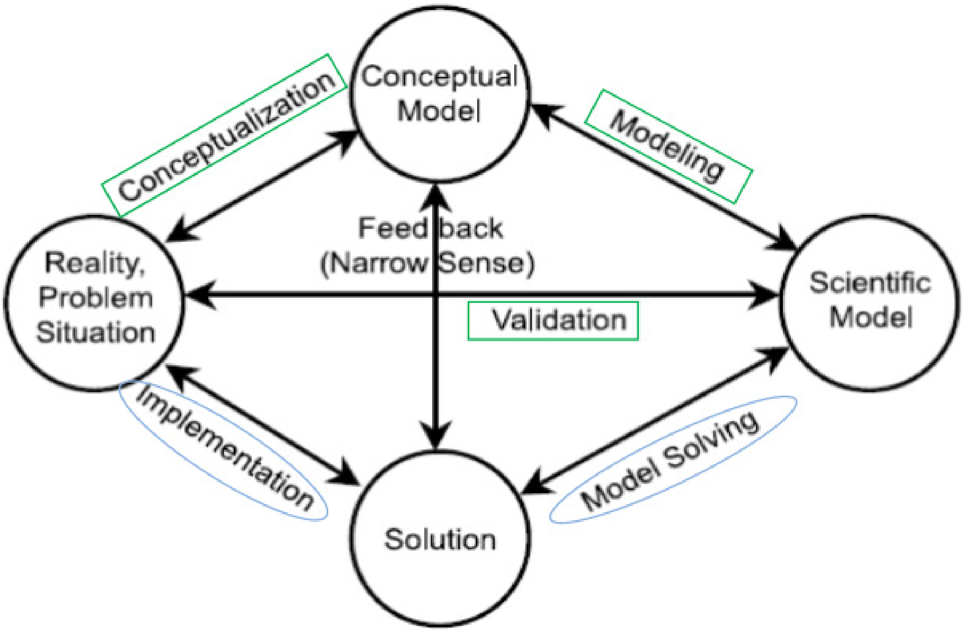


Figure 11: Research Model (Mittroff, BEtz, Pondy & Sagasti, 1974)

The problem situation of this research project is discussed in chapter two. The conceptual model on the tactical and detailed level is represented in the table below. In the following chapters the scientific models, solutions and implementation strategies are proposed for each level in the planning process.

	Current Manual Planning	Tactical Planning	Detailed Planning
Variables and	Estimations	Data driven	Data driven

Relations			
Model	Manual planning	Tactical Model optimizing Order Quantity and Frequency	Detailed Model in stochastic environment
Validation	Statistics	Compare supply chain cost	Compare to expected results Tactical Model

Table 10: Modelling Structure

4.2 Data Availability

All data used in this research project is directly retrieved from the data warehouse at PFCX or the data warehouse in Rotterdam. This data was stored to analyse and improve operational processes in general and is therefore not an exact fit on this specific research problem. This could cause difficulties in connecting different production processes. In this case, the missing connections where left out of the data. The data was then tested for outliers, which were deleted and replaced if appropriate. However, for most of the variables there was a sufficient amount of data available so the influence of missing data was small.

In the detailed model some of the input data was unavailable. Logically there is no data available with the potential new order rules given by the tactical model. To cope with this missing data, it was simulated under the most realistic circumstances. In contradiction to the tactical model, the detailed model acquires data which is stored at the partner. This data, concerning the weekly demand rate at the sales partner, was made available by the data analyst in Rotterdam. Overall, no major data flaws where encountered.

4.3 Methodology

The methodology of this research project is carried out by using the Design to Schedule Model. This model contains four phases: Concept Creation and Requirement Gathering, Planning and Designing, Implementation and Evaluation.

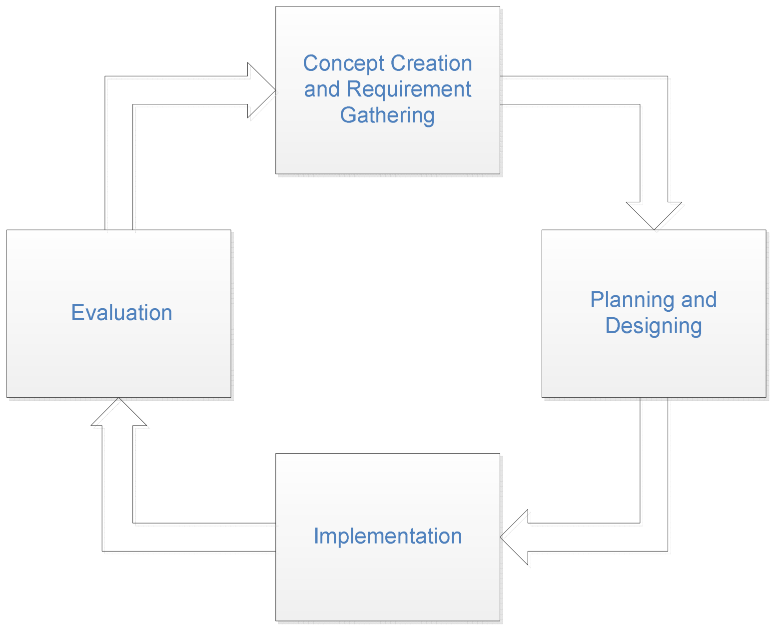


Figure 12: Design to Schedule Model

Concept Creation and Requirement Gathering
In the process of creating a concept for this research project boundaries are explored and the problem solution area is limited by requirements.

The concept that is developed considers a two phased problem solution. The Tactical Model will propose a method to determining the near-optimal order quantities and frequencies, while taking the overall capacity into account. In this method a simple mathematical algorithm is proposed with variables specific to each raw material.

The solution method proposed by the detailed model is a linear programming based solution. In the made-to-order part of this model orders are simulated and their influence on capacity is tested. In the made-to-stock part the LP-model for VMI presentations is suggested.

Before the development of the tool the requirements should be clarified. It should be able to convert production orders to a detailed production planning to machine, cleanroom and employee capacity. More realistically, the tool is restricted to propose an order planning and making better VMI decisions.

Planning and Designing
The Planning and Designing phase contains of the plotting of goals and prioritizing these goals during the execution of this master thesis. Planning is done using Microsoft Project Manager and constantly updating the deadlines and deliverables. The design of this research project concerns the structure of this project and in which form the solution content is represented.

Designing the tool in the current ERP system is expected to be difficult and the software engineers at PFCX have doubts if it is sufficient. Depending on the decision to procure a suitable software system the tool should be designed using Microsoft Excel.

Implementation
In the implementation phase the two models and the designed tools are tested on output and compared to the current situation. Depending on the impact of the tactical model an implementation method is chosen. Obviously results with a high return and a low operational impact are prioritized over results which are of the contrary. Further on the decision to either purchase or develop a tool is of great influence on the implementation method.

Implementation methods that are considered are the Big Bang, Phase Rollout and Parallel Adoption. If an Excel tool is locally developed a Phase Rollout method is suggested, while we can easily introduce each new rule at a time and see if the overall impact is similar to the expectations. Another advantage of using this implementation method is that it is less sensitive to errors because of the stepwise system. In the case of purchasing compatible software a Big Bang method might be most effective, while it would be unproductive to implement old rules into a new software tool.

Evaluation
The evaluation of the models and tools are repeated multiple times over the timespan of this research project. In this paragraph we consider the evaluation of the project as a whole, while evaluation takes place after every milestone that is reached. By comparing the results to the conceptual idea and test if the requirements are met, the processes are evaluated.

5. Tactical Model

In this chapter the conceptual model is reflected to the scientific model, which results in a solution method that fits the original problem description. First a solution method is developed, for which different solution areas were proposed. The results of these scenarios were finally compared to conclude a final tactical strategy. A tool was developed which fits the chosen strategy and finally an implementation plan was given.

5.1 Proposed Solution Method

The solution method should be capable of finding a near-optimal order cycle in which the order setup cost, total cleaning cost and stock keeping cost are minimized. A semi-fixed production cycle is introduced, including a fixed cycle of families and varying presentations underlying these families. This method assumes evenly distributed demand over the year and neglects capacity. These limitations in the solution approach obligate us to research the influence on the solution method. Another limitation is the influence of special orders on cost calculations.

5.1.1 Parameters

Before the introduction of the scientific model, the input-parameters are discussed. These variables are retrieved from data when possible, however for some of the cost it was inevitable to make an estimate.

A_i	Family Setup Cost of item i in €
a	Order Specific Setup Cost in €
D_i	yearly Demand for item i in units
v_i	Transfer Price of item i in €
r	Cost of Capital in %
m_i	the integer number of T intervals the replenishment quantity of item i will last
T	Time interval between replenishment orders
Q_i	Replenishment quantity of item i
L_i	Amount of lots per year $\epsilon \{1,2,3,4,6,8,13,26,52\}$
n	the number of items i

The presentation family setup cost exists of two sorts of cost: the cleaning cost and the cost of picking the raw material. The cleaning cost is derived from data by multiplying each item individual cleaning time by the average wage for production employees. The cleaning time is a variable that should be determined with a rolling horizon, where the average wage is diverse over the years. The bulk picking cost, among other expenses, is estimated values which are clarified in Appendix I. The following cost function is presented for A_i.

$$A_i = A_{i,Clean} + A_{Bulk-picking}$$

The order specific setup cost has a similar cost structure, in this case spread over the supply chain: the setup cost for each order made by PFCX and the reception cost at the sales companies. An estimation of the cost at PFCX is substantiated in Appendix I, while the estimated reception costs are based on data from Company X Belgium. In total, the following costs are calculated:

Setup Cost at PFCX	€72,33
Reception Cost at Sales Company	€4,-
Total a	**€76,33**

Table 11: Order Specific Setup Cost

The demand D_i is valued as the original demand in 2013, while this makes it comparable to actual results of this year. These values are derived directly from the data. The transfer price v_i is a fixed price updated once every year. The cost of capital r is estimated to be 10%.

5.1.2 Proposed Model

The proposed model has the objective to find the threshold between the two different setup costs and the stock keeping cost. A simplified approach, considering a single setup cost, is the Economic Order Quantity (EOQ) model. If an order cycle is considered, the EOQ can be expressed as a time supply by the following equation:

$$T_{EOQ} = \sqrt{\frac{2A}{Dvr}}$$

Note that T_{EOQ} increases if the ratio A/Dv increases. This indicates that an item with high setup cost A and a low capital value D_*v is respectively replenished less often as a contradicting item.

Under the assumption of equally spread deterministic demand, no shortages permitted and a predetermined delivery time, it makes sense to only include an item when their inventory level is below the safety stock. Therefor a reasonable type of policy to consider is the use of a time interval (T) between replenishments of the family, where m_i is the number of T intervals a replenishment quantity of item i last. For example if m=2, the production quantity will last 2T and so the item is produced every alternative cycle.

The integer m_i must be selected to minimization the following function:

$$1)\quad (A_i + \sum_{i=1}^{n} \frac{a}{m_i}) \sum_{i=1}^{n} m_i D_i v_i$$

To select the best m_i's an algorithmic approach is proposed to find the near optimal values of m_i within maximum 6% of the optimal. For this solution, the corresponding value of T is given by the following set of functions.

