MASTER

Prediction and reduction of MRP nervousness by parameterization from a cost perspective

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Prediction and reduction of MRP nervousness by parameterization from a cost perspective

Master Thesis

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Preface

This master thesis concludes my graduation research project for the Eindhoven University of Technology conducted at Prodrive Technologies B.V located in Son. Moreover, it marks the end of my dual degree master program Operations Management and Logistic & Business Information Systems. Hereby, I would like to take the opportunity to show my gratitude to a number of people who have supported, helped and inspired me during the project.

First of all, I would like to thank my two university supervisors Remco Dijkman and Decebal Mocanu. Remco, thank you a lot for your effort, your precision and your understanding. I am especially grateful for your constructive feedback upon structuring my research. Decebal, I would like to thank you a lot for your help upon the approach in the first stages of my research. Your experience and knowledge gave me a head start. I want to thank both of you for your fruitful contribution to the final result.

Next, I want to show my enormous gratitude to my company supervisor at Prodrive Technologies, Jeroen Kolp. Jeroen, I want to thank you for the guidance you gave, the pleasant collaboration and the interesting discussions we had from the beginning to the very end. Your critical thinking and your eye for structure have had a significant influence on what resulted in this master thesis.

Moreover, I want to thank my family and friends for their support and affection. A special word for the guys from Duçibus and Pleintje, who have made my student life unforgettable and filled with lots of great memories. Finally, a big hug goes to my dear girlfriend, Isabelle, who has always supported me during the long hours of coding and writing at our dining table.

Bram Linders
8 February 2019

Abstract

A stable production plan is essential in order to create efficiency throughout the supply chain and uphold the service levels in a complex production environment that involves comprehensive bills-of-materials, long supplier lead-times and continuous exhaustion of the available capacity. In a manufacturing environment that makes use of a Material Requirement Plan (MRP) that is driven to fulfill the Master Production Schedule (MPS), the instability of the top-level products in the bill-of-material (BOM) will echo throughout the whole supply chain, resulting in inefficiencies in the planning and procurement department at Prodrive Technologies and issues on delivery reliability. In this Master Thesis, an extensive overview of the concept MRP nervousness is given and the possibility the buffer or dampen this Nervousness with the MRP parameters. After the elaboration of this concept, several metrics are proposed to measure the top-level planning instability at Prodrive Technologies. Next, the characteristics of the instability are introduced as the MRP nervousness and the elements leading to planning instability are identified. The influence of the different MRP parameters upon the MRP nervousness are researched under supply and demand uncertainties and a supervised machine learning regression is trained to predict the MRP nervousness in different stages of the planning horizon with these influences. It is found that the dampening or strengthening effect of the MRP parameters upon the MRP nervousness highly depend upon the origin and size of net requirement changes. It is therefore essential to identify these uncertainties in the MRP parameterization whilst including penalty costs for unstable production plans in minimizing total expenses.

Executive summary

Problem Context

This master thesis describes the research upon the Material Requirement Planning (MRP) nervousness on the final products manufactured at Prodrive Technologies (PT). Operating in a high-tech, high-complex manufacturing environment requires the creation of MRP plans with extremely long horizons. The complexity of internal manufacturing processes, the scarcity and the high level of customization of critical components can result in total lead-times from a couple of months to over a year. The complexity of the MRP planning in combination with the characteristics of the described supply risks under a high level of MRP nervousness can be the cause of an increasing level in the inefficiency in the internal supply chain at PT and moreover into a growing level of missing components, capacity issues and a decrease of the service level.

The two most significant factors of the MRP nervousness are the uncertainties from the direct demand of PT's customers and the supply uncertainties. On the former, a misfit between the forecasted demand and the actual sales orders may exist, as well as a misfit between consecutive forecasts. Although restrictions upon allowed requirement changes exist, the enforcement of these restrictions are lacking or theses restrictions are not covering the complete horizon in which these changes still can result in a lot of pain into to planning instability. The external supply uncertainty can directly result from the delivery performance of the suppliers, but it can also be the result of the MRP nervousness resulting in changes within the supplier's lead time. This influence is known as the circular consequence between demand and supply uncertainty.

Where the top-level nervousness ripples down through all the levels of bill-of-material (BOM), this top-level nervousness is a major cause for nervousness through the complete supply chain. With MRP parameters having a direct influence on the creation of MRP plans, the possibility of dampening or even strengthening the nervousness, and these parameters being in control by PT, research upon their influence on the MRP nervousness on different parts of the planning horizon is essential in the first steps to reduce the MRP nervousness at PT.

MRP Nervousness

The instability of replenishment orders in the production is defined as the MRP nervousness. The nervousness is measured as the difference between two consecutive MRP plans, where at every timing point on the planning horizon the replenishment quantity is compared. For the absolute measurement the absolute sum of these changes is taken and for the relative measurements the relative sum. Adding weight to the timing point on the horizon can be used to add criticality to changes closer to the schedule creation date.

MRP parameter influences

Finding the influences of the MRP parameters on the MRP plan in the planning environment at PT is essential in the opportunity to use these parameters into reducing the MRP nervousness. Both detailed research and the use of a supervised neural network regression model are used upon finding the influence of the parameters upon the MRP nervousness. Both types of research conclude that its impact not only depends on the reason for the change and its direction, but that the horizon in which the uncertainty occurs is vital as well. Moreover, the mutual dependence of MRP parameters upon the replenishment date and quantity or the reschedule action that is initiated, is found to be of a high influence as well. The most important conclusions upon the parameter influences are the dampening effect of the Lot Size upon the relative nervousness with criticality in the free horizon and the dampening effect of the Safety Stock that can be used to fulfilled requirements in the frozen horizon. Upon the Safety Lead Time, a nervousness strengthening effect is found in the free schedule horizon, where on the frozen horizon a dampening result is found.

Cost model

The influence of the MRP parameters on the dampening or strengthening effect of the MRP nervousness upon different parts of the horizon comes with a cost. The three pillars included in the cost model to create a complete cost overview are the holding cost, the setup cost and a penalty cost introduced for different MRP nervousness factors. Where for the positive relative nervousness a bigger penalty cost is included than for the negative relative MRP nervousness.

Parameter proposals

The parameter proposals upon the total cost minimization show the balancing between the different costing pillars, where the set-up cost reduction is the retainer of the decrease in the period of supply under a highly uncertain demand pattern. The increase of the Safety Stock level for dampening the nervousness upon the net requirement changes into the frozen horizon is only proposed when this addition in holding stock leads to a more significant reduction in MRP nervousness cost. Upon the Safety Lead Time, the influence cannot be validated upon the MRP nervousness, as this effect is majorly caused by a manual action of how the planner deals with frozen production orders that receive a reschedule message and therefore impossible to validate in a simulation.

Conclusions and recommendations

The MRP nervousness reduction by MRP parameters on the final products is the first step that can be taken in dampening and buffering the uncertainties of the MRP environment at PT. Upon acceptable costs, the size of the periods of supply should be minimized for high uncertain demand changes which cannot be dampened with the size of the lot. Moreover, the Safety Stock is effective in preventing the replenishment orders that are not fixed to be rescheduled in the horizon by the result of requirement increases in the frozen horizon. These findings upon the research question in combination with other finding resulted in the following recommendations:

Performance indicators of MRP nervousness

To increase awareness upon the state of the MRP nervousness, performance indicators can be created upon the different MRP nervousness measurements. By periodically reviewing the parameters or actively alarming after overwriting certain levels of nervousness, the awareness can be increased on actions that resulted in this nervousness and therefore indirectly results in the stability of the planning system.

Small periods of supply in Lot Sizing

The second recommendation is related to the Period of Supply of the Lot Size of top-level products. With the finding that the quantity changes into the MPS of the customers have a significant influence on the MRP nervousness and this change is amplified through the start date of the lot, small lots are recommended for the products that encounter high demand uncertainty.

Small levels of Safety Stock

The third recommendation is related to the level of Safety Stock level that is used in fulfilling requirements. To buffer against MRP-nervousness upon net requirement changes by supply issues or close to due date demand changes, a small level of Safety Stock can be introduced to prevent the necessity of rescheduling fixed production orders and automatic rescheduling in planned orders.

Fixed levels of freezing periods

The freezing period is the period in which all the replenishment orders are fixed upon quantity and due date. Freezing the orders prevents the automatic rescheduling of these order upon net requirement changes. The length of the freezing period is essential in decreasing high critical MRP nervousness. Introducing and maintaining Customer Sales restrictions

Demand Flexibility restrictions

Given the finding that MPS changes are the direct requirements on the top-level products at PT, and these changes being one of the major causes of the MRP nervousness. Restrictions on the flexibility of these changes should be defined and uphold.

Abbreviations

ANN	Artificial Neural Network
ARP	Automatic Rescheduling Procedure
BOM	Bill-of-Material
CDBP	Cost-Based Dampening Procedure
CL	Capacity Leveling
CLIP	Confirmed Line Item Performance
CONR	Cost of not Rescheduling
COR	Cost of Rescheduling
D	Demand
Dl	Deletion measurement
DU	Delivery Uncertainty
EOQ	Economic Order Quantity
ESU	External Supply Uncertainty
FR	Freezing Period
ISU1	Internal Supply Uncertainty 1
ISU2	Internal Supply Uncertainty 2
KPI	Key Performance Indicator
LFL	Lot for Lot
LR	Linear Regression
LS	Lot Size
LTC	Least Total Cost
MAE	Mean Absolute Error
MCR	Material Capacity Requirements
MLP	Multi-Layer Perceptron
MLPR	Multi-Layer Perceptron Regressor
MPS	Master Production Schedule
MRP	Material Requirement Plan
MVTC	Credit Movement
MVTD	Debit Movement
NMCR	Net Material Capacity Requirements
PLFL	Periodic Lot-for-Lot
PLT	Product Lead Time
POS	Periods of Supply
PPB	Part Period Balancing

PT	Prodrive Technologies B.V.
RFR	Random Forest Regressor
RN	Relative Nervousness
RNC	Relative Nervousness with Criticality
RNN	Relative Negative Nervousness
RNNC	Relative Negative Nervousness with Criticality
RPN	Relative Positive Nervousness
RPNC	Relative Positive Nervousness with Criticality
RV	Rounding Value
SDP	Static Dampening Procedure
SLT	Safety Lead Time
SM	Silver Meal
SS	Safety Stock
SVM	Support Vector Machine
SVR	Support Vector Regressor
WW	Wagner Within

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Chapter 1

Research assignment

In this first chapter, the research assignment, an overview is created on the problem context resulting in the problem statement. For this problem statement, a research goal is defined that aims to solve the formulated problem. The novelty that the research brings is elucidated into the last part of the introduction. In the second part of the research assignment, the main research question and the sub-questions are defined, for which answering should result into achieving the defined goal. In the last part of this chapter, the research methodology is elaborated. The research methodology gives a systematical overview on how the research problem is solved.

1.1 Introduction

The instability of a production schedule makes it impossible to efficiently align all the business processes through the supply chain of manufacturing companies and leads to reduced productivity (Li and Disney 2017), the bullwhip problem (Wang and Disney 2016) and issues on delivery service, capacity plans and excessive inventory (Lee, Padmanabhan, and Whang 1997) . With a Material Requirements Planning (MRP) driven planning method in a highly complex product environment, consisting of extensive bill-of-materials (BOM) and component commonalities, changes in production schedules can echo throughout the whole chain. Moreover, these changes can have a significant influence on the productiveness, efficiency and performance of the complete supply chain. The perceived planning problems on all levels of the supply chain at Prodrive Technologies while performing in an uncertain environment leads to the following problem statement.