The objective is to minimize the total relevant cost for a set of m_i's in unit time, of which the derivation is given by the formulas below. The TRC implies a family setup cost in every replenishment T, with an order setup cost for each m_i'th time a presentation is produced within the cycle. A logical inventory cost is given by the second sum function of this equation.

$$2)\quad TRC(T, m_i) = \frac{A_i + \sum_{i=1}^{n} \frac{a}{m_i}}{T} + \frac{\sum_{i=1}^{n} D_i m_i T v_i r}{2}$$

The derivative $\frac{\partial TRC}{\partial T}$ is set to zero, to find the optimal total relevant cost for the m_i's.

$$3)\quad -\frac{A_i+\sum_{i=1}^{n}\frac{a}{m_i}}{T^2}+\frac{\sum_{i=1}^{n}D_i m_i v_i r}{2}=0$$

So, the optimal time interval T between replenishments of the family and a set of m_i's is given by the equation below.

$$4)\quad T^*(m_i's)=\sqrt{\frac{2(A_i+\sum am_i)}{r\sum m_i D_i v_i}}$$

By filling in the T* into the TRC function we compute TRC*, which is shown in the next equation

$$5)\quad TRC^*(m_i)=\sqrt{2\left(A_i+\sum\frac{a}{m_i}\right)r\sum m_i D_i v_i}$$

An algorithmic approach is set up, because we wish to select the m_i's to minimize TRC*.

STEP 1

From inspection of the previous equation the minimization of TRC* is achieved by minimizing the following equation. Note that the carrying charge does not influence the best values of the m_i's.

$$6)\quad F(\mathrm{m}_i's)=\left(A_i+\sum\frac{a}{m_i}\right)\sum m_i D_i v_i$$

Minimizing this function is considered difficult while the value of one m_i influences the other m_i's values and the m_i's must be integers. If the second restriction is chosen to be ignored, it can be minimized by setting its derivative equal to zero. This results in the following equation

$$7)\quad m_J=\sqrt{\frac{a\sum m_i D_i v_i}{D_j v_j\left(A_i+\sum\frac{a_i}{m_i}\right)}}=\sqrt{\frac{a}{D_j v_j}}*\sqrt{\frac{\sum m_i D_i v_i}{\left(A_i+\sum\frac{a_i}{m_i}\right)}}$$

By dividing the continuous solution j and k, where j≠k and a is similar for both items, it can be concluded that if

$$8)\quad D_j v_j \leq D_k v_k$$

the continuous solution m_j is smaller as the continuous solution m_k, therefor the items i having the smallest value $\frac{a}{D_i v_i}$ should have the lowest value of m_i. It is considered to hold similar behaviour when m_i's are restricted to being integers. So the items are sorted on the smallest value, starting with m_1=1.

STEP 2

By setting the second element of equation 7) to C the following equation arises

$$9)\quad C = \sqrt{\frac{\sum m_i D_i v_i}{\left(A_i + \sum \frac{a}{m_i}\right)}}$$

$$10)\ m_j = C * \sqrt{\frac{a}{D_j v_j}}$$

To express the elements of C in equation 9) into values of C the following equations are stated and filled in equation 9) to make this equation independent of m_i.

$$11)\ \sum_{i=1}^{n} m_i D_i v_i = D_1 v_1 + C \sum_{i=2}^{n} \sqrt{a D_i v_i}$$

$$12)\ \sum_{i=1}^{n} \frac{a}{m_i} = a + \frac{1}{C} \sum_{i=2}^{n} \sqrt{a D_i v_i}$$

By cross-multiplication some simplicity steps the following function for C was proposed

$$13)\ C = \sqrt{\frac{D_1 v_1}{A_i + a}}$$

Substitution of expression 13) into equation 10) gives the final equation for determination of the consecutive m_i's.

$$m_i = \sqrt{\frac{a}{D_i v_i} \frac{D_1 v_1}{A_i + a}}$$

This value is rounded to the nearest integer greater than zero.

STEP 3
Evaluate T^* using the m_i's of the previous step.

STEP 4
Determine

$$Q_i = m_i D_i T^*$$

This algorithm results in near optimal replenishment quantities (Q*) for each item i. An example of the replenishment of a family and its underlying presentations is given in Appendix II. To calculate the expected amount of orders in 2013, the Q_i*/D_i gives a number of reputations of each item per year (L_i). While the lot size L_i is an element of {1,2,3,4,6,8,13,26,52} and has a minimum of one reputation in each year, a clean replenishment cycle is pursued. The influence of this on the total amount of orders is quite significant, an increase of 30% from respectively 4000 to 5200 expected orders.

The influence of the perishability of goods was not even 1%, so it is considered very limited. For theses exceptions the minimum amount of replenishments per year increased the values given by the algorithm.

5.2 Total Cost Calculations

In this chapter the three main cost functions are provided: family setup cost, order setup cost and stock keeping cost. The influence of the changing policy could influence some other expenses, which are considered in the last paragraph.

5.2.1 Family Setup Cost

The total family setup cost consists of the total amount of cleaning cost of the proposed production cycle. The proposed model does not include special orders, which are of significant influence on the total cleaning time.

Special orders influence the total cleaning cost if the family which it belongs to is not produced during the specials lead-time. The occurrence of such a situation depends on the number of replenishments of the specific product family and the frequency of arriving special orders. For the probability function Poisson arrival times are assumed, which is underpinned in Appendix III. For this probability function the following variables are set:

P	Probability function
y_i	arrival rate of special orders of item i
LT	Lead Time for special orders
R_i	Number of replenishments of item i

This probability function represents the probability that a family in the production cycle can be combined with an incoming special order.

$$P(Combined\ with\ Special\ order) = e^{-y_i * LT * R_i}$$

Similarly, the proposed solution is influenced by the arrival of orders. These orders differ in lead time and arrival rate, but follow a similar solution approach as the special orders.

Finally the models direct cleaning cost is calculated by the following cost statement

$$Model\ Family\ Setup\ Cost = L_i * A_i * P(Combined\ Special\ Order) * P(Combined\ Normal\ Order)$$

The total family setup cost is considered in the following equation:

$$Total\ Family\ Setup\ Cost = Model\ Family\ Setup\ Cost + Special\ Family\ Setup\ Cost + Order\ Family\ Setup\ Cost$$

To allocate potential extra cost or cost savings to the different links in the supply chain, the family setup cost can be split into the cleaning cost and the bulk picking cost.

5.2.2 Order Setup Cost

The order setup cost is not influenced by the special orders or other made-to-order items proposed in the previous paragraph. This causes the calculating of the total order setup cost to be significantly less difficult. The total amount of order setup cost is given by the following equation:

$$Total\ Order\ Setup\ Cost = \left(\sum_{i=1}^{n} L_i + Number\ of\ Special\ Orders\right) * a$$

5.2.3 Stock Keeping Cost

For the stock keeping cost we only consider the items which are represented in the model. This cost calculation is represented in the following equation.

$$Total\ Stock\ Keeping\ Cost = \frac{1}{2} * \frac{D}{L_i} * v_i * r$$

All of these costs are made by the sales partners.

5.3 Scenario Results

While Company X is implementing VMI in stages and the progress is quite uncertain, two scenario instances are proposed with a different VMI implementation restriction. The first scenario instance proposes the current state of the VMI implementation process, the other the final stage of the implementation process. So, the current VMI introduced in the Benelux versus the final instance which assumes 100% VMI.

These scenario instances are split in three scenarios by an implementation restriction. This model implementation restriction concerns the level to which the stock keeping cost (SKC) can differ from its original value. The best solution considers no stock keeping cost restrictions and therefore finds the best supply chain solution. If stock positions at the partner are not allowed to rise a scenario with similar SKC is recommended. If the sales partners need an incentive for implementation of this model a decreasing SKC is advised. In the table below the six proposed scenarios are presented.

	Best Solution	**Similar SKC**	**Less SKC**
Benelux VMI	Scenario 1	Scenario 3	Scenario 5
100% VMI	Scenario 2	Scenario 4	Scenario 6

Table 12: Scenario's

5.3.1 Results Scenario 1

The first scenario proposes the current implementation status of VMI for the Benelux and considers a non-restricted solution area. The table below shows a positive result on the family cleaning cost and bulk picking cost, which implies a more optimal combination of orders. These costs are influenced by the VMI implementation restriction.

Family Cleaning Cost	€19.461,39
Bulk Picking Cost	€3.421,13
Order Setup Cost	€205.995,84
Order Reception Cost	€11.392,00

Stock Keeping Cost	- €38.732,62
TOTAL (SAVING)	**€201.537,74**

Table 13: Results Scenario 1

The order setup cost and subsequently the order reception cost are decreased. This is due to the significant reduction of orders caused by the proposed model. These costs will are influenced by the model implementation restrictions. In the table below the original results are compared to the results of the model.

	Original	Model
Total number of Orders	10233	7385
Special Orders	2204	2204
Regular orders	8029	5181
Order Setup Cost	76,33	76,33
Total Order Setup Cost	€781.085,89	€563.697,05

Table 14: Order Amounts

The stock keeping cost is increasing, due to rising stock positions at the sales companies. By comparing the average stock of the old set of rules to the rules proposed by the model the total result is computed. The table below shows the results.

Original SKC 2013	€257.796,80
Model SKC 2013	€296.529,43
Result Stock Keeping Cost	**€38.732,62**

Table 15: Stock Keeping Cost

A rise of €40.000,- in stock keeping cost corresponds to a €400.000,- increasing stock capital. This equals an increase in stock positions, which influences the short-term capacity.

In scenario one the total cost saved over the year 2013, is about €200.000,-. This is considered a significant cost reduction, though capacity restrictions and stochastic demand are expected to have a negative effect on the saved cost.

5.3.2 Results Scenario 2

The results of scenario two show similarities to scenario one, while order setup cost and stock keeping cost differ by the model implementation restriction not by the VMI implementation restriction. The total results show a positive effect on the family setup cost, while the negative influence of regular orders disappears.

Family Cleaning Cost	€45.668,19
Bulk Picking Cost	€13.140,26
Order Setup Cost	€205.995,84
Order Reception Cost	€11.392,00
Stock Keeping Cost	-€38.732,62
TOTAL (SAVING)	**€237.463,67**

Table 16: TOTAL Cost Savings

Because of the decreasing family setup cost a better result is achieved as in scenario one. The total cost saved are about €240.000,-, which is a 20% improvement on the first scenario.

5.3.3 Results Scenario 3

The result for scenario three differs from the previous scenarios in order setup cost and stock keeping cost. These results were produced after adding the restriction of equal stock keeping cost, as the results in the table below depict.

Family Cleaning Cost	€15.732,36
Bulk Picking Cost	€2.082,82
Order Setup Cost	€164.840,07
Order Reception Cost	€9.116,00
Stock Keeping Cost	-€76,28
TOTAL (SAVING)	**€191.694,97**

Table 17: Results Scenario 6

This equal stock keeping cost is reached by rounding the L_i above 1,14 and below 2 up instead of rounding it to the closest integer. This causes an increase in the expected number of orders which logically results in larger order setup cost and subsequently family setup cost. Still it this scenario proves to be very appealing with a total coast saving of €190.000,-.

5.3.4 Results Scenario 4

In scenario four a similar effect is recognized as in the previous scenario. From the table below it shows that the total savings dropped with an equal amount of €10.000,-. The total amount of cost savings is still a very profitable €230.000,-.

Family Cleaning Cost	€43.923,72
Bulk Picking Cost	€12.374,96
Order Setup Cost	€164.840,07
Order Reception Cost	€9.116,00
Stock Keeping Cost	-€76,28
TOTAL (SAVING)	**€230.178,47**

Table 18: Results Scenario 5

5.3.5 Results Scenario 5

In case the sales partners need to be convinced of the benefits of the proposed model, a scenario was developed with positive effects on the total stock keeping cost. Similarly to scenario three and four, this was done by rounding the lot size above one and below two up instead of rounding it to the closest integer.

Family Cleaning Cost	€13.826,56
Bulk Picking Cost	€1.428,20
Order Setup Cost	€146.395,92
Order Reception Cost	€8.096,00
Stock Keeping Cost	€11.910,29
TOTAL (SAVING)	**€181.656,97**

Table 19: Results Scenario 4

This has a stronger negative effect on total family and order setup cost, while the amount of orders increases even more. However, the scenario still proposes a positive result of about €180.000,- in overall cost saving.

5.3.6 Results Scenario 6

The final scenario shows compares to scenario five as four compares to three. The negative effect of the decrease of stock positions results in a lower total savings of €220.000,-

Family Cleaning Cost	€43.299,30
Bulk Picking Cost	€12.065,00
Order Setup Cost	€146.395,92
Order Reception Cost	€8.096,00
Stock Keeping Cost	€11.910,29
TOTAL (SAVING)	**€221.766,51**

Table 20: Results Scenario 3

5.3.7 Other Overall Results

We consider three major cost factors influenced by the proposed model: cost of transportation, cost of raw material supply and stock keeping cost at PFCX.

Cost of transportation is considered to decrease, but not significantly. The total transported quantity does not change, but the amount of similar items in each delivery increases. While this results in a more effective use of pallets and transport is paid per pallet a slightly lower cost of transportation is expected. However the measurement of this effect is not within scope of this research method.

The effect on cost of raw materials and stock keeping cost is expected to decrease while the fit between procurement and production benefits from the proposed fixed cycle. If forecasting was more accurate or lead-times longer, just in time (JIT) management could be applied. The measurements of these effects and the possible results are considered out of scope.

5.4 Scenario Selection

The overview of the scenario results is given in the table below. We can conclude that the overall implementation of VMI will probably have positive effects on the cost of the supply chain. In this restriction we see a large deviation in the family setup cost, which correspond directly to capacity increase. This leads us to the conclusion that the proposed model increases capacity with a maximum of 7,5% and a minimum of 3%. The VMI implementation restriction has no influence on stock keeping cost and order setup cost.

	Costs	*Best Solution*	*Similar SKC*	*Less SKC*
Benelux VMI	Family Cleaning Cost	€19.461,39	€15.732,36	€13.826,56
	Bulk Picking Cost	€3.421,13	€2.082,82	€1.428,20
	Order Setup Cost	€205.995,84	€164.840,07	€146.395,92
	Order Reception Cost	€11.392,00	€9.116,00	€8.096,00
	Stock Keeping Cost	- €38.732,62	-€76,28	€11.910,29
	TOTAL (SAVING)	**€201.537,74**	**€191.694,97**	**€181.656,97**
100% VMI	Family Cleaning Cost	€45.668,19	€43.923,72	€43.299,30
	Bulk Picking Cost	€13.140,26	€12.374,96	€12.065,00

	Order Setup Cost	€205.995,84	€164.840,07	€146.395,92
	Order Reception Cost	€11.392,00	€9.116,00	€8.096,00
	Stock Keeping Cost	-€38.732,62	-€76,28	€11.910,29
	TOTAL (SAVING)	**€237.463,67**	**€230.178,47**	**€221.766,51**

Table 21: Results Scenario's

In contradiction to the VMI implementation restriction, the model implementation restriction strongly influences the order setup cost. While this restrictions objective is to influence the stock keeping cost, the obvious effects these costs. The decreasing amount of order setup cost corresponds to the decrease in the number of orders. The number of orders respectively decreases with about 35% and 28% in scenario one and two, 28% and 22% in scenario three and four and 25% and 20% in scenarios five and six.

By discussion with the senior management of PFCX, the global supply chain manager, CIO and COO a scenario was selected. Due to political reasons within Company X, new methods are more efficiently implemented if there is no extra cost involved. Although scenario one and two are supply chain wide most cost efficient, scenario three and eventually four is most favourable. This scenario shows no increasing cost for one of the stakeholders with a maximum supply chain wide cost reduction. This research project considers the current situation, so the results of scenario three are considered as input in the detailed model.

5.5 Tool development

For this model a simple tool is developed in Microsoft Excel. The tool automatically retrieves the necessary data to compute all input variables. The only value that will significantly change over time is the yearly forecasted demand. Demand forecast is proposed by the sales companies on a monthly basis, which would imply monthly use of the tool to be most effective. After execution of the model, the proposed order quantities are implemented in the current ERP system and used on a daily basis.

The simplicity and effectiveness of the models results raised a high companywide interest. In the final stage of this research project the compatibility of the tool is used at different sales companies like Company X Germany and Company X Belgium. This positive feedback led to introduction of the model in Greece and Brazil.

6. Detailed Model

The output variables of scenario three of the tactical model were used as input in the detailed model. On a detailed level a model under stochastic demand and capacity constraints is proposed. Scenario three describes the current situation, where VMI is available only for the sales companies in the Benelux. This results in a model which considers a two stage solution method, first the made-to-order and second the made-to-stock part, respectively 31% and 69% of total demand. These two stages are selected due to the diverse level of influence that PFCX can apply on the input variables.

6.1 Order Solution Method

In the first stage of the proposed solution method, normal and special orders are considered. These orders have a predetermined order quantity and delivery time by the sales partners. The combination of orders of similar families is comparable to a MOJ-system. The machine production decision influences the expected production speeds and cleaning times. Eventually, the order planning proposal, influence on capacity and the results of this method are given. In the figure below the perceived order solution method is given.

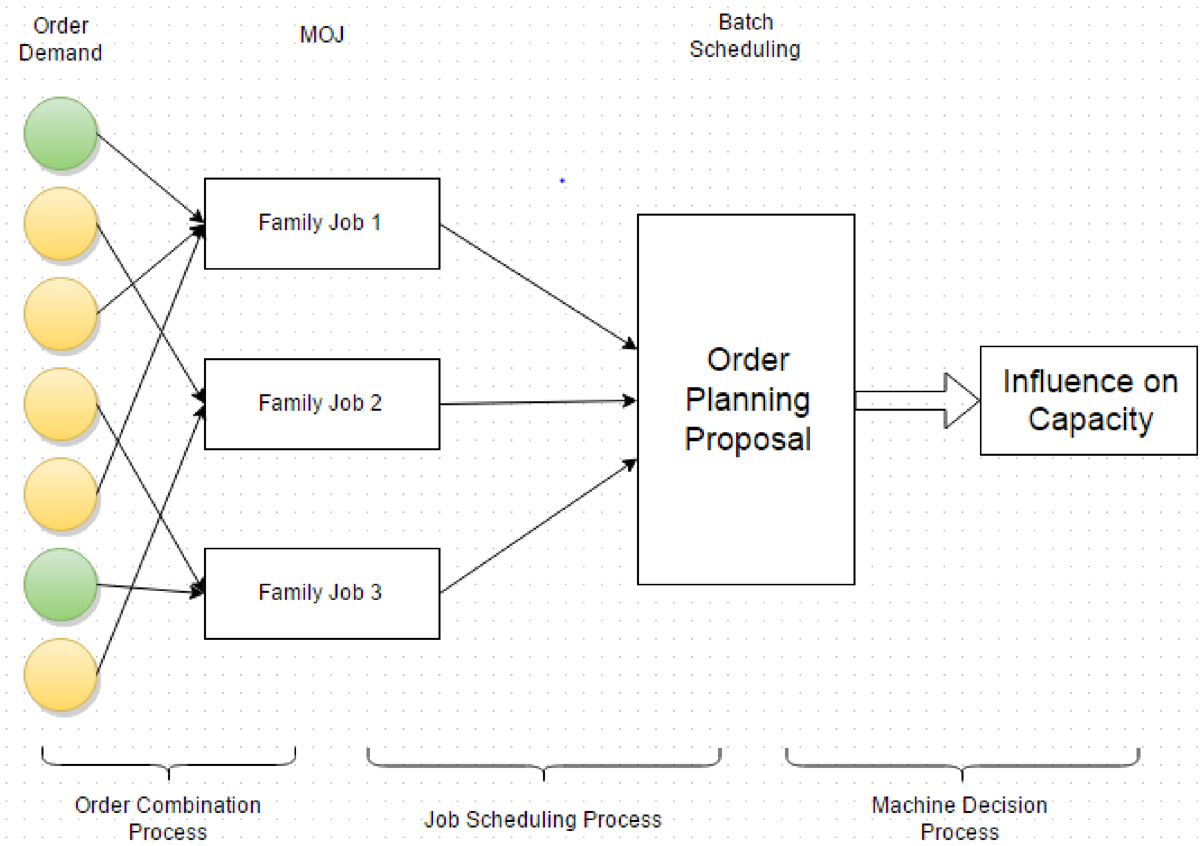


Figure 13: Proposed Order Solution Method

6.1.1 Order Demand

There are two types of incoming sales orders: regular orders with a lead time of 6 weeks and special orders with a lead time of 2 weeks. To be able to compare the results of the detailed model to the actual and tactical results, variability is kept as low as possible. While special orders do not depend on the rules set on a tactical level, the actual order demand data is used. Regular orders are subordinate to the rules set on a tactical level and therefore we have no data representing the arrival of regular orders under the new set of rules. So, the arrival of orders and its order quantity is artificially produced.

For the regular orders demand a simulation model is proposed which computes regular arriving orders with order quantities implied by the tactical model. The objective of the simulation model is to propose a situation as close to realistic as possible. First the distribution of the inter-arrival times and order quantity was identified by analysing the current order arrival situation. After having tested the inter-arrival times and order quantities for over thirty different distributions by using Easyfit 5.5, there was no proof for any of these distributions. Consecutively a standard procedure was chosen which assumes a compound Poisson distribution with exponentially distributed arrival times and uniformly distributed order quantities. This assumption holds, while these were the distribution with the most significance for the arrival process and order quantity.

The regular orders where simulated using the parameters and equation below. To assess the variability in the simulated demand and limit confidence intervals of the research results, the order solution method was simulated for 20 years.

λ_i	Order arrival rate of item i
d_{it}	Order arrival time for item i at time t
x	Random number between 0 and 1
y	Days in 2013 (365)

$$d_{it} = d_{i,t-1} + \left(-\frac{\ln(1-x)}{\lambda_i}\right) * y$$

Consecutively the uniformly distributed order size is proposed, which results in a list of orders with their time of arrival and appropriate uniform distribution.

6.1.2 Order Combination

The combination of orders is done in two stages, first a situation is proposed which combines all possible orders and secondly the optimality of this is checked. The optimality is checked by computing the threshold between the saved family setup cost and the increasing stock keeping cost.

In the first stage all orders are combined. Because of a start-up period, which is equal to the lead-time of about six weeks, orders in this period are combined on an earliest original due date (EODD) rule. After this start-up period orders are combined on an earliest combination due date (ECDD) rule, while these can differ from the original due date. For regular orders a rolling horizon of six weeks is proposed, for specials a two week rolling horizon. This leads to the following parameters and equations.

CDD	Combined Due Date
$EODD_f$	Earliest Original Due Date of Family f
$ECDD_{f,l}$	Earliest Combined Due Date of Family f in Lead-time l

$$ECDD_{\leq 6wk} = CDD_f$$

$$CDD_{>6wk} = ECDD_{(f,l)}$$

The optimality of this combination rule is questionable. To investigate this further a method is proposed to compute the threshold between family setup cost and stock keeping cost. If the following equation is valid, the ODD is reset as final due date. This rule is proposed with a similar rolling time horizon as the previous proposed combination rule.

$$\frac{(CDD - ODD)}{365} * r * O_{it} * v_i > A_i$$

These rules result in the most cost efficient combination policy, which is not equal to the most capacity efficient solution proposed by the first rule. This optimization step caused a cost saving of approximately €5000,- compared to the most capacity efficient solution.