Problem statement: *Prodrive Technologies experiences difficulties in stabilizing the production schedules among all of its production levels originating from both internal and external supply and demand uncertainties.*

MRP parameterization is the most researched topic to buffer or dampen the nervousness of the production schedule (Koh 2002). As described by Kadipasaoglu and Sridharan (1995) and Vollmann et al. (1997), Safety Stock (SS) is most effective in buffering against the quantity uncertainty, while Safety Lead Time (SLT) protects against the timing uncertainty. Furthermore, Lot Sizing has a vital role in the nervousness of the system, where a Lot Size (LS) rule can reduce or strengthen this effect (Collier, 1982). For nervousness reduction in a MRP environment, a cumulative effect appears between Lot Sizing Rules and Safety Stock on all the different production echelons. A lot of studies have been related to the parameterization of the MRP parameters. Where nervousness and reduction algorithms are in place for the individual parameter optimization (Ho and Ireland 1998, Kazan et al. ,200) and for inventory control rules (Kok, de, A. G., & Inderfurth, K. (1997). For a set of parameters these optimizations methods are not computationally possible to determine due to the mathematical complexity resulting from their mutual, non-linear dependencies (Almeder et al., 2009). To deal with the problem of mathematical complexity in MRP parameterization, simulation-based optimizations are applied in many research studies (Köchel and Nieländer, 2005) (Molinder, 1997), (Ehrenberg and Zimmermann, 2012), (Arakawa et al. ,2003). The aim of these simulation-based optimizations is the reduction of overall costs. The costs included during these simulations are related to Inventory holding cost, back-order cost and set-up cost. These cost parameters optimize the inventory versus the service level. However, in multi-level, manufacturing systems, the schedule changes are an essential factor as they may impose change-over costs on a short horizon, affecting total performance. The inclusion of a planning instability cost factor is therefore firstly included into Lot Sizing formulations by Carlson (1989). However, these simulation models can deal with the mathematical complexity of optimization models, this method is very time consuming and requires complex simulation modeling, which should be able to copy the whole MRP logic as implemented in a business perspective.

Next to mathematical optimization and simulation models, in the world of demand forecasting and production scheduling, developments of computer technology and artificial intelligence have led to new approaches to deal with MRP parametrization and inventory management problems. These approaches typically precede the MRP planning. Gaafar and Choueki (1999) created a neural network model related to the MRP problem of Lot Sizing, based upon carrying cost and ordering cost. In this research, the focus is on the inclusion of the expected demand pattern from multiple sources to predict the most efficient Lot Sizing Rules. Zhong and Zang (2015) used artificial intelligence for inventory management and Safety Stock forecasting. However, on schedule-instability in an MRP-planning environment and optimization of multiple parameters these research topics are short due to their complexity.

The complexity of joint optimization parameterization of the MRP, the highly time-consuming characteristic of the simulation models and the development of predicting models, gives the opportunity to combine them as a solution direction for the stated problem, resulting in the following research goal.

Research goal: *The creation of a method to propose multiple planning parameters from a wide range of possibilities focused on minimization of the holding, set-up and MRP nervousness costs in a computationally feasible manner with the use of historical data.*

Novelty: The novelty this research brings is the application of measuring the nervousness on real historical data, tailored to a practical MRP environment. Measuring the MRP nervousness on a practical planning environment requires an adjustment of the formulas described in the literature. Moreover, it will create new knowledge and insights of the MRP nervousness problem at Prodrive Technologies, on its causes and possibilities to dampen or reduce the Nervousness by MRP parameterization. As far as the author is aware there is no earlier work carried out on predicting the MRP nervousness on the complete planning horizon with the goal to find the influences of MRP parameters on the nervousness. Next, the adjustment of the costing function with the inclusion of penalty costs for different MRP nervousness measurements requires an extension of the costing formulas on parameterization as found in the literature and give the possibility to adjust the equations based on the importance of the nervousness captured with different methods.

1.2 Research Questions

The research goal formulated in introduction should aid to remedy the stated problem. The main research goal is translated into a research question, for which answering should result in achieving this goal.

Research question: *"How can MRP parameters be determined to reduce the nervousness of the Material Requirement Planning under uncertainties and minimal costs?"*

Multiple sub-questions are defined which combined can give a complete answer to the main research question.

Sub-question 1

The first sub-question is concerned with finding a Metric to measure the MRP nervousness at Prodrive Technologies.

How can the MRP nervousness be measured at Prodrive Technologies?

Sub-question 2

The second sub-question is concerned with the relevant variables and uncertainties related to the MRP nervousness and finding the expected influence of the parameters on the relation between the uncertainties and the MRP nervousness from literature and practical point of view. The question to this sub-goal is formulated as:

What is the expected influence of variables on the relationship between net requirement changes and the MRP nervousness?

Sub-question 3

The third sub-question is concerned with a data-focused understanding of the MRP at PT by showing relevant descriptive statistics based on the MRP nervousness, MRP parameters and uncertainties. Resulting in the following sub-question:

What are the parameter settings, net requirement changes and MRP nervousness at Prodrive Technologies?

Sub-question 4

The fourth sub-question is concerned with the creation of a model to predict the MRP nervousness, formulated as:

Which variables and predictive model combination can be used to predict the MRP nervousness?

Sub-question 5

The fifth sub-question is concerned with using the created model to propose MRP parameters under cost considerations.

Which MRP parameter settings minimize overall costs of the MRP system?

Sub-question 6

In the evaluation phase, the effectiveness and the quality of the model are reviewed with a simulation study, which can simulate the behaviour of an MRP system based on prescriptive MRP parameters with a rolling MPS schedule.

What are the simulated cost minimizations from the proposed MRP parameters?

1.3 Research Methodology

To answer the research question in a structured way the research is designed upon the CRISP-DM (Chapman et al., 2000) reference model, which is the Cross-industry standard methodology for data mining research. This reference model contains six phases; *Business Understanding, Data Understanding, Data Preparation, Modelling, Evaluation and Deploymen*t. The defined sub-question can all be linked to one step of this methodology and therefore this research methodology seems a perfect fit.

As stated in the CRISP-DM methodology, the first step of the research is related to the understanding of the business. Understanding the business and the process central in this thesis require an explanation of the MRP algorithm and the MRP nervousness, which is the central term in this research study. General theory on the MRP and the MRP algorithm as used in practical at PT is provided in chapter two, which gives the Background of this research project. At Prodrive Technologies (PT) the MRP nervousness is suspected to be a major influencer of the productivity level, the delivery performance, capacity problems and excessive inventory. Therefore, in the third chapter, a quantitative way to measure this phenomenon is formulated. Before applying this metric to capture the MRP nervousness, extensive research is executed into the way of working at the planning department, the Master Production Schedule (MPS) as the requirements at the top level of the bill-of-material (BOM), the MRP logic and settings applied at PT. Next to the modifications to capture the nervousness correctly, modifications to the formula related to 'what' to measure are made upon the importance of the possible ways to capture the nervousness whereas a distinction is made between capturing the quantitative schedule changes relatively or absolutely and moreover the inclusion of a criticality factor to prioritize over the planning horizon of the schedule change as proposed by Shridharan (1990). To study the influencers of the MRP nervousness both a literature review as well as a field study is performed. In 4.1 the variables suspected to be relevant to the MRP nervousness are divided into the MRP parameters, uncertainties and products specific characteristics. These MRP parameters can be applied in buffering and dampening the MRP nervousness. The causes leading to the MRP nervousness are essential in the study to reduce it. Therefore in chapter 4.2, the possible uncertainties leading to the nervousness are explained and formulas are defined to measure these uncertainties quantitatively.

To obtain more business understanding of the MRP logic and its variables and to find the relations between the uncertainties and the parameters on the MRP nervousness, a detailed study is executed in chapter 4.3. During this study, MRP plans of 50 different products will be daily reviewed and changes within these plans will be linked to the occurrence of the different uncertainties and parameters as described in chapter 4.1 and 4.2

In Chapter 5 the state of the MRP environment at PT is shown with descriptive statistics on the nervousness at PT, the planning parameter settings and the uncertainties. In more detail, the statistics on the demand uncertainty are shown as being the major influencer of the MRP nervousness. Next, to descriptive statistics, a linear regression analysis is performed upon the moderating influence of the MRP parameters on the relation between the MPS uncertainty and the MRP nervousness, to find the possible influence of these parameters.

Predicting the MRP nervousness requires the creation of a prediction model, which is the central goal in Chapter 6. The creation of a model contains the selection between the different prediction techniques and the selection of the technique suited the best in predicting the outcome with the available data. Next to the selection of the model, a feature selection is performed to only include the variables that are relevant in predicting the outcome. The model selection and feature selection are performed with a wrapper and an embedded method, in which the model in combination with the features leading to the most accurate prediction is selected. To find the parameter influences in the model, the parameter input is changed and its result on the outcome is reviewed.

To use the model in the MRP nervousness in a business setting, the costs of the parameter setting should be included as well. Therefore, in Chapter 7, a costing model will be created to include a cost of nervousness as well as the introduction of the costs for the parameters where will be prescribed upon. Next to this costing model, which uses a brute force technique upon all the MRP parameters and the predicted nervousness upon historical data, a step-wise approach upon MRP parameterization is created as well. This step-wise approach can be used for products without the required historical data as well. Both methods should result in minimizing the overall costs, which is a combination of the holding, set-up and the Nervousness cost.

The evaluation of the models is essential in validating its results. The effectiveness of the prescribed parameters is tested with the use of a simulation study in Chapter 8. This simulation includes the MRP logic on a rolling horizon as practically is applied at PT.

The feedback between the evaluation and the business understanding phase includes overviewing the complete goal of the research methodology, answering the main question. Moreover, the limitations are discussed upon the created model.

The step between the evaluation and the deployment includes the recommendations upon the found results, an implementation plan and the possibilities upon future research.

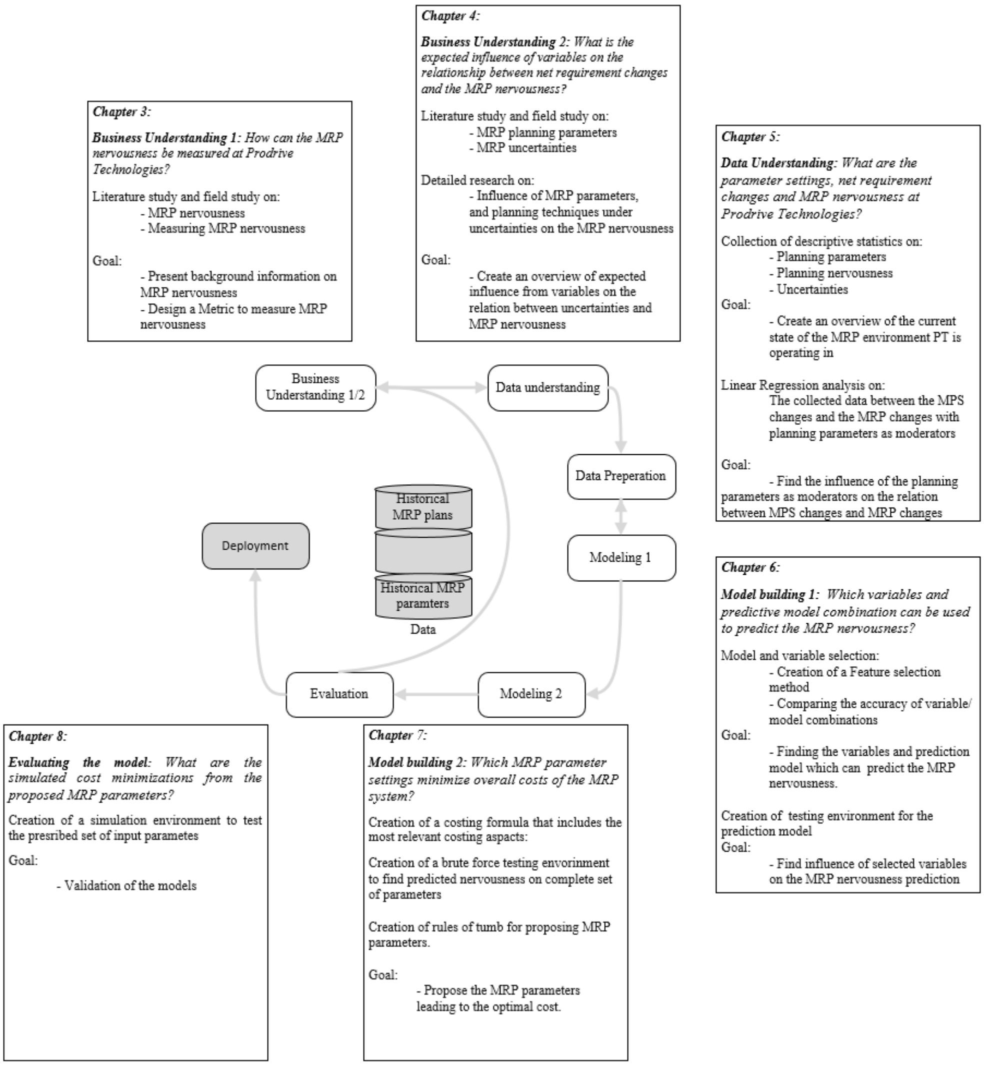

Figure 1: Visual presentation of the research methodology

Chapter 2

Background

This chapter starts with an extensive description of the working of the Material Requirement Planning (MRP) system in general and as applied at Prodrive Technologies B.V. (PT).