6.1.3 Machine Decision

The machine decision depends on the fixed parameters proposed in appendix IV. The machine decision is presentation specific, while different units of measure fit different machines. The first table presents the units of measure and their corresponding machine production point, which is the quantity from which a production order is machine produced. The machine categories according to the units of measure are given in the third table of this appendix. The second variable in the machine decision is the compatibility of the presentation for machine production. Considering these variables the individual machine decision is made.

All individual machine decisions of a combined order may be negative, while the combined production quantity might result in a positive decision. In table one of appendix IV the machine production points for this decision are given. However, the influence of this addition for combined orders is very limited.

6.1.4 Model output

The perceived output of the order solution method is the yearly production proposal and its influence on capacity, while this information is required in the VMI selection proposal. The yearly production proposal depends on the combination decision, while the machine decision influences the capacity utilization. There are three capacity factors that limit the production process: employee capacity, cleanroom capacity and machine capacity.

The available employee capacity is retrieved out of the workforce planning of 2013. The capacity demand of the production proposal is given on a weekly basis, while daily capacity highly fluctuates. In the graph below we see an example of the weekly fluctuating employee capacity in percentage of the total available capacity.

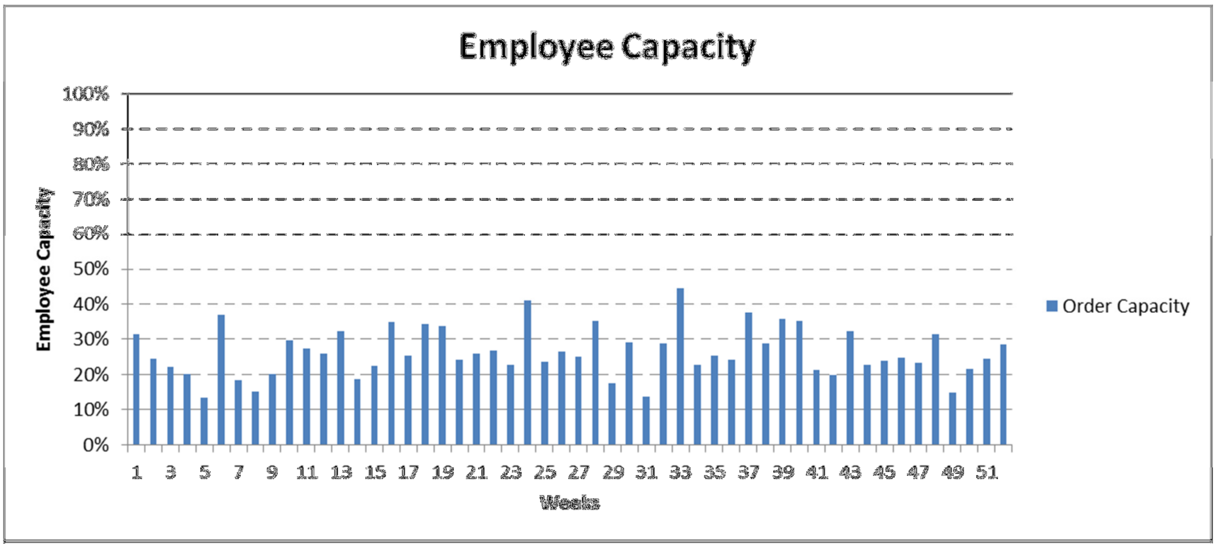


Figure 14: Order Capacity in %

Out of the graph above we can conclude the average order capacity is about 30%. However, this fluctuates between 45% and 13%.

The cleanroom capacity differs for High Risk (HR) presentations and normal presentations, respectively 2 and 9 cleanrooms. The influence of the production proposal on both types of cleanroom capacity is given in the two figures below. These figures show a slightly higher normal cleanroom utilization rate as HR cleanroom, however both are significant.

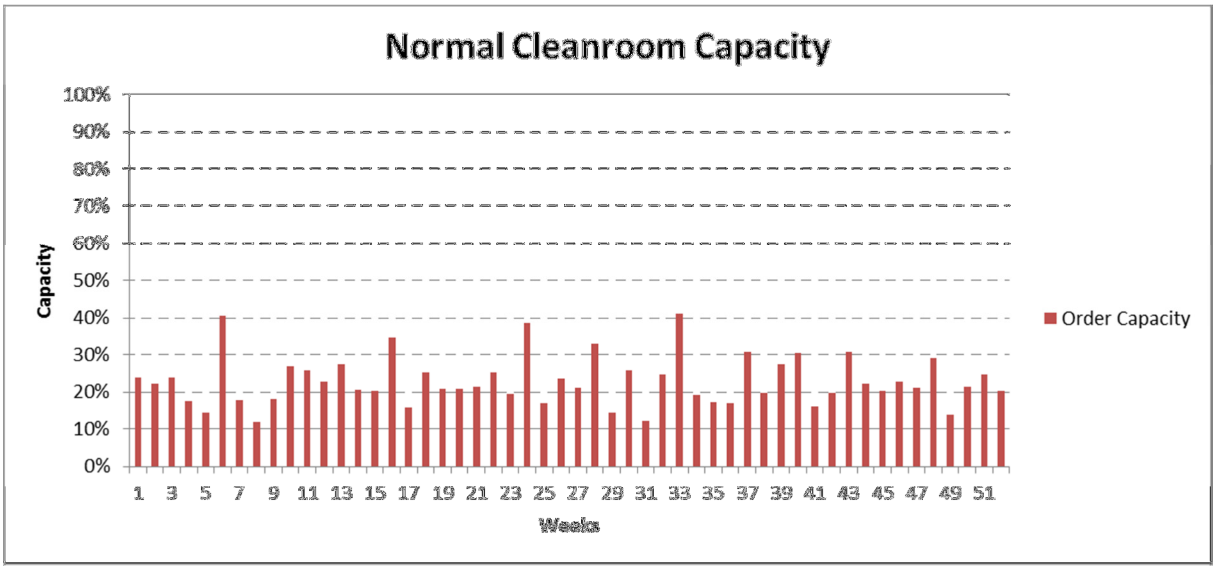


Figure 15: Normal Cleanroom Capacity

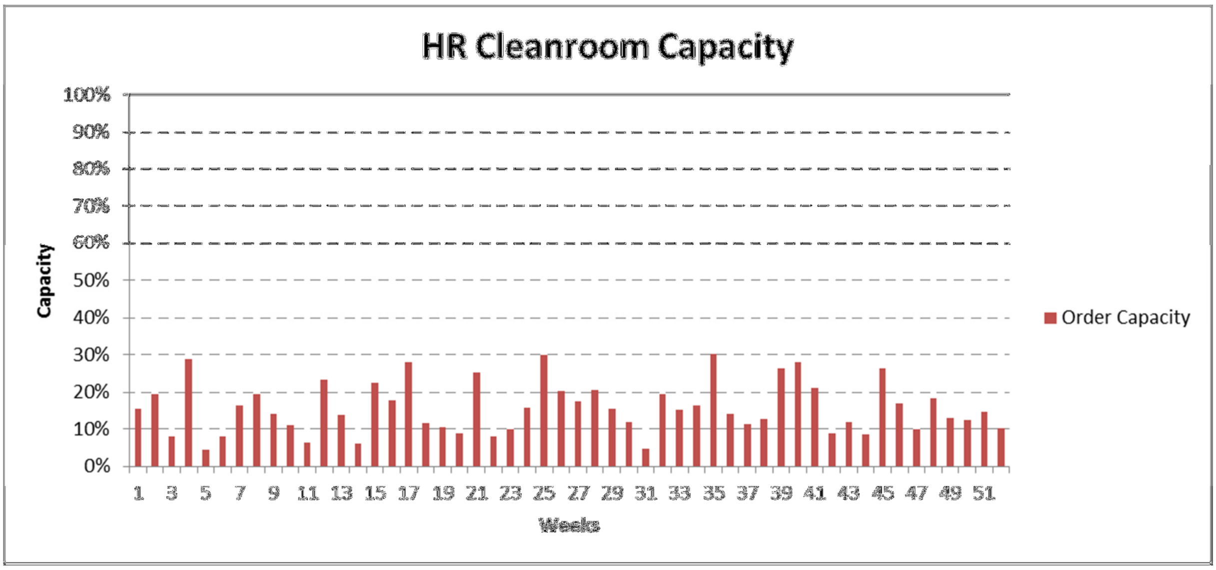
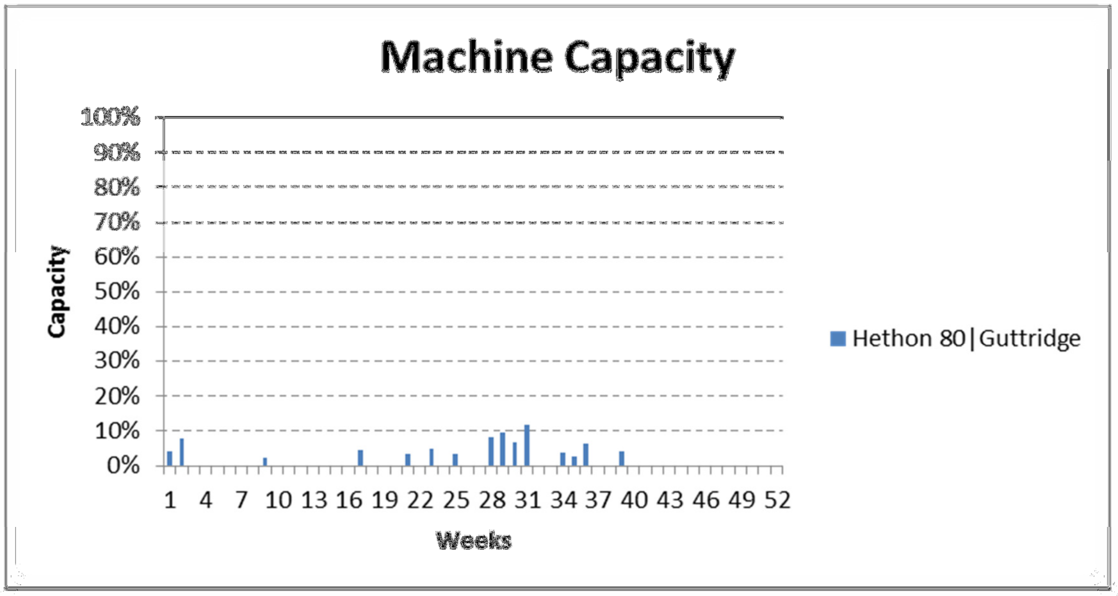


Figure 16: HR Cleanroom Capacity

If we consider the machine capacity in the next figure, it seems to not really restrict the production process. For the highest utilized machine, the Heton 80, an average utilization rate of 2-3% is shown with a maximum of 11%.



In conclusion, the employee capacity and normal cleanroom capacity are the bottleneck in the production process. HR cleanroom capacity can still restrict the production process, but in a les significant way. Machine capacity is not considered a restriction, while 31% of demand causes a maximum of utilization rate of 11%. The final results of the multiple simulation runs are saved for input in the proposed VMI selection method.

6.1.5 Simulation Results

In the simulation results we consider the following performance measurements: the total amount of packages produced, the amount of orders, total cleaning time, service level, stock keeping cost and finally the machine production percentage.

After deriving the performance measurements out of the twenty simulated data results, the average performance measurements and its confidence intervals can be calculated. The average values of *n* simulations, with X as the mean, x_i as observation of the different performance measurements and n the total amount of simulations can be calculated by:

$$\bar{X}(n) = \frac{\sum_{i=1}^{n} x_i}{n}$$

The corresponding variance, of which the standard deviation is its square root, is calculated by:

$$S^2(n) = \frac{\sum_{i=1}^{n}[X_i - \bar{X}(n)]^2}{n-1}$$

Finally, the 95% confidence interval can be calculated by:

$$\bar{X}(n) \pm 2.064 * \sqrt{\frac{S^2(n)}{n}}$$

These calculations result in the following table with the average results, standard deviation and a lower and an upper bound for each performance measurement.

	Production Amount	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost	Machine Production %
Actual Results	346.500	5356	-	95%	€ 80.000,00	26%
Tactical Model	347.042	4249	-	100%	€ 80.000,00	26%
Detailed Model (Average)	349.269	4.250	67.097	100%	€ 82.054,48	23%
Detailed Model (St. Dev.)	30.572	44	1.362	0%	€ 3.051,27	2%
Upper bound (95%)	412.369	4.342	69.909	100%	€ 88.352,31	28%
Lower bound (95%)	286.168	4.159	64.286	100%	€ 75.756,65	19%

Table 22: Order Process Simulation Results

The performance measurements for the actual results and the tactical model are determined by taking a proportional 31% of the total results. It is not fair to compare the results on total cleaning time, while this performance measurement does not fit a similar linear proportion as the rest.

The average production amount slightly rises in comparison to the actual and tactical results, but not significantly. The amount of orders is almost similar to the expected amount by the tactical model. The service level increases, which is mainly due to the assumption of the 100% availability of raw materials and the priority of orders over VMI. The stock keeping cost slightly increases, which is probably caused by the stochastic demand. The machine percentage is slightly lower, but not significantly. For the confidence intervals, a statement can be made that in 95% of the times the actual performance measurements value will be within this range.

6.2 VMI Selection Method

For the remaining capacity a selection method is proposed for presentations which have VMI, so only these items are included. If capacity is mentioned in this paragraph it refers to the leftover capacity after reserved capacity for regular and special orders. Before a mathematical linear programming model is proposed, the input variables are selected and valued. For the VMI selection process, different solution areas are explored which are represented by the scenarios.

6.2.1 Variables

Before the mathematical model is explained, the used variables must be set. In this part of the paragraph the determination process of the used variables are briefly discussed.

A_i	Product Family Setup Cost of item i in €
DY_i	Yearly Demand at PFCX for item i in units
v_i	Transfer Price of item i in €
r	Working Average Cost of Capital in %
Q_i	Optimal Production Quantity of item i in units
t	time-step in weeks
L_i	Lead time of item i in weeks
s_i	Safety level of item i in weeks
w	Total weeks in 2013
O_i	Re-order point of item i in units
PQ_{it}	Production Quantity of item i at time t in units
DW_i	Weekly Demand at Partner for VMI item i in units
IP_{it}	Inventory Position of item i at time t in units
P	Probability density function
T_j	Time period between two arriving orders of family j
λ_j	Special and regular order arrival rate per year of family j
C_{it}	Cost efficiency function of item i at time t in €
B_{jt}	Binary variable of family j produced in time t
PT_{it}	Production Time of item i at time t in minutes
M_{it}	Binary machine decision variable
PS_i	Production Speed of item i in products per minute
CT_{jt}	Cleaning Time of family j in minutes

The first five variables are already explained in the tactical model, so the first variable to determine is the re-order point of each item i. This is executed by using the lead-time, safety stock and yearly demand. In this model the lead-time for each VMI item is set to two weeks, while this gives a sufficient amount of preparation time and limits uncertainty. The calculations of the re-order points of each item i are given in the following equation:

$$O_i = \frac{L_i + s_i}{w} * D_i \text{, where w} = 52 \text{ weeks}$$

The production quantity of item i at time t depends on its corresponding re-order point, inventory position and optimal production quantity. With an R,Q order policy, the production quantity varies as shown in the equation below. For an s,Q order policy $PQ_{it} = Q_i$.

$$PQ_{it} = Q_i + O_i - IP_{it}$$

The inventory position of item i at time t depend on the inventory position at time t-1, the production quantity at time t and the demand in time t. This is represented in the following equation, where at time 0 a fixed order position is retrieved from the data.

$$IP_{it} = IP_{i,t-1} + PQ_{i,t-1} - DW_{i,t-1}$$

In the next equation the cumulative distribution function of the inventory position of an item i at time t dropping below its re-order point in the time set between two arriving orders is given. This probability function depends on the amount of arriving orders of each family j and the expected time t before the item drops below its re-order point. This leads to the following two equations.

$$T_j = \frac{IP_{it} - O_i}{DY_i}$$

$$P_{ijt}\left(IP_{it} < O_i \; in \; T_j\right) = 1 - e^{-\lambda_j T_j}$$

With the probability function the cost efficiency of each production decision of item i can be calculated. The cost efficiency function depends on two cost calculations: a potential savings in family setup cost and stock keeping cost. Although the order setup cost is left out of perspective in this model, the model's influence on this will be tested.

The binary variable B_{jt} results out of the final production proposal and is valued one if the family j of item i is in the order production proposal at time t or the inventory position of an item of this family drops below the re-order point, which happens when $P_{ijt}\left(IP_{it} < O_i \; in \; T_j\right) = 1$. In conclusion, the potential amount of cleaning cost that can be saved depends on the binary variable B_{jt}, the probability of the item dropping below its re-order level in the period between two arriving orders of family j and the cleaning cost A_j.

The stock keeping cost depends on the difference between the inventory position and the re-order point at each time t, while this would be in stock for the expected time in between replenishments of item i considering the PQ_{it}. The actual stock keeping cost further depends on the items price and WACC r. Finally, the cost efficiency function is given by the equation below.

$$\begin{aligned} C_{it} = {} & Saved\ Family\ Setup\ Cost - \ Stock\ Keeping\ Cost \\ & = B_{it} * A_i * P_{ijt}\left(IP_{it} < O_i \; in \; T_j\right) - (IP_{it} - O_i) * v_i * \frac{PQ_{it}}{DY_i} * r \end{aligned}$$

Finally the presumed production time and cleaning time are determined. The computation of the production time and cleaning time are quite straight forward. The production time depends on the production quantity and the machine decision parameter and its influence on the production speed. A cleaning time is calculated for the items of which its corresponding families B_{jt} is valued zero, while this implies they are not in the production proposal after the re-order points were checked. The production time and cleaning time are calculated by using the following equations and depend on the machine decision. The machine decision making process is discussed in paragraph 6.1.3 and similar in the proposed VMI selection method.

$$PT_{it} = PQ_{it} * PS_{M,i} \text{ with } M_{it} \text{ as the machine decision parameter}$$

$$CT_{jt} = CT_{M,j} \text{ with } M_{it} \text{ as the machine decision parameter}$$

6.2.2 Linear Programming Model

In this sub-paragraph a mathematical linear programming (LP) model is proposed, which solves a similar problem in series in each week t. Linear programming is a method to propose the best outcome of a mathematical model under requirements that represent linear relationships. The solution space of the objective function is limited by some restrictions. Some more, not earlier mentioned, variables of the LP-model are presented below.

d_i	Production decision variable of item i
MIN d_i	Minimum value of the decision variable d
MAX d_i	Maximum value of the decision variable d
EC	Employee Capacity in minutes
HR_i	Binary variable which is valued 1 if item i is a High Risk item
NHR_i	Binary variable which is valued 1 if item i is a Non-High Risk item
HRC	HR Cleanroom Capacity in minutes
NC	Normal Cleanroom Capacity in minutes

The objective function of the LP-model is to maximize the cost efficiency function declared in the previous paragraph. It provides the threshold between the potential savings in cleaning cost and the stock keeping cost involved. The potential saved cleaning cost can only take-on positive values, while the stock keeping cost can be a positive or negative number. This depends on inventory position in comparison with the re-order point. An inventory position significantly below its re-order point will increase the value of its individual cost efficiency function. This objective function is presented in the following equation.

1) $\sum_{i=1}^{i=n} C_i = \sum_{i=1}^{i=n} d_i \left(B_i * A_i * P_i\left(IP_i < O_i \text{ in } X_j\right) - (IP_i - O_i) * v_i * \frac{PQ_i}{DY_i} * r \right)$ $, 1 \leq n \leq 3438$

Next the solution area is defined by a set of linear equality and linear inequality constraints. In this solution space the linear programming algorithm finds the maximum value, if there is a feasible solution possible. It does this by adjusting the variable values, which is the production decision variable d_{it}.

The first two linear inequality functions propose a restriction on the value of the production decision variable d_i. Whenever an inventory position of item i drops below the re-order level, the minimum value of the decision variable is 1, otherwise 0. The maximum value depends on the yearly demand in 2013, if there is no demand the value is 0, otherwise 1.

2) $d_i \geq MIN\ d_i$ $, 1 \leq n \leq 3438$

3) $d_i \leq MAX\ d_i$ $\quad ,1 \leq n \leq 3438$

The following linear equality restriction implies a 100% employee utilization rate. While the workforce of PFCX is considered inflexible it is argued the available employees should be utilized at all times. So the sum of the production and cleaning times should be equal to the available employee capacity.

4) $\sum_{i=1}^{i=n} PT_i + CT_i = EC$ $\quad ,1 \leq n \leq 3438$

The last two restrictions concern the cleanroom capacity. While cleanroom capacity is different for high risk items and non-high risk items, there are two inequality restrictions proposed. Both imply that the total amount of production and cleaning time may not exceed the capacity.

5) $\sum_{i=1}^{i=n} HR_i * (PT_i + CT_i) < HRC$ $\quad ,1 \leq n \leq 3438$

6) $\sum_{i=1}^{i=n} NHR_i * (PT_i + CT_i) < NC$ $\quad ,1 \leq n \leq 3438$

When employee or cleanroom capacity is not sufficient to obtain the minimal value restriction in equation 2) there is no feasible solution found by the LP-model. In this case, restriction 2) is deleted and the MAX d_i in restriction 3) is replaced by the MIN d_i. Now the LP-model will solve a problem instance were the set of minimal d_i's consists solely of items of which the inventory position is lower as the re-order point.

The LP problem is solved by the Open Solver add-in for Microsoft Excel, which uses a Branch and Cut Algorithm for LP-models. However, while the relation between the value of the decision variable d_i and its contribution to the objective function is linear, an optimal solution based on solely the contribution value should be found.

Because this LP-problem is solved for each week t, the computation time was about one hour per simulated year. Subsequently for twenty reputations the total computation time is twenty hours.

6.2.3 Scenario results

In this paragraph six different scenarios are proposed, which are selected based on two decisions. First, we consider two different types of reorder policies: a fixed time period system and a fixed order quantity system. These different strategies measure the re-order quantity in a different way and this might significantly influence the results of the LP-model.

The fixed time period system, checks the inventory position every time period t and it assumes a target inventory level R. In this policy the order quantity is constantly differing due to different order moments. The production amount in the LP-model are defined conform this policy. With this policy the actual reorder point is variable and depending to the availability of capacity in time period t. The figure below describes such an order policy.