Material Requirement Planning (MRP) is the standard in business information systems used by manufacturing firms. MRP aims to ensure the fulfillment of the demand by releasing a set of production/supplying orders for each item of the Bill-Of-Materials (BOM) that allows synchronizing the internal and external logistics flows (Orlicki, 1975). The logic of the MRP is based on what, how much, and when it is needed? (Hopp & Spearman, 2000). The first and second aspect is related to the quantity of sales-demand of the final product and its underlying BOM and the third aspect to the demand date of the final product as well as the requirement dates of all of its components. An MRP run is executed to get a detailed plan that gives answers to three questions above. Before executing this run, the calculation input data is required. This data consists of Master Production Schedule (MPS), the BOM and the up-to-date inventory records. These three aspects are based on two dimensions, which are the material identification and quantity. The MPS is a schedule that includes the product demand from the sales orders and forecasted demand on the final product. This demand is called the independent demand, as it is the demand that comes from outside orders. Every product has a structure, the BOM, which includes the list of components needed to manufacture the end product. This list can contain raw materials as well as sub-assemblies. The dependent demand is defined as the component demand, necessary for the completion of the final product. For the calculation of the "how much" and "when", the inventory records are needed as input. Net Material Capacity Requirements (NMCR), are calculated by the subtraction of the inventory from the calculated MCR. If the inventory level gets below a predefined level at the time of an MRP run, a new procurement or production order is released (D'Avino, Simone, Schiraldi, 2014). In the high-tech industry, the composition of the BOM can be extremely complex. This complexity results in production- and supplier- lead times that are often longer than sales lead times. The dissimilarity in lead times possibly causes that at the time a product needs to be ordered or produced, the sales data is not available yet and therefore is based on a forecast. This forecast and even the sales order can change over time in quantity or date and therefore during the next MRP run, the production orders which include these material requirements can change as well. In short, product's final due date and due dates for each component can be calculated if production variables such as lead time, production time, and order time are known. The independent demand will result in dependent demand by the system calculations based on planning parameters and available stock.

Figure 36: MRP way of working at PT in appendix A.1 shows the working of the MRP system at Prodrive Technologies. The requirements at a higher level result in replenishment orders for that level. For the End-item level (FERT), the MPS, including the Sales orders and Sales forecast, shows the customer demand requirements and is seen as the direct requirements of the end items. To fulfill these requirements a replenishment order is created. This replenishment order is a planned order and can be rescheduled during every MRP run. This planned order is converted into production order to freeze its quantity and due date. There are no rules at PT that prescribe the timing of this conversion. From the moment of conversion, automatic rescheduling during the MRP run will not take place anymore, but reschedule messages give the instructions if the order should be manually rescheduled in or out. The replenishment orders on the highest level lead to requirements for sub-assemblies or purchase parts. The requirements from production orders and planned orders on sub-assembly level (HALB) are shown as either order reservations from production orders, or dependent requirements from planned orders. The requirement on sub-assembly level is converted into planned orders and production order including other sub-assemblies or components (ROH). For the components, requirements from planned order and production orders are shown as dependent requirements and order reservations respectively. For these requirements, purchase requests are calculated and afterwards converted into purchase orders. This also relates to sub-assemblies that are procured externally. Next to requirements that are calculated through the BOM by sales order demand, other requirements include transfer offers, transfer requisitions and material reservations. These appear from ea. requirements from other plants within Prodrive Technologies and Projects. Production orders, on FERT and HALB level, are released before production can start. A release is possible when the required components to fulfill the order are available and can be allocated to this production order. This production order is confirmed as started after the first production step, at this moment the requirement on its lower leveled components (HALB or ROH) is fulfilled. The production order is Partially Delivered at the moment

some parts in the batch are finished and on stock already, and completed after completing the production order. This completion means that the production order is finished, with the possibility of having a certain scrap quantity. After this completion the production order is removed, the inventory of the certain product is increased and demand can be delivered to.

Figure 37 in Appendix A.2 gives an overview of the calculation of a simple MRP algorithm. Where input parameters (the total lead time and BOM structure), MRP parameters (the Lot Size Rule, based on a periodic Lot Size) and sales orders will lead to a production plan. This figure shows that the production order of the end product (ID1), triggers dependent requirements for the lower-level products (ID2 and ID3), based on their Lot Size Rules and lead times, the start and due dates and the consolidation of requirements will result in their own production orders. In Appendix A.3 the mathematical formulation of the MRP calculation based on MRP parameters is given.

Chapter 3

Measuring the MRP nervousness

The nervousness of the MRP system can be described as the instability in replenishment orders on either quantity or due date between two sequential schedules. Mather (1997) defines the nervousness as "changing the required due date or quantity on a related replenishment order for either a purchased or manufactured material". In this chapter, research is done upon how these metrics can be modified to be used at PT.

How can the MRP nervousness be measured at Prodrive Technologies?

3.1 Basic MRP nervousness measurements

Sridharan and Berry (1988) proposed the SBU metric to measure system nervousness, which calculates the average of changes in order quantity per time unit over subsequent planning cycles. The proposed nervousness is measured as the absolute changes and described in the first formula below. Where the absolute measurement gives insight on all the changes that take please between two productions schedules per time unit, measuring the nervousness relatively only gives the total difference in quantity between two schedules over all the time units.

$$I_{abs} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N-1} \left|Q_t^k - Q_t^{k-1}\right|\right)}{S-1} \qquad 3.1\text{-}1$$

$$I_{rel} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N-1} (Q_t^k - Q_t^{k-1})\right)}{S-1} \qquad 3.1\text{-}2$$

where

t = *Time period*

Q_t^k = *Scheduled order quantity for period t during planning cycle k*

M_k = *The start of the planning cycle k*

N = *Planning horizon length*

S =*Number of subsequent planning cycles*

3.2 Adding Criticality

In general schedule changes close to the due date have a more significant impact than changes far away in the planning horizon. To deal with this priority difference, Shridharan et al. (1990) extended the instability formula with a weight parameter based on the criticality of the change. These extensions are added to the formula defined by 3.1-1 and 3.1-2.

$$I_{abs_a} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N-1} \left| Q_t^k - Q_t^{k-1} \right| (1-\alpha)\alpha^{t-M_k}\right)}{S-1} \quad 3.2\text{-}1$$

$$I_{rel_a} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N-1} (Q_t^k - Q_t^{k-1})(1-\alpha)\alpha^{t-M_k}\right)}{S-1} \quad 3.2\text{-}2$$

With:

α = a weight parameter to represent the criticality of changes in schedule ($0 \leq a \leq 1$).

The weight parameter gives a decreasing weight to the periods further in the planning horizon. A small value, close to zero, gives a rapid decrease in the value of α and a bigger value of α gives slowly declining weights. The total sum of quantity changes including the weight factor is divided by the number of subsequent planning cycles, to get an average change per planning cycle.

3.3 Multi-echelon

For the calculation of instability through the layers of the bill of material, multi echelons, a weight can be assigned to its level in the BOM by introducing a new weight parameter: β. Kadipasaoglu, & Sridharan, (1997) introduced this parameter in the instability factor as follows:

$$I_i = \sum_{\forall k>1} \sum_{j=0}^{m} \left[\sum_{i=1}^{n_j} \sum_{t=M_k}^{M_{k-1}+N-1} \left| Q_{ijt}^k - Q_{ijt}^{k-1} \right| (1-\alpha)\alpha^{t-M_k} \right] (1-\beta)^{\beta^j} \quad 3.3\text{-}1$$

Where

j = item level, j = 0 … m (based on low level coding)

i = item i at level j, i = 1… n_j

Q_{ijt}^k *= scheduled order quantity (open and/or planned) for item i at level j, in period t during planning cycle k,*

β *= the weight parameter for levels,* $0 < \beta < 1$

The difference between the multi-level instability formula and the first two formulas is that for the former one, there is no deviation by the number planning schedules. Therefore a bias may be created in the cases where the planning cycle length divided by the horizon is big.

3.4 Criticality adjustment

Adding criticality to the calculations of the nervousness is a valuable addition for making the nervousness a useful measurement method at Prodrive Technologies. A slightly different approach than adding the alfa factor is to predefine time buckets, in which the criticality will drop for every bucket further away from the planning start date. The edges of the time buckets are defined based on procedures in the planning process at Prodrive Technologies. These moments with the corresponding time buckets are described in Table 1, including a criticality factor. The choice for this linear approach is based upon the distribution of the component lead-time which tend be linear as well as can be found in Figure 38 in Appendix A.4.

$$IQ_i = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N-1} \left|Q_{i,t}^{k} - Q_{i,t}^{k-1}\right| * F_{i,t}\right)}{S_i} \qquad 3.4\text{-}1$$

The calculation of $F_{i,t}$ is based upon the criticality factor and the time buckets as described in Table 1. These calculations are as follows:

$$F_{i,t} = \begin{cases} 1 & if\ t \leq\ 14 \\ 1 - \left(\left\lceil \frac{t - M_k}{7} \right\rceil\right) * 0.1 & if\ 14 < t \leq\ 77 \\ 0.05 & otherwise \end{cases} \qquad 3.4\text{-}2$$

Where:

$F_{i,t}$ = *Criticality factor*

M_k = *Horizon start date*

t = *Time period in the planning horizon*

Table 1: Criticality for time buckets in the planning horizon

Planning action	Time bucket in days	Criticality factor
Start production order	[0-14]	1
The release of production orders	(14-21]	0.9
Conversion of planned or to production order	(21-28]	0.8
	(28-35]	0.7
Further in the horizon:	(35-42]	0.6
	(42-49]	0.5
	(49-56]	0.4
	(45-63]	0.3
	(63-70]	0.2
	(70- 77]	0.1
	(77-End horizon]	0.05

3.5 MRP nervousness Adjustments

The metrics proposed in 3.1 - 3.4 does not take into account the practical scenario in which production orders can be partly finished between two subsequent planning runs. Therefore, an MRP nervousness measurement is proposed that can deal with this issue. The solution to this is subtracting the number of products that are finished between the creations of the subsequent planning runs from the nervousness formula. This addition leads to the following nervousness formulas:

$$I_{ABS} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_{k-1}}^{M_{k-1}+N} \left|Q_t^k - Q_t^{k-1}\right| - \boldsymbol{FQ_t}\right)}{S-1} \quad 3.5\text{-}1$$

$$I_{ABS_a} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N} \left|Q_t^k - Q_t^{k-1} - \boldsymbol{FQ_t}\right| * a\right)}{S-1} \quad 3.5\text{-}2$$

$$I_{REL} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_{k-1}}^{M_{k-1}+N} Q_t^k - Q_t^{k-1} - \boldsymbol{FQ_t}\right)}{S-1} \quad 3.5\text{-}3$$

$$I_{REL_a} = \frac{\left(\sum_{\forall k>1} \sum_{t=M_k}^{M_{k-1}+N} (Q_t^k - Q_t^{k-1} - \boldsymbol{FQ_t}) * a\right)}{S-1} \quad 3.5\text{-}4$$

FQ_t^k $=$ *Finished production orders with due date t in schedule period k*

3.6 Horizon length

The proposed MRP nervousness measurements do include a planning horizon (N) for which orders with a due date within this horizon are included into the calculations. As this planning horizon is not fixed at PT, a fixed length is chosen, which makes it possible to compare to MRP plans on the relevant horizon. This length represents the lead time (supply + production) for the most important and most prominent group of finished products at PT and therefore is set to 150 days. In finding the influences on the difference between two planning schedules, it is important that both schedules include the same horizon. With a fixed horizon length, the horizon length may differ as a result from using a rolling forecast by the customers of PT, by missing forecasts or by wrongly updated forecasts. The principle of the rolling forecast is given in the figure below. The rolling principle means that the forecast horizon with a fixed length, so if the replanning interval is X the forecast horizon is extended with X as well.

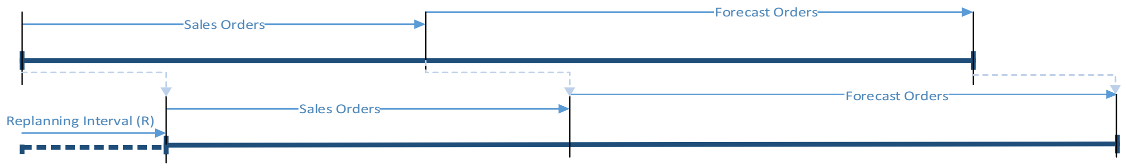

Figure 2: Rolling Horizon Principle

If this forecast horizon is bigger than the planning horizon over which the nervousness is calculated, a set of rules needs to be applied, such that replenishment orders only include the demand within this horizon. This means that for replenishment orders at the end of the horizon, the demand out of the horizon should be subtracted from this order. Figure 3 is used in the explanation on how this demand is subtracted while dealing with Safety Lead Times (SLT) and Lot Sizing Rules. The orange arrows in Figure 3 show the replenishment orders and the blue arrows show requirement orders. In this example, a horizon length of 150 days, a Lot Size of three weeks is used and a Safety Lead Time of 2 days, which means that replenishment has an order finish date of two days before the first demand order they should fulfill. As the fixed planning horizon end is before the rolling forecast end, only the demand before the end of the fixed planning horizon should be included.