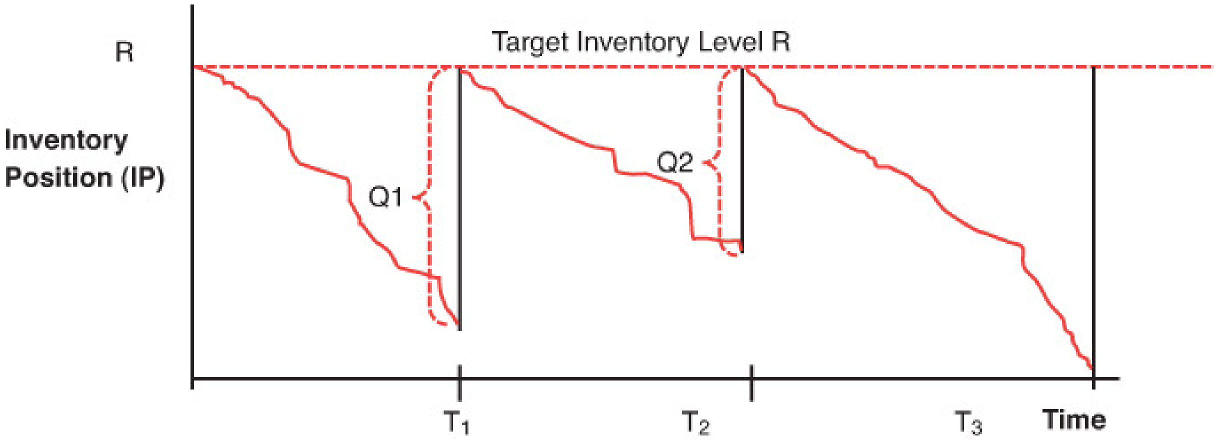


Figure 17: R,Q-policy

In the fixed order quantity system, the inventory system is constantly monitored and as soon as the inventory position drops below the re-order point a fixed quantity Q is produced. In this case the production amount should be fixed and equal to the order quantity Q proposed in the tactical model. Equally to the previously proposed policy, the re-order point is variable due to the variability in capacity.

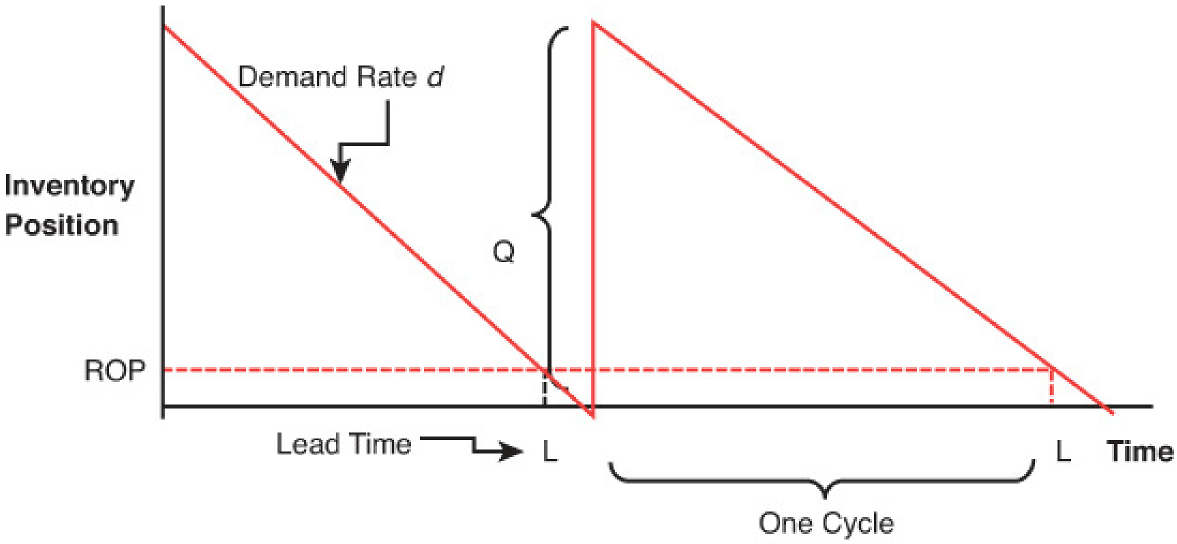


Figure 18: s,Q-policy

For this order policy the following adjustment to the input variables should be made

$$PQ_{it} = Q_i + O_i - IP_{it} \rightarrow PQ_{it} = Q_i$$

The second decision concerning the scenarios is the capacity input of the total detailed model. Three different scenarios are proposed for each reorder policy. The first scenario uses the exact capacity output as measured in 2013. The second scenario adjusts this capacity in proportion to produce a similar production amount as achieved in 2013. The last scenario assumes a variable workforce with a maximum deviation from average of 10%. The last two scenarios have effect on the capacity output of the order solution method, which is used as input to the LP-model proposed in the previous paragraph. In the table below all proposed scenarios are presented.

	100% Utilization rate	Similar Production Amount	Variable workforce (10%)
R,Q-policy	Scenario 1	Scenario 2	Scenario 3
s,Q-policy	Scenario 4	Scenario 5	Scenario 6

Table 23: Simulation scenarios

The average results of the VMI selection part are given in the table below, however in appendix V the extended results for each scenario individually is given (including the standard deviation and the confidence interval of each performance measurement).

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Scenario 1	870.754	8.556	148.140	99%	€ 178.017,58	36%
Scenario 2	766.397	7.214	112.932	97%	€ 177.832,86	36%
Scenario 3	896.961	9.019	155.185	99%	€ 176.732,86	35%
Scenario 4	797.952	3.661	68.556	99%	€ 192.218,84	42%
Scenario 5	772.001	3.588	63.009	98%	€ 184.309,79	42%
Scenario 6	798.362	3.667	66.866	99%	€ 188.789,68	42%

Table 24: Scenario Results

6.3 Scenario selection

If the production amounts of scenarios presented in the previous paragraph are considered, a large difference between the scenarios of different order policies stands out. This is caused by a selection of items with the least effect on stock keeping cost, which are in general less time consuming production orders. While capacity constraints are similar, this leads to an increasing production amount. In the limitations of this research project, the reason for this is explained in more detail. The following graph gives an example of the behaviour of the different order policies considering the production amount.

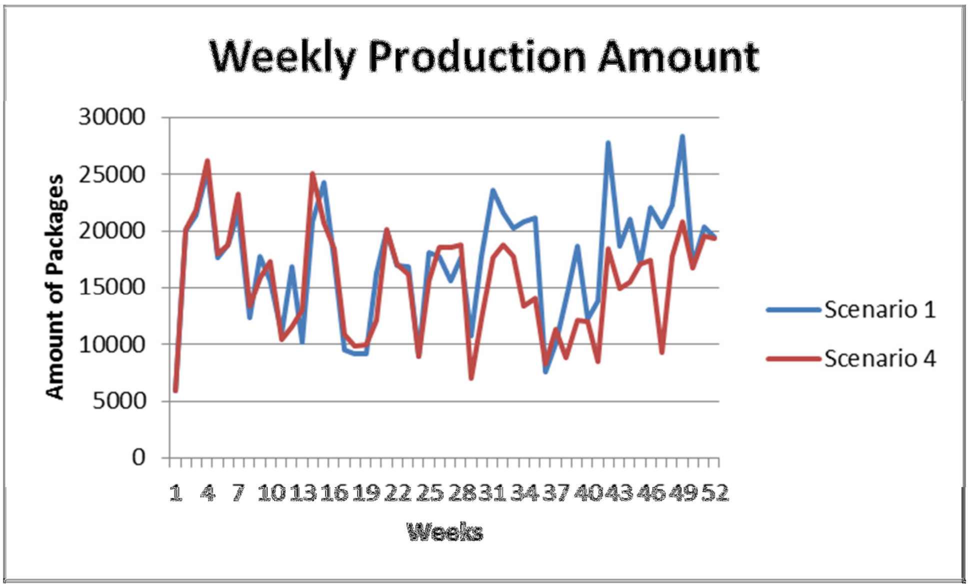


Figure 19: Influence of Order Policy on Production Amount

Another performance measurement which is strongly influenced by the selected order policy is the amount of orders. This is explained by the variable production quantity; in case of overcapacity the model tends to produce a large amount of orders with small production amounts. The graph below shows an example of such behavior for Macrogolum 4000 powder. Here we see that with an R,Q order policy the item is produced nine times to respectively six times with an s,Q order policy. The item is produced more frequently in the first half year, in which the most overcapacity appeared.

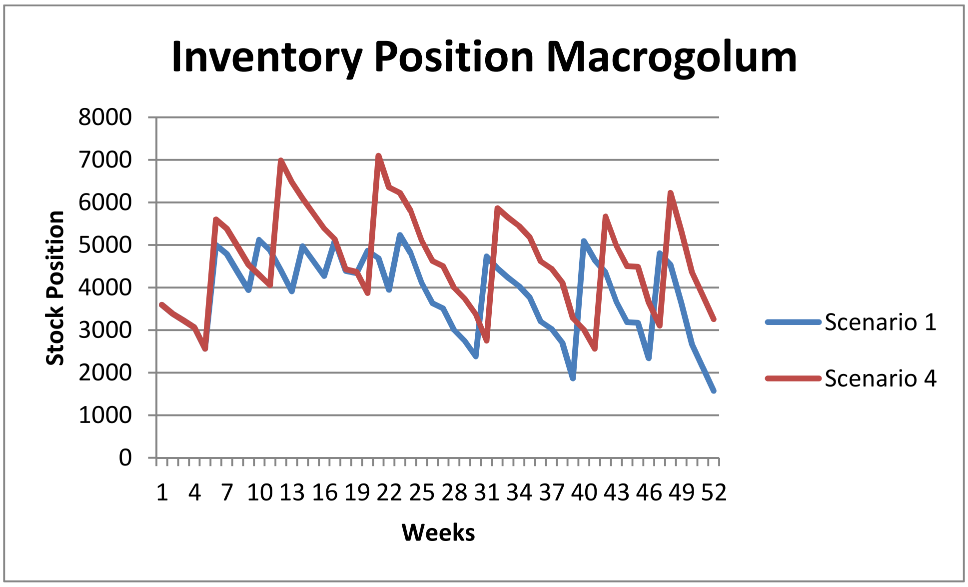


Figure 20: Order policy effect on Inventory Positions

A larger amount of orders should generally result in lower stock keeping cost, as is confirmed by the graph above. In comparison between the order polices a significant lower stock keeping cost is proposed by the R,Q policy. The service level and machine production rate is not really depending on the order policy. The cleaning cost does differ greatly by the order policy, which is directly, but not proportional, related to the amount of orders.

If we compare the different capacity strategies, we focus on the scenarios that differentiate from workforce planning, while the scenario of less utilization is selected to make a good comparison for the total cleaning cost. The scenario results representing a variable workforce are slightly beneficial over the fixed workforce scenario. One thing does stand out, an increase in the amount of orders which is explained by the increasing production amount due to a smaller cleaning time.

In the tactical model the order setup cost was argued to be significantly larger as the family setup cost. This implies a scenario with a minimum amount of orders, which is represented by the s,Q order policy. Scenario four represents a comparable situation to the actual and tactical results. If scenario four and six are compared, scenario six shows slightly more beneficial results: higher production amount, lower total cleaning time and lower stock keeping costs. However it has a slightly higher amount of orders and a similar service level and machine production rate. While scenario six also proposes a more realistic situation, it was selected as the best scenario.

6.4 Total Results

To make conclusions on the influence of stochastic demand and capacity constraints the total detailed model results are compared to the results of the tactical model. In appendix IV the detailed total results are given including the standard deviation and confidence intervals. The performance measurements of the selected scenario are given in the table below.

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	**1.148.757**	**7.920**	**134.236**	**99%**	**€ 271.122,12**	**36%**
Standard Deviation	10.143	70	5.161	0%	€ 5.451,23	1%
Upper bound (95%)	1.169.693	8.065	144.889	99%	€ 282.373,47	38%
Lower bound (95%)	1.127.821	7.775	123.583	99%	€ 259.870,77	35%

Table 25: Results Scenario 6

The first thing to notice is the slightly increasing production amount, this is declared by the increase of the machine production rate. The increasing order amount is caused by the capacity constraints, while in periods of overcapacity VMI items are selected for production before they reach their re-order points. For a similar reason the total cleaning time and stock keeping cost are slightly higher. Another reason for the increasing stock keeping cost is the larger production amount. The stochastic demands results in slightly lower service levels, in example the total weekly demand for VMI items in week 51 was 400% of the average weekly demand. While the machine production rate depends on the production quantities, which are fixed with an s,Q-policy, it shows a similar value for the tactical and detailed model.

6.5 Tool Development

To represent the two stage solution method in one tool is considered difficult to manage. For this reason two tools are proposed, one which computes order lines in a final planning taking the combination and machine decision into account and the second to select VMI items for production.

At the moment of writing this thesis, the development of these tools is still in progress. However it is already certain to be an Excel compatible tool for daily use at the planning department of PFCX. While the tool will be a translation of the simulation tool used in this research proposal, this is assumed to be not very time consuming.

The global supply chain manager of Company X proposed a work-in period of the tool of about six months. This would give the planning department a sufficient amount of time to spot errors and flaws in the Excel tool. In the near future there will be an actual planning tool introduced, which is most likely to be Solventior.

7. Conclusion and Recommendations

7.1 Conclusion

The conclusion will answer the different level of research questions given in chapter 2. By answering these questions a final conclusion on the outcome of this research project can be provided. This is followed by some limitations and recommendations.

7.1.1 Research Question

To answer the main research question of this master thesis, which is cited below, a bottom-up approach was chosen. By starting with the answers to the investigative questions, directly followed by the research question a final management decision can be made.

Research Question

"To what extend can we reduce the total supply chain cost, by using a data-driven tactical and detailed model, and how can we transform this into an easy-to-use, compatible tool(s)?"

First we consider the investigative questions. At the start of the research project a thorough analysis was executed considering the internal planning process at PFCX as well as the companywide planning process. In conclusion, the decisions made on a tactical and a detailed level where not data driven. Secondly, capacity shortage was considered really hard to spot which led to a downhill effect while orders are not combined and sometimes even split.

Considering the data availability, we can conclude the date warehouse of Company X is quite complete. There was almost no missing data; however because of the difficulties encountered in linking the data the value determination was very time-consuming. This leads us to conclude that all data is available which implies that a more data-driven decision process is possible.

In the tactical model a solution method was proposed to combine multiple orders into one job with the objective of proposing a semi-fixed production cycle. Limitations of this model were the assumption of evenly spread deterministic demand and no capacity constraints. The model proposed solution values that had a positive effect on the supply chain wide cost and even decreasing utilization rate was expected. The best supply chain wide solution proposed a large cost savings at PFCX and an increasing stock at the sales partners. To ensure a smooth implementation, a scenario was selected which proposed a significant lower supply chain wide cost and no rise in stock keeping cost. This scenario proposed a theoretical cost reduction of about €190.000,-, of which in reality 75% should be realized. It can be concluded that the most cost efficient solution is not always the best practical solution.

In the tactical model the effects of the mixed production process on the algorithmic approach were tested. Out of the results of the tactical model, presented in the table of paragraph 5.4, we can conclude this has a negative influence of which the proportion depends on the SKC restriction. The negative influence on the chosen scenario is approximately 17,5%.

On a detailed level, it was tested if the proposed outcome of the tactical model holds under the influence of stochastic demand and capacity constraints. To decrease the variability of the detailed model, real data was preferred when available. While the demand for specials can be considered uninfluenced by the tactical model the actual demand data for these orders were used. The regular orders were influenced by the tactical model, so this demand was simulated using the rules set in the tactical model. For the VMI selection part of the detailed model, the actual weekly demand at the sales partners was used. The two stage model proposed a solution to a MOJ scheduling problem for the first stage and a Linear Programming problem for the second stage.

Out of the results of scenario two and four in Appendix VI, we can conclude a €47.500 increase in the supply chain wide cost for the s,Q-policy and a €364.000 increase for an R,Q-policy. Based on the origin of these cost, we can conclude the s,Q-policy is preferred if the relative order setup cost over stock keeping cost are high. The R,Q-policy is preferred in a contradicting environment.

The influence of stochastic demand and capacity constraints on the expected results of the tactical model is considered negative for both order policies, respectively 25% and 200%. The last conclusion considers the variable workforce, which is made possible by capacity insights, that has a positive effect on the results for both order policies. However, these conclusions are case specific and not generalizable.

Now we can answer the research question. On a tactical level a semi-fixed production cycle was proposed which implied a cost decrease of €190.000,-, by the influence of stochastic demand and capacity constraints in the detailed model this dropped to €142.500,-. While the model was entirely data driven a tool for the tactical model is developed and implemented on a global basis. On the detailed level, two tools were developed for the MOJ and the VMI selection.

On a scientific level, the main conclusions were based on a case study conducted at PFCX. This conclusion concerned the influence of a mixed production process on the tactical level and the influence of stochastic demand, capacity constraints, order policy and workforce variability on a detailed level.

7.1.2 Management Decision

By concluding the positive influence of the proposed models for the entire supply chain, the management question can be answered and the final decision can be made. By implementing the developed tactical order quantity tool, the data driven model was introduced into the company. This results in a more automated, data-driven order rules.

For the detailed model, the management decided on an implementation at PFCX in the form of an Excel Tool. If this is proven to be beneficial and an improvement to the current situation then a planning tool will be purchased.

7.2 Limitations and Recommendations

An important limitation of the research model is the effect of forecast uncertainty. The model assumed actual demand, while the forecasted demand is about 20% reliable. With this level of reliability, the influence on the results of the model is strong. However, while 71% of demand is VMI, for which the proposed lead-time is two weeks, a large percentage of actual demand is already known. By reducing the lead-time the level of uncertainty is minimized. For the leftover uncertainty, mainly special orders and newly combined orders, a part of capacity should be reserved. Note that better forecasts would directly lead to decreasing stock and a more efficient production process. It is definitely recommended to put some research in this subject.

In the computation of regular orders following the new set of rules suggested in the tactical model a compound Poisson arriving process was assumed with uniformly distributed order quantities. This assumption was not proven by the available order data, but was the most closely related solution. By using real data in the future, the reliability of the model can be further improved.

A third limitation concerns the linear programming model, which is a static model. A static model limits the variability of input to the model, in this case the order production proposal. If one of the presentations of a similar family is neither in the order production proposal nor under its re-order level, but the model still proposes a positive production decision, the model will seem it not more beneficial to produce other items of this same family. This situation appears if there is overcapacity with a large amount of orders. If a dynamic model would be introduced, this could be handled into some extend. However, this is a difficult problem instance and computation times will increase significantly. Overall, the influence of this limitation is not really significant for an s,Q order policy, but it is for the R,Q policy due to its larger amount of orders. While PFCX chose an s,Q order policy the use of the current model is recommended.

Another limitation of the linear programming model is that the decision variable d_i is considered variable between 0 and 1, while it is actually binary. This results in partly produced orders, which will have a slight negative effect on the results. While this only appears for one order every week, the influence is expected to be insignificant. In reality, this partly positive production decision could be hand made by the employees of the planning department.

While most of the conclusions are based on the case study represented in this master thesis, it is hard to generalize this to a whole market or a wider range of companies. The conclusion could be generalized to companies with a similar production process and influence of stochastic demand and capacity constraints.

Further on, some minor limitations are mentioned. In production cleaning time and production time are split, but there is no setup time for an order or machine defined. A more detailed production time, would gain the company new insights concerning the effectiveness of machine utilization. Another limitation is the assumption of always available raw materials, which could have a minor influence on the service level.

While we use a data-driven model now, expected production times for each order can be determined. This makes it possible to deliver a more precise planning proposal to the operation level and foresee capacity shortages. On an operational level it provides the production manager with a performance indicator for the production employees. These are all beneficial side effects and recommended to implement. The exact implementation plan or influence of this is something that could be further investigated.

Another recommendation is to investigate the influence of the proposed model on the procurement process of PFCX. This is another area that could be highly beneficial, definitely after the full implementation of VMI.

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Appendix I: Cost Specifications

To determine some of the order specific and bulk specific cost at PFCX a percentage of each department's budget is allocated to these costs. This is preferred over timing each step of the process, while the overall slack is better encountered for and other non-time dependent cost are taken into account. This cost calculation process is executed by following the steps below:

1. Sum the departments which have order specific and/or bulk specific cost.
2. Determine the drivers of these departments.
3. Retrieve the % of the budget we can subscribe to order and/or bulk specific cost.
4. Calculate the total order and bulk specific cost made at PFCX

The results of these steps are given in the table below:

Department	**Budget 2013**	**Drivers**	**% of budget**	**Order Specific**	**Bulk Specific**	**Budget Order**	**Budget Bulk**	**Setup Cost/Order/Driver**	**Setup Cost/Bulk/Driver**
Warehouse	376749	In Coming Goods	29,0%	0%		0,0%	0,0%	0	0
		Order Picking	71,0%	80%	20%	56,8%	14,2%	20,91209147	5,228022867
Expedition	256256	Expedition	100,0%	50%		50,0%	0,0%	12,52105932	0
Labelling	254519	Label Analyses	46,0%	25%		11,5%	0,0%	2,860322975	0
		Archive Prod. Orders	4,0%	100%		4,0%	0,0%	0,994894948	0
		Label control	50,0%	0%		0,0%	0,0%	0	0
Sales	170906	Create Sales Orders	20,0%	100%		20,0%	0,0%	3,340291215	0
		Rest	80,0%	0%		0,0%	0,0%	0	0
Planning	180617	Planning	75,0%	100%		75,0%	0,0%	13,23783348	0
		Rest	25,0%	0%		0,0%	0,0%	0	0
QI (incl qa/qc)	208177	Label Control	37,5%	100%		37,5%	0,0%	7,628884491	0
		After Control	37,5%	60%		22,5%	0,0%	4,577330695	0
		Monsters (ICG)	25,0%	0%		0,0%	0,0%	0	0
QA	208177	Clear Orders	13,5%	100%		13,5%	0,0%	2,746398417	0

		Rest	86,5%	0%		0,0%	0,0%	0	0
QC	40000	Identification Test	90,0%	100%		90,0%	0,0%	3,518029903	0
	40000	Rest	10,0%	0%		0,0%	0,0%	0	0

Table 26: Setup Cost Calculations

Appendix II: Product Example

Below is an example of a product family and the underlying items with their parametric values and model values.

Bulk	Presentation	D (Production quantity 2013)	a (Setup Cost Presentation)	v (Price per unit)	Prod. Cost (Direct)	A (Direct Clean Cost bulk)	A (Bulk Warehouse Picking Cost)	m	Q*	Adjusted Q*	# lots / year	Adjusted # Lots (shelf life)	Rounded # Lots / year
Acetazolamidum	509957	1158	76,33	4,04	0,56	9,09	5,23	1	749,44	597	1,55	1,55	2
Acetazolamidum	504783	494	76,33	9,15	0,85	9,09	5,23	1	319,71	247	1,55	1,55	2
Acetazolamidum	504782	482	76,33	4,03	0,66	9,09	5,23	1	311,94	241	1,55	1,55	2
Acetazolamidum	506098	129	76,33	4,04	0,70	9,09	5,23	3	250,46	129	0,52	0,52	1
Acetazolamidum	514037	25	76,33	6,86	1,05	9,09	5,23	5	80,90	25	0,31	0,31	1
Acetazolamidum	513952	0	76,33	3,86	-	9,09	5,23	0	-	0	-	-	0
Acetazolamidum	514179	0	76,33	3,52	0,76	9,09	5,23	0	-	0	-	-	0
Acetazolamidum	514199	0	76,33	70,30	3,47	9,09	5,23	0	-	0	-	-	0

Table 27: Result Example

Appendix III: Special order distribution

We expect a Poisson distribution in the arrivals of special orders. Visually this expectation is reassured as shown in the figure below.