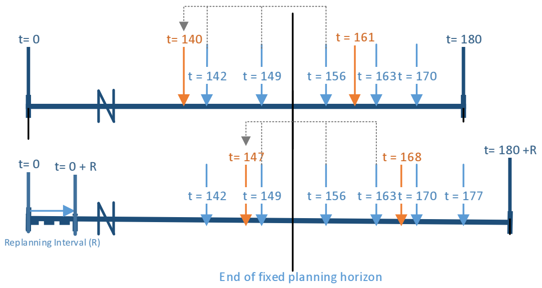

Figure 3: MRP behavior around the end of planning horizon 1

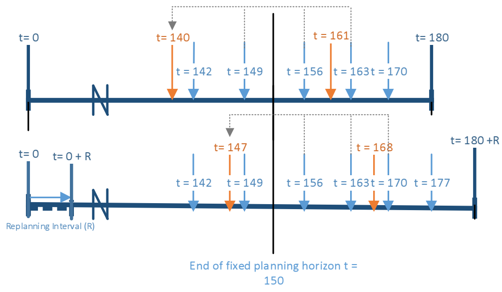

Figure 4: MRP behavior around the end of planning horizon 2

In example 1, Figure 3, t =149 is the last demand order that is within the defined horizon of 150 days. For the first planning schedule, the requirement order on t = 156 should be subtracted from the total replenishment order quantity of t =140. For the replenishment in the second schedule t = 156 and t = 163 should be subtracted. Figure 3 gives an example which deals with an SLT of seven (working) days, while seven days always include one weekend, this automatically results in at least nine days of SLT. Figure 4 shows how the same production orders replenish the demand orders as in the previous example. For the first schedule, this means that demand order 142 is not included in the replenishment order of t =140 and that the demand on t = 163 is included. For the second schedule, a similar shift has taken place, and therefore requirement orders should be subtracted from the replenishment orders fulfilling demand over the fixed planning horizon.

The addition of this horizon correction to the MRP formulation results in the formula which subtracts the demand beyond the horizon fulfilled by the last replenishment order in this schedule and subtracts the Safety Lead Time from the planning horizon, as within this period the replenishment orders only fulfill demand from beyond the planning horizon.

With these two adjustments the absolute nervousness formula looks as follows:

$$I_{ABS} = \frac{\left(\sum_{\forall k>1} abs(IQ_{fp}^{k}) + abs(\ IQ_{ep}^{k}) - FQ_t\right)}{S-1} \qquad 3.6\text{-}1$$

$$IQ_{fp}^{k} = \sum_{t=M_{k-1}}^{M_{k-1}+N-LS-SLT-1} (Q_t^k - Q_t^{k-1}) \qquad 3.6\text{-}2$$

$$IQ_{ep}^{k} = \sum_{t=M_{k-1}+N-SLT-LS}^{M_{k-1}+N-SLT} (Q_t^k - Q_t^{k-1}) - \sum_{t=Mk-1+N}^{t_{end}^{k}+LS+SLT} D_t^k + \sum_{t=Mk-1+N}^{t_{end}^{k-1}+LS+SLT} D_t^{k-1})) \quad 3.6\text{-}3$$

Where

$$t_{end}^{k} = \max(t \quad \forall\, Q_t^k \ with\, t < \ M_{k-1} + N \ ) \quad 3.6\text{-}4$$

$$t_{end}^{k-1} = \max\left(t \quad \forall\, Q_t^{k-1} \ with\, t < \ M_{k-1} + N \ \right) \quad 3.6\text{-}5$$

For the relative nervousness the formula is similar:

$$I_{REL} = \frac{\left(\sum_{\forall k>1} IQ_{fp}^{k} \ + IQ_{ep}^{k} - FQ_t\right)}{S-1} \quad 3.6\text{-}6$$

$IQ_{ep}^{k} =$ *MRP nervousness on the end of the planning horizon at k*

$IQ_{ep}^{k-1} =$ *MRP nervousness on the end of the planning horizon at k-1*

$t_{end}^{k} =$ *t of last replenishment order in k*

$t_{end}^{k-1} =$ *t of last replenishment order in k -1*

$D_t^{k-1} =$ *Demand quantity on t at k-1*

$D_t^{k} =$ *Demand quantity on t at k*

3.7 Planning Horizon Split

In the nervousness measurement formulas presented earlier in the chapter, the instability is calculated over the whole planning horizon. Kabak and Ornek (2009) propose a metric that calculates the instability separately for firmed orders and open orders. Figure 5 shows two planning cycles with the replanning interval (R) between them. These two cycles show the frozen interval (F), the forecast window (W) and the automatic planning horizon (N). As

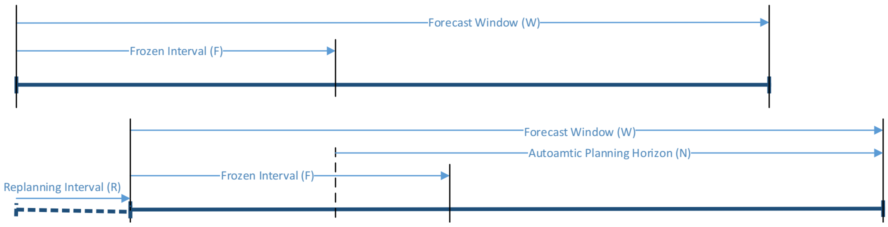

Figure 5: Rolling forecast principle

can be seen in this figures is that only in the automatic planning horizon, the MRP system will recalculate the replenishment orders, while in the frozen interval only reschedule messages on a date are given, while net requirement can be met within this period. These two intervals, including fixed reschedule orders and planned reschedule orders contain respectively only manually scheduling and automatic rescheduling. While automatic rescheduling is only based on the MRP calculations parameters, the manually rescheduling is done by planners due to uncertainties and reschedule messages as a result from the MRP run. Calculating the nervousness separately for the frozen interval and the automatic planning interval includes a decoupling point in the production schedule. This decoupling point is at the point where the first 'not-fixed' replenishment order can be found after the last "frozen" replenishment order. If this decoupling point is not equal for two production schedules, there are two decoupling points (DP1 and DP2) including a transition period between these two decoupling points. At the decoupling points, the same rules should be applied as described in 3.7, based on the inclusion or exclusion of demand orders within and without certain horizons. Figure 7- Figure 8 shows three scenarios of how this decoupling point can be implemented. In Figure 7 a simple scenario is given with similar decoupling points, in Figure 6 a scenario is shown in which one of the planned replenishment orders is 'frozen'. Moreover, in Figure 8 a more challenging scenario is given, which is a 1:1 copy of a true scenario at PT. The red arrows indicate the 'frozen replenishment orders whereas the orange arrows indicate the planned replenishment orders. In the first two examples, there is no overlap for the demand of replenishment orders beyond the decoupling point, although in the third example this overlap exists. For the first and second example, the end of the ‘frozen’ period and the start of the ‘free’ period is indicated with the Decoupling point. However in the first planned replenishment order, DP1 and DP2 are similar, in the second example, DP1 and DP2 are different. To make this situation easier, if the planning schedule with DP1 has a replenishment order on DP2 as well. The decoupling point will be at DP2.

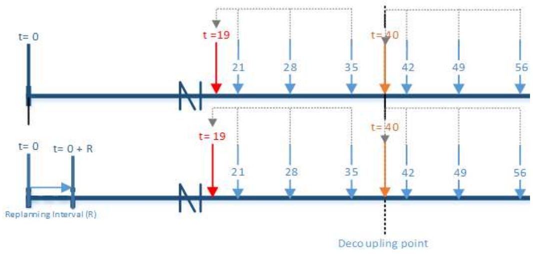

Figure 7: Decoupling point in planning horizon example 1

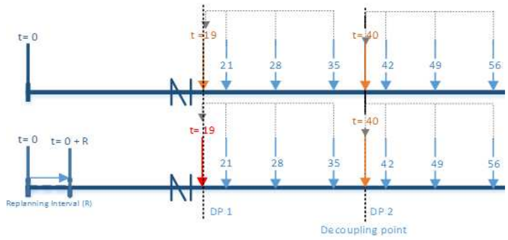

Figure 6: Decoupling point in planning horizon example 2

Regarding the third example; for the comparison within the frozen period, the end horizon is at DP1. For the demand within the transition period at the production schedule that did not deliver the DP1, the rules as presented in the previous chapter are included. For the comparison out of the frozen period, demand that is in the transition period at the production schedule that delivers the DP1 is subtracted from the production order at DP1. This subtraction makes it possible to only find nervousness within the same horizon, on both its start and end date.

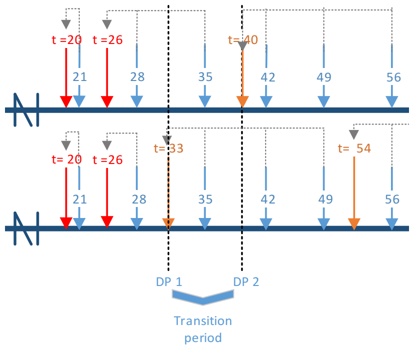

Figure 8 Decoupling point and transition period in planning horizon 3

The practical issue that quantity increases and decreases are not automatically calculated into the ‘frozen’ replenishment leads to the result that at the first planned replenishment order, this difference in quantity is added or subtracted. Therefore to compare the two automatic rescheduled planning schedules this result should be neutralized for the first planned replenishment order. This can be done by comparing the available quantity before the first replenishment order and adding this to the replenishment order quantity defined as SQ_{k-1} and SQ_k.

For the frozen period, the MRP calculations are equal to formula 3.6-1 and 3.6-6, with DP1 being the end horizon. While SLT also occurs in this case, this time is added to the DP1.

For the automatic reschedule period, formula 3.6-1 and 3.6-6 are expanded with a dynamic starting point, and for the reschedule order at DP1, the replenished quantity between DP1 and DP2 is subtracted. These adjustments are shown in formula 3.7-1 and 3.7-2.

$$\boldsymbol{I_{ABS}} = \frac{\left(\sum_{\forall k>1} (\boldsymbol{abs}(\boldsymbol{IQ_{tp}^{k}}) + \boldsymbol{abs}(\boldsymbol{IQ_{fp}^{k}}) + \boldsymbol{abs}(\boldsymbol{IQ_{ep}^{k}}) - \boldsymbol{FQ_t} + (\boldsymbol{SQ^{k}} - \boldsymbol{SQ^{k-1}}\right)}{\boldsymbol{S-1}} \quad 3.7\text{-}1$$

$$I_{REL} = \frac{\left(\sum_{\forall k>1} (IQ_{tp}^{k} + IQ_{fp}^{k} + IQ_{ep}^{k} - FQ_t + (SQ_k - SQ_{k-1})\right)}{S-1} \quad 3.7\text{-}2$$

$$IQ_{tp}^{k} = (\, Q_{t_{pl1}}^{k} - \sum_{t=DP1+SLT}^{DP2+SLT} \left(D_t^k * X_{dp}^{k}\right)) \; - \; (\, Q_{t_{pl2}}^{k-1} - \sum_{t=DP1+SLT}^{DP2+SLT} (D_t^{k-1} * X_{dp}^{k-1})) \quad 3.7\text{-}3$$

$$DP1 = \min(pl1, pl2) \quad 3.7\text{-}4$$

$$X_{dp}^{k} = 1 \text{ if PL2 == DP1 else } 0 \quad 3.7\text{-}5$$

$$X_{dp}^{k-1} \; 1 \text{ if PL1 == DP1 else } 0 \quad 3.7\text{-}6$$

$$DP2 = \max(pl1, pl2) \quad 3.7\text{-}7$$

$$t_{pl1} = \min\left(t \; \forall \; Q_{planned,t} \in k-1\right) \quad 3.7\text{-}8$$

$$t_{pl2} = min(t \; \forall \; Q_{planned,t} \in k) \quad 3.7\text{-}9$$

$$SQ^{k-1} = AVQ^{k-1}{}_{t_{pl1}} - Q_{t_{pl1}}^{k-1} \quad 3.7\text{-}10$$

$$SQ^{k} = AVQ^{k}{}_{t_{pl2}} - Q_{t_{pl2}}^{k} \quad 3.7\text{-}11$$

With

$DP1 =$ *Decoupling Point 1*

$DP2 =$ *Decoupling Point 2*

$t_{pl1} =$ *Planned Order 1*

$t_{pl2} =$ *Planned Order 2*

$SQ^{k-1} =$ *Available quantity before first replenishment order at k-1*

SQ^k = *Available quantity of before first replenishment order at k*

${AVQ^{k-1}}_{t_{pl1}}$ = *Available quantity after first replenishment order at k-1*

${AVQ^{k}}_{t_{pl2}}$ = *Available quantity after first replenishment order at k*

$Q^{k-1}_{t_{pl1}}$ = *Replenishment quantity of first replenishment order at k-1*

$Q^{k}_{t_{pl2}}$ = *Replenishment quantity of first replenishment order at k*

3.8 Conclusion

How can the MRP nervousness be measured at Prodrive Technologies?

The MRP environment at PT is an environment in which requirements on the top-level of the MRP systems are delivered based upon a rolling forecast. Moreover, the MRP environment is not static, and orders can change in quantity and due date up until delivery. This includes partly deliveries of replenishment and requirement orders. The MRP planning horizon at Prodrive Technologies can be split into a 'frozen' and a 'free' schedule horizon, which is determined by the conversion of a planned order into a production order. There is no fixed period for this 'frozen period' defined at PT and is often based upon the complexity of the product and the interpretation of the planner responsible for this product. The importance of changes of replenishment orders on the planning horizon is related to the possibility to deal with these changes, based upon the component lead-times. Therefore a change of replenishment orders close to the order start-date is more critical than for an order further on the planning horizon. Furthermore, the nervousness can be measured on 1 level or multiple echelons. In the further study has been focused upon the highest level in the BOM, which is supplied directly to the customers. The choice for including only the final products is to focus on the parts for which the requirements are the direct translation of the MPS of this product. Moreover, simulation experiments by Jensen (1996) gave the impression that the control rule applied at the end-item level has a dominating influence on the stability performance of the whole system. Therefore, while focusing on the end-level, the stability of the whole system can be influenced.

All these observations require a translation on the way of measuring the MRP nervousness to capture the planning instability relevant to the MRP environment at PT. This is done with the adjusted formulas proposed in Chapter 3.4 - 3.7

Chapter 4

The expected influence of variables on the MRP nervousness

The variables that are suspected to be relevant for predicting the MRP nervousness are divided into MRP planning parameters, uncertainty factors and product-specific characteristics. A literature study is conducted to gain knowledge about these variables and their influence on the MRP nervousness. Moreover, open interviews, roundtable discussions with the primary stakeholders into the planning process at PT in combination with detailed research upon MRP changes is conducted to create a complete overview possible influencers of the MRP nervousness to answer the following research question.

What is the expected influence of variables on the relationship between net requirement changes and the MRP nervousness?

In Table 2 an overview is created upon the three categories of variables together with their source.

Table 2: Overview of variables

	Variables	Literature Sources	Field research
MRP Planning Parameters	Lot - Sizing	Ho (2002), Ho & Ireland (1998)	x
	Rounding values		x
	Minimum Lot Sizes		x
	Maximum Lot Sizes		x
	Safety Stock	(Koh, Saad & Jones, 2002). Kadipasaoglu and Sridharan (1995)	x
	Reorder level	Jenssen (1993)	x
	Safety Lead Times	Molinder (1997) ,Hegedus (2001)	x
	Freezing Periods	Kadipasaoglu & Sridharan (1995) Sridharan & Berry, (1988). Zhao, X., & Lee, T. S. (1993).	x

	Rescheduling Methods	Carlson (1989), Ho (1992)	
Uncertainty factors	Internal supply uncertainties	(Wybark and Willems 1976, Mather 1977). Koh, Saad & Jones (2002)	x
	External supply uncertainties	(Pujawan, 2004). (Wybark and Willems 1976, Mather 1977). Koh, Saad & Jones (2002)	x
	Internal demand uncertainties	Koh, Saad & Jones (2002)	x
	External demand uncertainties	(Pujawan, 2004). Koh, Saad & Jones (2002)	x
Product specific Characteristics	Bill-Of-Material		x
	Product Lead Time		x
	Material group		x
	Vendor		x

4.1 MRP planning parameters

The MRP system calculates on the basis of deterministic demand and lead times. However, most production systems are stochastic, originating in uncertainties and problems both internally as externally (Louly, Dolgui, Al-Ahmari 2009). The MRP approach can be tailored to absorb these uncertainties by setting the MRP planning parameters.

In the context of MRP planning, the parameters set for this planning in combination with the MPS will define the production and procurement orders calculated by the MRP run. The most relevant planning parameters at PT are in the category of: Lot Sizing Rules, Safety Stocks, Safety Lead Times, Freezing Periods and Reschedule Techniques.

It is possible to reduce the MRP nervousness with buffering or dampening approaches, which are respectively inventory and non-inventory related. The buffering and dampening approaches in the MRP environment can be set as material-specific variables rules for Safety Stocks, Lot Sizes, Safety-times as well as non-material specific rules as freezing periods (Kadipasaoglu & Sridharan, 1995) and reschedule decisions (Ho,1992).

4.1.1 Lot Sizing

The Lot Size parameters include the Lot Size rules, minimum and maximum Lot Sizes and rounding values. These parameters are relevant upon production time uncertainty, quality risk aversion and overall cost optimization. The Lot Size can either based on quantity or time window. Quantity based approaches calculate the optimal order quantity, based on minimizing the total cost as proposed with the Economic order Quantity method (EOQ), the Least Total Cost method (LTC), the Wagner Within Algorithm (Wagner & Within, 1958) and the Silver-Meal heuristic (Silver & Meal, 1973). Time-based approaches are POS (periods of supply), where for a fixed time window the replenishment order quantity is equal to the net requirement in this period. The Lot-for-Lot rule is equal to the POS, with the period equal to one day.

The Lot Sizing Rules (LSR) used at Prodrive Technologies are either lot-for-lot (LFL) or periodic lot-for-lot (PLFL)/POS. Where lot-for-lot creates a production order for every individual requirement, and periodic lot-for-lot batches requirement for a specified period. This period can differ from one week to a quarter. The addition of a Rounding value, a minimum and a maximum Lot Size are a set of restrictions to the Lot Size calculation,

Ho (2002) concluded that using LFL rules resulted in the most nervous schedules. When the cost ratio between inventory carrying cost and set-up cost increased LTC and WW give the best results regarding planning nervousness by less disruption of production schedules then LFL, EOQ or SM. Therefore the PPB and LTC Lot Sizing Rules are described as the two most effective Lot Sizing Rules to reduce system nervousness. Ho & Ireland (1998) found that an appropriate Lot Sizing rule can be useful in dealing with forecast errors when the lead times tend to fluctuate. He concluded that it would be more appropriate to find a suitable Lot Size method than depend the operating environment on a perfectly fitted forecast method.

4.1.2 Safety Stock and reorder level

Safety Stock can be used in multiple ways in production planning. One possibility is to only use it as “dead stock” and never let the MRP plan requirements on this stock to consume. This method makes sure, a fixed number of products will be on stock, which can cover quality issues or last-minute material requirements.

The second possibility is to use the whole share that is available for the planning in the planning run, this means that the Safety Stock is used to cover requirements up unto a certain level equal to its Safety Stock level. When requirements exceed the available stock plus Safety Stock, a replenishment order will be planned to fulfill these net requirements.

A third, hybrid solution is using a percentage of the Safety Stock available to cover requirements. A production order will be planned if the net stock level is less than the Safety Stock that can be used to fulfill the requirements.

The two latter applications of the Safety Stock results in the implementation of a negative reorder level. In which the Safety Stock in combination with the percentage that can use to fulfill the requirements determine this reorder level.

"Safety Stock is applied predominantly to buffer input uncertainty" (Koh, Saad & Jones, 2002). Safety Stock parameters are related to the use of Safety Stock for demand fulfillment and the quantity of the Safety Stock. Kadipasaoglu and Sridharan (1995) determined the Safety Stock quantity to be equal to the standard deviation of the forecast error. When using the strategy of Safety Stock at the end item, changes of the demand uncertainty can be absorbed at the top level and less nervousness is transmitted to the lower levels.

Jennsen (1993) concluded that the implementation of a hybrid solution resulted in a more stable planning, although making this portion too high will no longer increase the stability, but only have a negative influence on the service level.

4.1.3 Safety Lead Times

Safety Lead Time is defined for the items to bring the requirements forward in the MRP schedule. By this parameter extra safety is included in the supply lead time of the replenishment order At PT this safety lead-time is either included as the safety time or as a schedule margin key.

Safety time is added to products to set the due date of a production order N days before the required due date. This safety time for end products and sub-assemblies will result in production orders with a start date triggered N days earlier. For purchase parts, this Safety Stock is set to request the due date of the part N days earlier than its required date, mainly used to cover the transportation lead times.

Schedule margin keys are floats added to the production lead time, as safety time before or after the start of the production order. These floats add ‘extra’ production time either before or after the production lead time. These floats are the first safety that is used in the production order scheduling.

Molinder (1997) indicated that as demand variability increased, Safety Stocks were preferred, and as lead time variance increased, Safety Lead Time was preferred. In the case of high lead time variability and high demand variability, Safety Lead Time is the best option. The setting of procurement lead-times is research by Hegedus (2001). Hegedus found that safety lead-times have a positive effect on the stability under lead-time uncertainty. Moreover, with deterministic supply, safety lead-times can be useful in the form of increased production flexibility.

4.1.4 Freezing periods

Freezing periods are the periods in which replenishment orders are “frozen”. This means that for these orders, automatic re-planning during an MRP run does not take place, but only reschedule-messages are created. This reschedule messages are time-based, so they either suggest to reschedule the order in or out. This means that quantity changes are not suggested.

Kadipasaoglu & Sridharan (1995) describe that in a multi-level system, freezing the MPS is the most effective way to deal with instability and to reduce the total cost for a stochastic demand process. On the other hand for a single-level, deterministic case, freezing can lead to a tremendous increase in costs (Sridharan & Berry, 1988). The recommended length of the frozen interval is equal to the cumulative lead time. The influence of the frozen interval further depends on the length of the planning horizon, where an MPS environment with a deterministic demand performs better than with an uncertain demand under a longer planning horizon. Zhao, X., & Lee, T. S. (1993) concluded that when forecasting errors exist, lower schedule instability can be gained by implementing a more extended freezing period, but often results in a higher total cost and a lower service level.

4.1.5 Rescheduling methods

Rescheduling methods procedures are rules and methods on how rescheduling is done if orders change over time and do not match the current MRP schedule anymore.

The static dampening procedure (SDP) is a dampening method making use of a set of heuristic rules, which ignores due date changes within a certain period around the original due date. This method is comparable with the method of the freezing horizon.

The automatic rescheduling procedure (ARP) is an automatic rescheduling method that reschedules all the "feasible" rescheduling messages. The feasibility of a rescheduling message is based on the minimum lead time of the product. If this lead time is feasible with its highest priority, the product can be rescheduled, and if not the due date of the open order should be revised.

The cost-based dampening procedure (CBDP) is a concept inspired by the Lot Sizing algorithm designed by Carlson (1989), which includes the costs of rescheduling. Ho (1992) suggests that an order should be rescheduled if the costs of rescheduling (COR) are less than the cost of not rescheduling (CONR). The costs of not rescheduling only include the penalty costs of the open order to be rescheduled, where the costs of rescheduling also include the penalty costs of the jobs that are affected by the rescheduling.

Ho (1992) concluded that the SDP and CBDP performed better than the ARP. Under a low production uncertainty, the three methods are equal regarding performance. Although, under a high production uncertainty or a high capacity level the performance of the ARP regarding total costs is much worse.