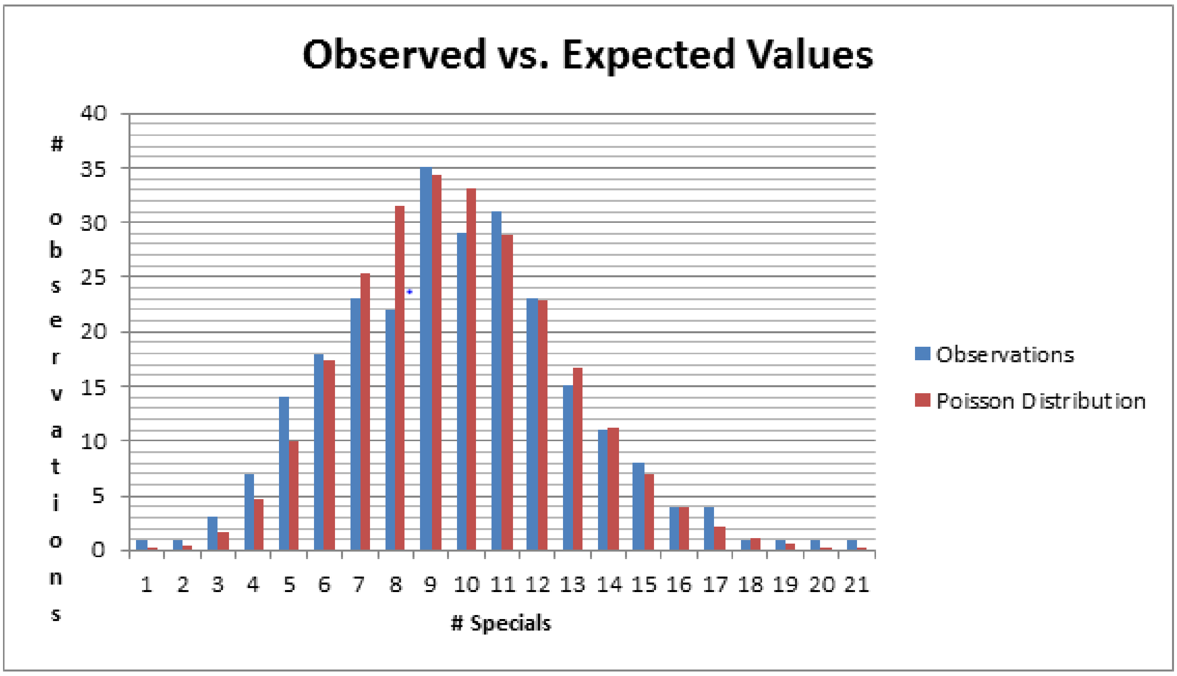

Figure 21: Visual Poisson-test

To test if our arrival times of Specials can be actually considered Poisson distribution we do the following goodness of fit test. In the table below we see the amount of specials per day in column 1, observations in column 2, the expected value under a Poisson Distribution and the X^2 test value in column 4.

Specials/Day	Observations	Poisson Distribution	(O-E)^2/E
0	1	0,04	22,04
1	1	0,36	1,12
2	3	1,58	1,27
3	7	4,59	1,26
4	14	10,00	1,60
5	18	17,42	0,02
6	23	25,29	0,21
7	22	31,48	2,85
8	35	34,28	0,02
9	29	33,18	0,53
10	31	28,90	0,15
11	23	22,89	0,00
12	15	16,62	0,16
13	11	11,13	0,00
14	8	6,93	0,17
15	4	4,02	0,00
16	4	2,19	1,49

17	1	1,12	0,01
18	1	0,54	0,38
19	1	0,25	2,26
21	1	0,05	20,26

Table 28: X^2-test

Out of column 4 we can conclude that the most outer rows can be considered outliers. Under this assumption we have 17 degrees of freedom (21(intervals)-2(outliers)-1(unidentified parameter)-1), which leads to the p-value of 0,701. While 0,701 > 0,05 we can conclude that the observed data follows a Poisson distribution.

Appendix IV: Machine Production Parameters

While there is a trade-off between the production speed and the cleaning time, several minima are given from which an order is machine produced. In the tables below the parameters for the machine decision are given.

Nr.	Name	Range min	Range max	BUM	0,1	0,25	1	5	10	Combination
BU 030	King Junior	0,06	25	L	250	200	100	30	25	125
BU 040	King Senior	0,06	25	L	250	200	100	30	25	125
BU 045	KBW pomp	0,06	25	L	250	200	100	30	25	125
BU 050	Watson 624DI	0,003	5	L	150	100	50	20		100
BU 052	Watson 624DI	0,003	5	L	150	100	50	20		100

Table 29: Liquid Machine Parameters

BU 070	Microfill	0,0001	0,015	kg	200
BU 320	Hethon	0,005	0,025	kg	200
BU 321	Hethon DK800	0,05	0,5	kg	250
BU 322	Hethon 80	1	10	kg	400

Table 30: Solid Machine Parameters

With these parameters 9 production categories are defined, where each category has his own capacity constraints. Further on the total capacity of category 2-4 is 5 and of category 5-7 is 2, the other individual capacity restrictions are given in the table below.

Category	Machine	Min	Max	Capacity
1	MANUALL	0	50	# of Empl.
2	B 050/052	0,0003	0,06	2
3	BU 030/040/045/050/052	0,06	5	5
4	BU 030/040/045	5	25	3
5	BU 070	0,0001	0,005	1
6	BU 070/320	0,005	0,015	2
7	BU 320	0,015	0,025	1
8	BU 321	0,05	0,5	1
9	BU 322	1	10	1

Table 31: Machine Capacity Constraints

Appendix V: VMI selection Scenario Results

In the following six tables the VMI selection results of the different scenarios are given, including the average values, standard deviations and confidence interval of each performance measurement.

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Simulation Average	870.754	8.556	148.140	99%	€ 178.017,58	36%
Standard Deviation	38.170	700	15.609	0%	€ 5.523,50	1%
Upper bound (95%)	949.536	10.001	180.358	100%	€ 189.418,07	38%
Lower bound (95%)	791.972	7.111	115.922	98%	€ 166.617,08	33%

Table 32: Results Scenario 1

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Simulation Average	766.397	7.214	112.932	97%	€ 177.832,86	36%
Standard Deviation	22.657	263	5.686	0%	€ 4.843,57	1%
Upper bound (95%)	813.161	7.756	124.668	98%	€ 187.830,00	38%
Lower bound (95%)	719.633	6.672	101.197	96%	€ 167.835,73	34%

Table 33: Results Scenario 2

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Simulation Average	896.961	9.019	155.185	99%	€ 176.732,86	35%

Standard Deviation	26.266	423	11.983	0%	€ 5.723,83	1%
Upper bound (95%)	951.173	9.891	179.918	100%	€ 188.546,85	36%
Lower bound (95%)	842.749	8.146	130.452	98%	€ 164.918,87	33%

Table 34: Results Scenario 3

	Amount Produced	**Amount of Orders**	**Total Cleaning time (min)**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Simulation Average	797.952	3.661	68.556	99%	€ 192.218,84	42%
Standard Deviation	22.674	70	5.353	0%	€ 7.268,64	0%
Upper bound (95%)	844.752	3.806	79.605	99%	€ 207.221,32	43%
Lower bound (95%)	751.153	3.515	57.507	98%	€ 177.216,36	42%

Table 35: Results Scenario 4

	Amount Produced	**Amount of Orders**	**Total Cleaning time (min)**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Simulation Average	772.001	3.588	63.009	98%	€ 184.309,79	42%
Standard Deviation	20.748	56	3.804	0%	€ 6.202,54	1%
Upper bound (95%)	814.825	3.705	70.860	99%	€ 197.111,84	43%
Lower bound (95%)	729.176	3.472	55.158	97%	€ 171.507,74	41%

Table 36: Results Scenario 5

	Amount Produced	**Amount of Orders**	**Total Cleaning**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**

			time (min)			
Results 2013	771.500	7.060	-	95%	€ 180.000,00	26%
Tactical Model	771.500	3.197	-	100%	€ 180.000,00	26%
Simulation Average	798.362	3.667	66.866	99%	€ 188.789,68	42%
Standard Deviation	23.179	70	5.753	0%	€ 7.131,91	0%
Upper bound (95%)	846.203	3.812	78.741	99%	€ 203.509,95	43%
Lower bound (95%)	750.520	3.522	54.991	98%	€ 174.069,41	42%

Table 37: Results Scenario 6

Appendix VI: Total Scenario Results

In the following six tables the total results of the different scenarios are given, including the average values, standard deviations and confidence interval of each performance measurement.

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	1.220.023	12.806	215.238	99%	€ 260.072,05	32%
Standard Deviation	19.839	702	15.289	0%	€ 4.518,91	1%
Upper bound (95%)	1.260.970	14.256	246.794	100%	€ 269.399,08	34%
Lower bound (95%)	1.179.075	11.357	183.681	99%	€ 250.745,02	30%

Table 38: Results Scenario 1

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	1.115.666	11.464	180.030	98%	€ 259.887,34	32%
Standard Deviation	12.909	263	5.260	0%	€ 3.834,41	1%
Upper bound (95%)	1.142.310	12.007	190.887	99%	€ 267.801,56	34%
Lower bound (95%)	1.089.022	10.921	169.173	97%	€ 251.973,12	30%

Table 39: Results Scenario 2

	Amount Produced	Amount of Orders	Total Cleaning time (min)	Service level	Stock Keeping Cost (r=10%)	Machine Production %
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	1.246.229	13.269	222.282	99%	€ 258.787,34	31%
Standard Deviation	19.081	431	12.039	0%	€ 5.112,49	1%
Upper bound (95%)	1.285.613	14.159	247.131	100%	€ 269.339,51	33%

Lower bound (95%)	1.206.846	12.379	197.434	99%	€ 248.235,17	30%

Table 40: Results Scenario 3

	Amount Produced	**Amount of Orders**	**Total Cleaning time (min)**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	1.147.221	7.911	135.654	99%	€ 274.273,32	36%
Standard Deviation	10.457	71	4.904	0%	€ 5.941,61	1%
Upper bound (95%)	1.168.805	8.057	145.775	99%	€ 286.536,80	38%
Lower bound (95%)	1.125.638	7.765	125.532	99%	€ 262.009,83	35%

Table 41: Results Scenario 4

	Amount Produced	**Amount of Orders**	**Total Cleaning time (min)**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	1.121.269	7.839	130.106	99%	€ 266.364,27	36%
Standard Deviation	12.475	53	3.118	0%	€ 4.422,57	1%
Upper bound (95%)	1.147.019	7.948	136.542	99%	€ 275.492,45	38%
Lower bound (95%)	1.095.520	7.729	123.670	98%	€ 257.236,09	35%

Table 42: Results Scenario 5

	Amount Produced	**Amount of Orders**	**Total Cleaning time (min)**	**Service level**	**Stock Keeping Cost (r=10%)**	**Machine Production %**
Results 2013	1.118.176	10.233	146.398	95%	€ 257.796,80	26%
Tactical Model	1.118.176	7.446	115.041	100%	€ 257.873,08	36%
Simulation Average	1.148.757	7.920	134.236	99%	€ 271.122,12	36%
Standard Deviation	10.143	70	5.161	0%	€ 5.451,23	1%
Upper bound (95%)	1.169.693	8.065	144.889	99%	€ 282.373,47	38%

Lower bound (95%)	1.127.821	7.775	123.583	99%	€ 259.870,77	35%

Table 43: Results Scenario 6