4.2 Uncertainty factors

The instability in production schedules is mainly caused by the uncertainty in demand and/or supply (Pujawan, 2004). The demand and supply uncertainty can both originate internally and externally. Koh et al. (2002) created a structure of uncertainties by this categorization. Where internal demand and supply changes are originated within the production area and external demand and supply changes are caused by suppliers or customers. Figure 9 shows a cause and effect diagram on MRP nervousness with input from the overview provided by Koh (2002), applied to the planning processes of PT. Internal supply issues and external supply issues result in material availability changes. Internal demand and external demand changes are the cause of the material requirement changes. The changes in material availabilities and material requirements will result in changing replenishment orders from a supply and demand side leading to MRP nervousness

Internal causes within the production can, among other things, be caused by quality issues, machine breakdowns, material and tooling unavailability, design issues, production variabilities and capacity issues. In all these cases, the material availability changes lead to a need of the revision of production orders on either their quantity or due date. However, it is easy for these orders to capture these changes in quantity or due date, the causes leading to these changes are not directly linked to the orders in the MRP system at PT. Therefore, it hard to track and analyze which internal causes lead to specific changes in material availability.

External causes leading to schedule changes can be split into external supply and demand changes. Uncertainties related to the external supply is typically caused by late supply or quality issues from the supplier. Uncertainties related to the external demand can either be caused by forecast inaccuracy or by customer order changes.

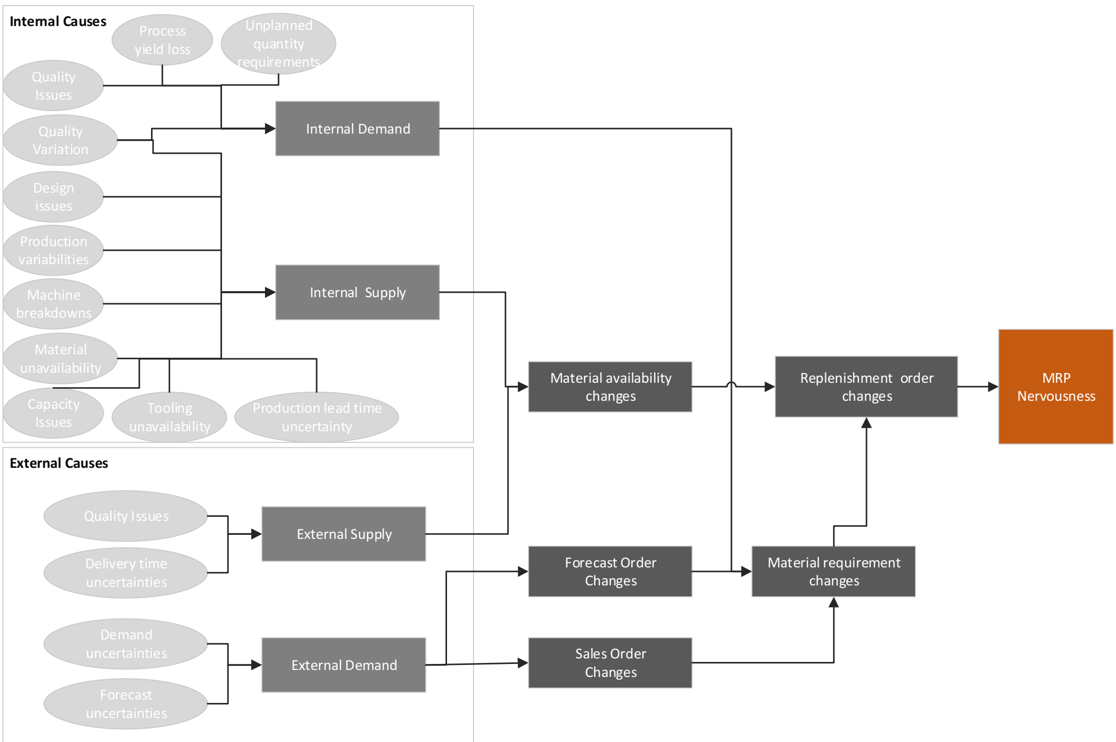

Figure 9: Cause and effect diagram on MRP Nervousness

4.2.1 External demand uncertainty

The external demand uncertainties are the changes in the Master product schedule. The MPS plans the items that have a direct demand or forecast from the customer. Therefore the MPS is the input in the MRP system that creates requirements directly from the customer requirements. Changes in the MPS have a significant influence on the MRP planning. The instability of the MPS can be calculated with the same formulas as provided for the MRP nervousness, where for the MPS sales orders and forecast orders are used instead of production orders and planned orders. Forecast orders can contain a n-monthly or an n-weekly forecasted demand, while sales orders commonly contain a daily or weekly demand. The parameters for the conversion of monthly forecast into a weekly forecast, or the conversion of forecasted orders into sales orders depend on sales agreements.

4.2.2 Internal demand uncertainty

The internal demand uncertainties are the changes in the requirements arising from products on a higher level of the Bill-of-Material. The internal demand uncertainties can be measured in the same way as the external demand uncertainties.

4.2.3 External supply uncertainty

The external supply uncertainties (ESU) are related to the delivery reliability of the purchased components. At PT a KPI is designed to measure the delivery reliability called the CLIP (confirmed line item performance). This CLIP measures the average on-time delivery with the date that is confirmed by the supplier. Although this KPI also gives a lower score for too early deliveries, as external supply uncertainty measurement in this research only a lower score will be given for too late deliveries. To include the delay at good at PT's goods receipt department, external supply uncertainty gets its 100% score for delays up to 2 days. The following formula is used for the ESU for a purchase component

$$ESU_i = \frac{\left(\sum_{j=1}^{n} x_{ij}\right)}{n} \qquad 4.2\text{-}1$$

ST.

$$x_{ij} = \begin{cases} 100 & , d_{ij} - c_{ij} \leq 2 \\ 90 & , 2 < d_{ij} - c_{ij} \leq 5 \\ 60 & , 5 < d_{ij} - c_{ij} \leq 8 \\ 0 & , d_{ij} - c_{ij} > 8 \end{cases}$$

With

d_{ij} = *Delivery date of product item i for order line item j*

c_{ij} = *Confirmed delivery date of product item i for order line item*

$x_{i,j,h}$ = *{0,1} the factor if product i in production order j is in delivery performance group h*

With the above mentioned external supply uncertainty measurement, partial deliveries are not taken into account. Partial deliveries originated when the supplier cannot meet the total demand for the shipment on time, but can deliver a portion of the requested quantity. Adding this option requires the addition of a quantity value (q) and the split of the order j into j_1 *..jm.* The external supply uncertainty formula with partial deliveries will look as follows:

$$ESU_i = \frac{\left(\sum_{j=1}^{n} x_{ij} * q_{i,j,k}\right)}{n} \quad 4.2\text{-}2$$

ST.

$$x_{ij} = \begin{cases} 100 & , d_{ij} - c_{ij} \leq 2 \\ 90 & , 2 < d_{ij} - c_{ij} \leq 5 \\ 60 & , 5 < d_{ij} - c_{ij} \leq 8 \\ 0 & , d_{ij} - c_{ij} > 8 \end{cases}$$

4.2.4 Internal supply uncertainty

Internal supply uncertainties occur when the product availability date of a subassembly will get delayed. In other words, if the availability date of the finished sub-assembly of a production order gets rescheduled out. Categorization can be made upon the internal supply uncertainties arising from capacity issues/production issues and missing components. The derivation of these uncertainties is based on a specific set of rules. Important to set-up these rules is a complete understanding of the MRP calculation algorithm and the planning process at PT as described in the background

The internal supply uncertainty is divided into two categories, movements before at after releasing the production order. These categories are moreover divided into reschedule in and reschedule out movements and including a reschedule message or not including a reschedule message. Rescheduling-in while having a Re-in message, and rescheduling out while having a reschedule out message are excluded from the uncertainties as these are just the follow-ups of the MRP logic and are not uncertainties, but are results from uncertainties.

Internal supply uncertainty 1 *(ISU1)* is measured as the quantity in the production orders that are not released yet, does not have a Re-out message, but are rescheduled out. This is most of the times a result from missing components, resulting in an order that cannot be released yet.

Internal supply uncertainty 2 *(ISU2)* is measured as the quantity in the production orders that are already released or partially delivered, does not have a Re-out message, but are rescheduled out. This is most of the times a result from capacity problems or quality issues.

Capacity leveling *(CL)* is measured as the quantity in the production orders that are rescheduled in, but does not have a reschedule-in message.

Because planners are not always changing the due date of a production order when it cannot be finished on time, not the whole internal supply uncertainty can be captured in ISU1 and ISU2. Although production orders are not always compiled with the real expected Due date, sales orders are commonly changed if their due date cannot be met. The due date of these sales orders is changed on the day when it is known that the due date cannot be met, which is most of the time on the day of the due date. Therefore, another internal supply uncertainty factor can be added which is related to the delivery uncertainty.

Delivery Uncertainty *(DU)* is measured as the sales orders that are rescheduled out with the old due date as being the planning date and the new date as being rescheduled out. The DU can be calculated with a relative factor, which only includes the difference in quantity and with an absolute measurement, which calculates the sum of the quantities in the changed sales order.

Another manual action by a planner is the deletion of production orders. This deletion often goes in hand with changing other production orders in quantity and time. This Deletion measurement (*Dl*) is measured as the quantity of the deleted orders.

The last feature that is added, is related to the stock changes of a product other than the delivery by a production order or delivery from a sales order or internal demand order. These credit and debit stock movement types are summed to get the stock difference by one of these stock movements. Stock movement uncertainty is measured as the sum of the credit (*mvtc*) and debit stock (*mvtd*) movements of the product, not related to the delivery from a production order and delivery for a sales order.

4.2.5 Product specific characteristics

Next to the nervousness directly influencing the net available quantity and requirements, there are product specific characteristics that can influence the nervousness level or make it possible to cluster over products. The product-specific characteristics that are included in this study are:

Bill-of-Material characteristics; the structure of an end product can either be relatively simple or can be extensive and therefore extremely complex. The number of layers and the total number of components will be used to describe the bill-of-materials.

Product Lead time, the time it takes to manufacture the product plus the component lead time.

Vendor number of the end products can be an influencer on the MRP nervousness. With the reasons that vendor agreements have been set on the allowed change in quantity or delivery dates of sales orders. These agreements cannot be put on a continuous scale and therefore are binary flag-fields created for the existence of a vendor number at a product.

The material group is a cluster of multiple products with similarities on functional or physical design. This makes it a possible cluster factor. Similar to the vendor number, only the frequent material groups will be selected and the rest is grouped, where after the binary-flags are created for the values in the set.

4.3 Detailed research.

This sub-chapter is included in the research to dive deeper into the individual and mutual influence of MRP parameters, planning techniques and forecasting techniques on the MRP nervousness under different uncertainties as described in 4.1 and 4.2.

A set of 50 different products is selected based on the criteria to cover a wide range of customers, of forecast processing methods and having different planners being responsible. The research included the daily analysis of production schedule changes and tracing down the causes of these changes. The results of the MRP parameter setting on the nervousness are elaborated in Table 3. A distinction of the influence of the different parameters is made upon the point on the planning horizon as described in chapter 4.1 and the appearance of a positive and negative demand/requirement change. Abbreviations used: Relative Positive Nervousness (RPN), Relative Negative Nervousness (RNN), Absolute Nervousness (AN),

Table 3: Overview of MRP parameter influences from detailed research

MRP parameter	Influence on	Demand/Net Requirement change	By	Influence on Nervousness	Period of scheduling
Rounding Value	Planned order Size,	D+	Rounding up to value	-**Strengthen** the RPN and AN at moment of a new (planned) order creation or quantity increase resulting in new rounding up value. - **Dampen** the RPN and AN as the quantity increase is within the extra quantity to which is rounded-up	Free schedule period
	Planned order Size, number	D-	Rounding up to value	-**Strengthen** the RNN and AN at moment of planned order 'removal'. - **Dampen** the RN and AN at the moment of quantity change within the rounding boundaries.	Free schedule period
	Production order quantity	R+	Extra safety by rounding up value,	- **Dampen** RPN and AN at the moment scrap occurred or requirement increase occurred due to supply uncertainties within the buffer created by rounding up	Frozen Period
Lot Size	Planned order quantity	D+	Aggregating requirements of n periods	- **Dampen** RPN and AN for quantity shifts between requirements orders supplied by same replenishment lot - **Strengthen** RPN and AN for quantity shifts between requirement orders supplied by different replenishment lots - **Strengthen** RPN and AN for quantity increase of single requirement order	Free schedule period
	Planned order quantity	D-	Aggregating requirements of n periods	- **Dampen** RNN and AN for quantity shifts between requirements orders supplied by same replenishment lot - **Strengthen** RNN and AN for quantity shifts between requirement orders supplied by different replenishment lots - **Strengthen** RNN and AN for quantity decrease of single requirement order	Free schedule period
	Planned order quantity	R+/R-	Aggregating requirements of n periods	- **Strengthen** RPN, AN by net requirement decrease earlier in planning	Free schedule + frozen period

				horizon leading to reschedule-in of complete Lot Size. - **Strengthen** RNN, AN by net requirement increase earlier in planning horizon leading to reschedule-out of complete Lot Size.	
Reorder point (SSR) Safety Stock + requirement rule	Planned order creation trigger	+ / R+	Delaying planned order creation+ re-in message creation	- **Dampen** RPN and AN for net requirement increases before replenishment lot – date - **Strengthen** RPN and AN by a small increase in quantity leading to overriding of reorder point. - **Strengthen** RPN and AN by new planned order creation where requirements of demand + reorder quantity should be fulfilled.	Free schedule + frozen period
		-/ R-		- **Strengthen** RNN and AN for net requirement decreases just below reorder quantity.	Free schedule + frozen period
Safety Stock	Production order/ planned order quantity	D+/R+	Extra stock to fulfill requirements	- **Dampen** RPN and AN for net requirement increase due to increased demand or supply uncertainties and quality issues.	
Minimum Lot Size	**Planned Order Size**	D+/ R+	Restriction for a minimum Lot Size of a planned order	**- Strengthen** RPN and AN for Lot Size creation to fulfill a net requirement lower than the Minimum Lot Size **-Dampen** RPN and AN for quantity increase which let the net increase fulfilled by the Lot Size be increased from lower than the MLS to higher than the MLS.	Planned order creation
		D-/ R-	Restriction for a minimum Lot	- **Strengthen** RNN and AN for Lot Size ‘deletion’ to initially fulfill a net requirement lower than the Minimum Lot Size	Planned order creation

			Size of a planned order	**-Dampen** RPN and AN for quantity decrease which let the net increase fulfilled by the Lot Size be decreased from higher than the MLS to lower than the MLS	
Maximum Lot Size	**Planned Order Size, Planner order creation trigger**	D+/ R+	Restriction for a maximum Lot Size of a planned order	- **Dampen** RPN and AN by new Lot Size creation when requirements exceed the MxLS, by the creation of a new lot with a due date later than the original Lot Size. -**Strengthen** RPN and AN by new Lot Size creation when requirements exceed the MxLS, if the newly created lot results, by Lot Sizing period, in combining requirements from further in the horizon and the shift of these requirements is higher than the dampening effect by the creation of a new lot as explained above.	Planned order creation
		D-/ R-	Restriction for a maximum Lot Size of a planned order	- **Strengthen** RPN and AN by a reversed effect on the dampening effect as described in the row above. - **Dampen** RNN and AN by a reversed effect of as strengthening in the row above.	Planned order creation
Safety Lead Time	**Planned order date**	D+/ R+		- Strengthening effect on RPN and AN with criticality by setting a time between the requirement date and the replenishment date,	Planned order creation
		D-/ R-		- Strengthening effect on RNN and AN criticality by setting a time between the	Planned order creation

				requirement date and the replenishment date	
Safety Lead Time	**Production order date**		Rescheduling order	- Dampening effect on all the nervousness measurements by not needing to reschedule the order while supply uncertainty occurs, to still deliver the order on time.	Frozen period

Next to influences from the parameters that influence the MRP algorithm, specific planning techniques that are applied at PT are reviewed. The results can be found in Table 4:

Table 4: Influence of planning techniques of Nervousness

Planning techniques		**By**	**Influence on Nervousness**	**Period of scheduling**
Order Freezing period	Automatic production rescheduling	Frozen Production Orders	Dampening all the nervousness by not allowing production orders to be automatically rescheduled.	Frozen period
VSF → Sales orders	Requirement deviation and quantities	While sales orders are 'fixed' VSF (forecast) orders are possible to be changed.	The conversion of VSF to sales orders is often not 1:1, therefore deviation between these two lead to nervousness. The further this conversion window is on the planning horizon, the less the nervousness including criticality is observed. On the other hand, it is often that VSF lines are monthly based, while the sales order are weekly based. This conversion from monthly based to weekly based has a strengthening effect on the RNN nervousness value and can lead to higher inventory costs than required.	All horizons

4.4 Conclusion

What is the expected influence of variables on the relationship between net requirement changes and the MRP nervousness?

The creation of the MRP-plans is the translation of the net requirements into replenishment orders based upon the MRP parameters. The MRP parameters that are used at PT the Lot Size rule based upon periods of supply, minimum and maximum Lot Sizes, rounding values, multiple Safety Lead Times and a reorder quantity as a negative Safety Stock which can be used to fulfil requirements. This MRP planning is runt daily and changes upon replenishment orders are the translation of net stock level changes by uncertainties as described in chapter 4.2

From the results as shown in Table 3 and Table 4 can be concluded that it is not straight to say in which way the MRP parameters and planning techniques cooperate into reducing or strengthening the Nervousness. It all highly depends on the direction and time on the horizon of the net requirement changes by demand and supply uncertainty, the mutual dependence of the MRP parameters and on following-up the rescheduling messages. In Figure 10 an overview of the Parameters and the planning techniques and the interval of the planning in which they influence the planning was presented. This figure shows where on the planning horizon the parameters have the most influence, which is for most of the parameters during the creation of a planned order (automatic planning). On the other hand, the Safety Lead Time has its most significant influence during the 'frozen' period as it is implemented as the extra time the production order can be delayed to still fulfil the demand on time. The different Safety Lead Time parameters do have an influence on the urgency to follow-up reschedule messages. An example of this is the follow-up of a re-in reschedule message for a production order with a Safety Lead Time, this message can be ignored when this the new proposed date is within this lead time. The Safety Lead Time has a strengthening influence on the Lot-creation by bringing the net requirement date forward on the planning horizon with the number of safety days added. Moreover, the Safety Stock rule has an influence on the creation of planned orders when 'net stock' is below the 'reorder' point. The Safety Stock rule allows the available quantity to drop below zero, by which the creation of the first planned order is delayed. This is often the case when production orders are not able to deliver their target quantity by component availability or quality errors. Instead of the creation of a planned order within the frozen period, this additional quantity is added to the first planned order in the automatic planning horizon. The rounding values, the Lot Size Rules and the maximum and minimum Lot Size have all a direct influence on the Lot Size creation based on their available date and quantity. Finally, the rounding value can have a dampening effect with the inclusion of a small percentage additionally added replenishment quantity that can be used as Safety Stock, but at lot creation and deletion, a strengthening effect is found by the probability of covering more quantity than the net requirements.

Next to the parameters, the influence of planning techniques is reviewed. The conclusion on these techniques is the dampening effect on the frozen horizon, in which rescheduling is not be executed automatically during requirement changes. Moreover, the period for which conversion of forecast into sales orders occur shows that there is a deviation between the forecasted quantity and the actual demand. Therefore, the closer this conversion is done close to the planning start date, the more nervous the planning system will probably be.

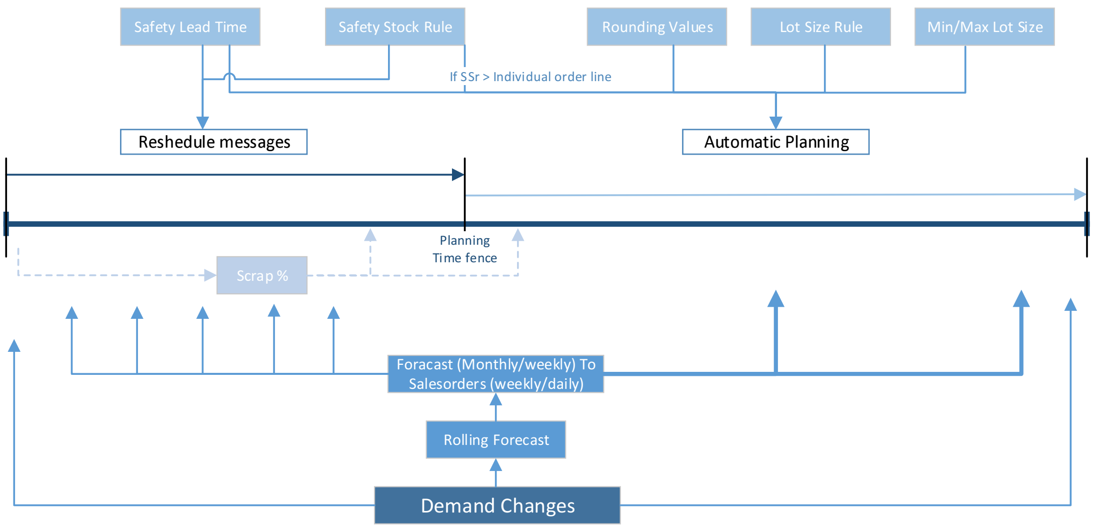

Figure 10: Parameter influences on MRP plan

Chapter 5

Descriptive statistics of the MRP nervousness, the variables and its relation.

This chapter contains the descriptive statics for the planning parameters at PT, the MRP nervousness, the uncertainties of the planning environment and answers the following sub-question:

What are the parameter settings, net requirement changes and MRP nervousness at Prodrive Technologies?

5.1 Planning Parameters at Prodrive Technologies

The most important planning parameters at PT are categorized into the Lot Sizing Rules, the Safety Stock and the Safety Lead Times.

Lot Sizing Rules at Prodrive Technologies are implemented in all the product levels, from procurement items till end-products. Figure 11 gives an overview of the Lot Sizing Rules used at end-item level and for sub-assemblies respectively. The analysis is done for 1869 finished products. The Lot Size rule is divided into the Period of Supply (POS) Lot Sizes or the LFL. As can be seen Figure 11 the Lot Sizing rule W2 with 29% is used the most for the finished products. All the Lot Sizing Rules starting with a W or Y are Lot Sizing Rules that collect all the sales orders of the number of weeks that is described after the W. These Lot Sizing Rules all fall in the category of a Periods of supply (POS) Lot Sizing rule, which the number specifying for how many periods in the future the Lot Size Rule should supply the net requirements. As can be seen in Figure 11, the periodic Lot Sizing rule used for 76% of the end products. Next to this periodic Lot Sizing rule, for 24% of the end-times, the lot-for-lot order quantity is set. This means that for every sales order entered in the system, a production order is created.

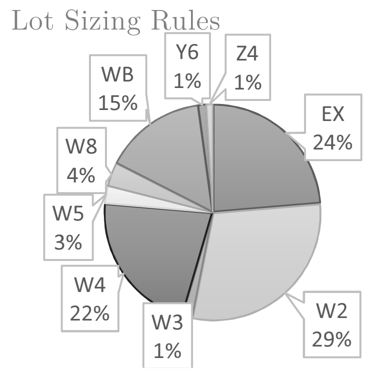

Figure 11: Lot Sizing Rules

At Prodrive Technologies, all the three methods of Safety Stock requirement usage are used. Figure 12 gives an overview of the distribution of the use of the different methods for the 603 end products, for which currently demand is known. When there is no Safety Stock assigned to an item, it does not matter if one of the rules is applied. Figure 12 shows four different categories. The biggest group of products does not have any Safety Stock (54%), the second largest group (22%) makes use of the hybrid Safety Stock rule. 18% does use its total Safety Stock for meeting requirements and the last 6 % only use Safety Stock as dead stock. For the 276 end-products, which contains a safety-stock, Figure 14 gives an overview of the frequency of set quantities divided by its average order quantity. As can be seen in the figure, the most used value is to hold Safety Stock equal to the average size of one order. Figure 13 shows the distribution of the Safety Lead Times at the end item level. For 98% of the items, Safety Lead Time is defined with a range between zero and ten days, where two days is the most used Safety Lead Time for almost 50% of the items.

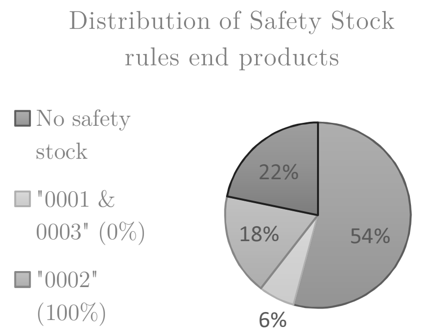

Figure 12: Distribution of Safety Stock rules

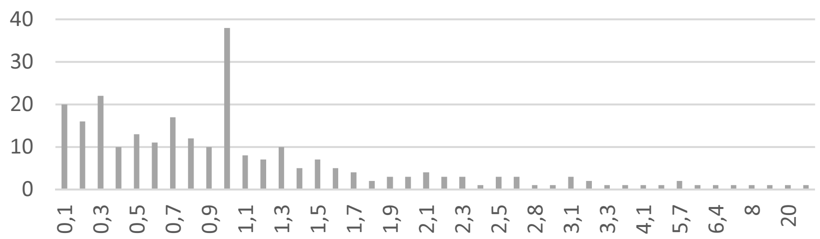

Figure 14: Frequency of Safety Stock per average order quantity

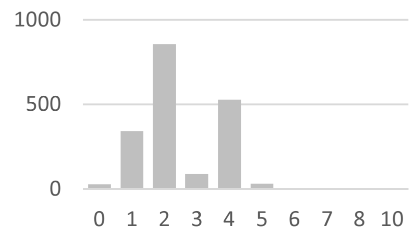

Figure 13: Safety Lead Time

5.2 Planning Nervousness at Prodrive Technologies

The data set for the calculation of the planning nervousness contains the MRP plans that have been collected from the first of May till the end of August for 797 final products. Whenever a change in the MRP plan occurred, the old MRP plan was saved including the start and end date when this MRP plan was active.

A data line in the dataset is indicated with the product number in combination with the active start date of the MRP plan. This combination is always unique as the MRP plans are saved once a day overnight. Each data line contains all of the MPR nervousness measurements which are calculated between two succeeding MRP plans as explained in Chapter 2. The MRP nervousness measurements are calculated at the original way as found in the literature with formulas in 3.1 and with the adjustments as proposed on these formulas in chapter 3.2 till 3.7. The complete set of MRP-nervousness measurements that are executed is shown in Figure 39 in Appendix A.5. The first split in Figure 39 shows which horizon is included into the nervousness measurement. In this research three different horizons are used. The first horizon includes all the replenishment orders till 150 days in the future. The second horizon includes only the replenishment orders in the 'free' schedule horizon, which is defined by the first planned order. The third, hybrid, horizon excludes the first three weeks of the planning horizon in which direct supply uncertainties probably the result of the nervousness changes, and therefore can this uncertainty be let out of the scope. The difference between the second and the third horizon is that the decoupling point is included in the scope.

As Figure 39 in Appendix A.5 shows, next to the deviation into the 4 MRP measurement possibilities and the three different horizons, a distinction can also be made upon the direction of the requirement changes. As can be seen in this figure is not every branch completely deviated in all the possibilities, but only for the distinction that adds value to this research.

This MRP nervousness measurements result in 30789 lines of data, at which in 8951 lines at least one of the nervousness occurrences is found on the planning horizon up to 150 days in the future. The results from the current MRP status at PT is described with the below charts and tables. In Table 5 for the different nervousness measurements techniques, descriptive statics are shown for individual data points over a horizon of 150 days expressed into financial value. Expressing the nervousness measurement into this financial term makes it possible to compare the nervousness impact between products. Moreover, this term is chosen as it will show the total impact on the supply chain, with the relation between the complexity of the bill material and the product value.

Table 5 gives an insight on the nervousness that is measured individually for products between two succeeded MRP plans if changes are measured. From this table in combination with the number of observations, can be concluded that the MRP nervousness results in lots of financial movement and the occurrence is frequent. From Table 5 and Figure 15 can be concluded that the quantity movements on average are more quantity decreasing or movements to the back with the average relative factor being a negative number. Although this number is on average number negative, the schedules with a positive number, as described by MRPrel> can result to more significant problems than only extensive stock, leading for example to missing parts of shared components or capacity problems. Moreover can be concluded that the bigger portion of the MRP nervousness is captured in the frozen horizon, although the average changes are larger in the free horizon.

Table 5: Current MRP nervousness state complete horizon,

Horizon	**M**	**N**	**mean**	**std**	**cov**	**max**	**min**
Full	MRPabs	6115	72840.02	159754.38	2.19	3205278.58	3.99
Full	MRPabs_a	7235	40594.47	77902.78	1.92	1334847.15	1.22
Full	MRPrel	1616	-8130.07	55870.37	-6.87	250294.55	-943470.00
Full	MRP_rel>0	794	11285.79	21870.75	1.94	250294.55	3.99
Full	MRP_rel<0	822	-26884.57	70438.53	-2.62	-8.87	-943470.00
Full	MRPrel_a	4385	-3664.35	18224.32	-4.97	219235.30	-396886.54
Full	MRP_rel_a>0	1498	3732.71	11549.74	3.09	219235.30	0.00
Full	MRP_rel_a<0	2887	-7502.52	19803.69	-2.64	-0.00	-396886.54
Free	MRPabs	1852	53946.65	124357.89	2.31	1872517.64	7.98
Free	MRPabs_a	1852	36085.92	86839.40	2.41	1459013.79	4.19
Free	MRPrel	1038	1888.13	41215.79	21.83	274872.00	-416874.05
Free	MRP_rel>0	639	17277.02	29421.55	1.70	274872.00	17.39
Free	MRP_rel<0	399	-22757.24	45269.92	-1.99	-13.81	-416874.05
Free	MRPrel_a	1655	936.92	25297.37	27.00	234283.97	-416874.05
Free	MRP_rel_a>0	911	9397.17	20341.02	2.16	234283.97	0.00
Free	MRP_rel_a<0	744	-9422.34	26881.98	-2.85	-0.00	-416874.05

From the difference in the distribution between the Relative Nervousness and Relative Nervousness with criticality in Figure 15 can be concluded that the distribution of positive values for the Relative Nervousness is much larger than for the relative nervousness with criticality. This suggests that quantity decreases in the earlier phases of the planning horizon occur more often, whereas the quantity increases occur further away in the horizon.

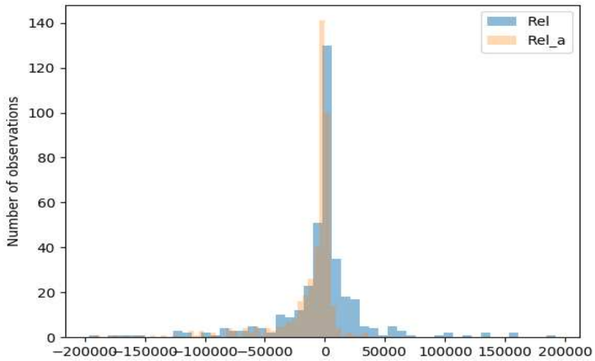

Figure 15: Financial MRP nervousness Relative measurement

An ABC- analysis is created to have an insight in which percentage of the financial MRP nervousness is originated by which percentage of products. As can be concluded from the Figures in Appendix, below figures, 80% of the nervousness measures around 20 % of the products. Therefore to tackle the MRP nervousness priority can be given to the products grouped into category A.

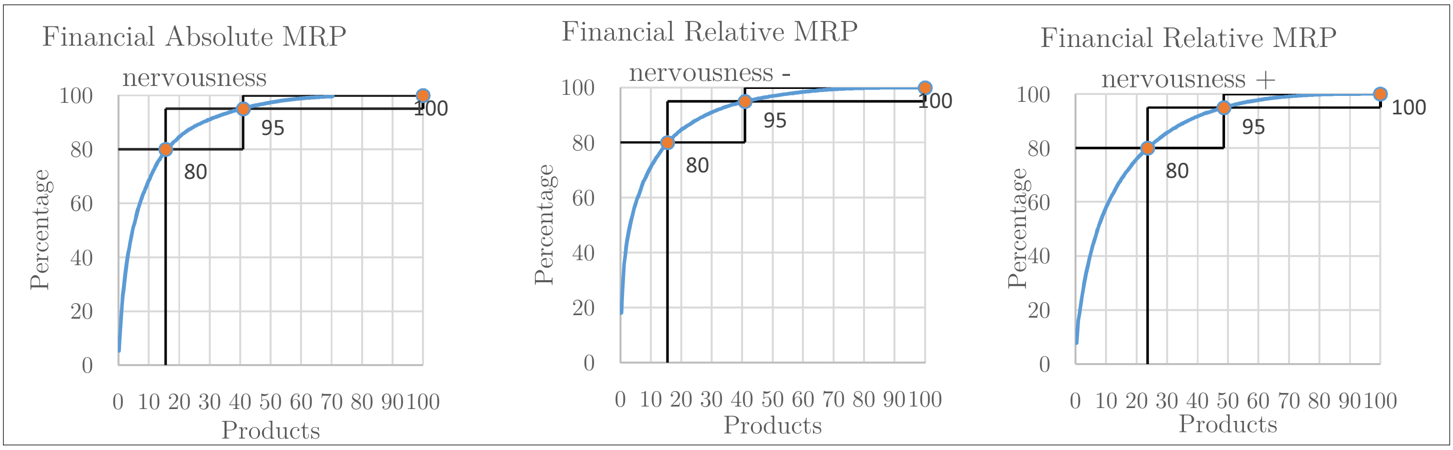

Figure 16: ABC analysis on financial MRP Nervousness

5.3 Descriptive statistics on uncertainties

Figure 18 shows the distribution of influence of the MRP nervousness by the MPS nervousness and the added planning uncertainties described in this chapter. In total there are 1961, 4551, 5820 and 5794 data points where nervousness occurred between two production schedules for the four different MRP measurements. Table 7 shows the perceptual values shown in Figure 18. In more than 95% of the cases, while MRP nervousness occurred, one of the uncertainties occurred as well. The internal supply uncertainty (ISU), the Re-in difference, the internal supply uncertainty 2 and the Stock difference after production and fulfilling all demand are the uncertainties that occur the most. Uncertainty analysis on the "free" planning period is performed as well. The results of this analysis are shown in Figure 17 and Table 7. The results show that next to the changes in the MPS, a difference in the net stock position at the start of the horizon occurs a lot as well. These changes show the net results from the 'frozen' horizon. The differences at the end of the horizon are the differences in net stock level at the last included order, which does not have to be zero by Safety Stock rules which can fulfill requirements.

Data collected from this free period can be combined with the data collected from the entire horizon to split the MPS uncertainty into MPS occurring during the 'frozen and the 'free' period. This result is added to Table 7 and Figure 18. The results show that for at least 20% of the MRP-nervousness occurrences a MPS change in the frozen horizon is the only causer.

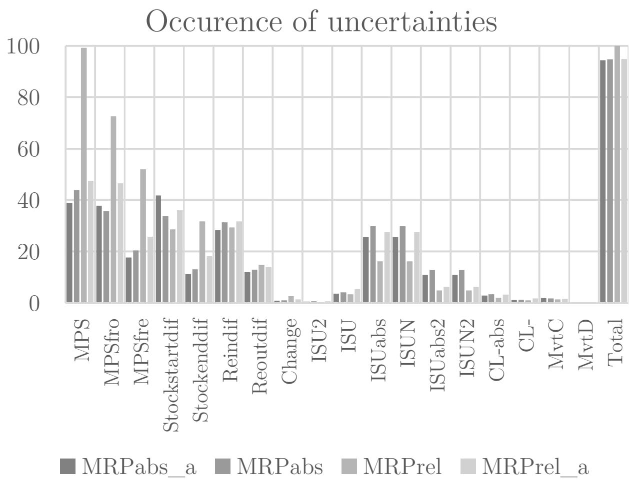

Figure 18: Occurrence of uncertainties complete Horizon

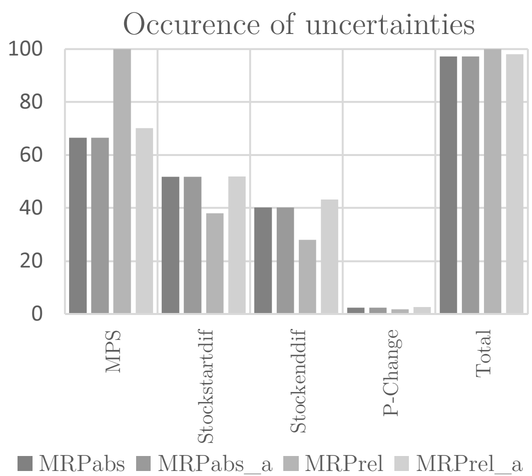

Figure 17: Occurrence of uncertainties Free Horizon

Table 7: Percentage occurrence of uncertainties complete horizon

MRP	*MRPabs_a*	*MRPabs*	*MRPrel*	*MRPrel_a*
MPS	38,89	43,83	99,11	47,44
MPSfro	x	35,67	72,60	x
MPSfre	17,57	20,40	52,00	25,68
StockSdif	41,81	33,85	28,61	36,13
StockEdif	11,18	13,05	31,79	18,21
Reindif	28,40	31,36	29,37	31,71
Reoutdif	11,97	12,95	14,81	14,09
P-Change	0,91	1,04	2,61	1,38
ISU2	0,55	0,64	0,25	0,70
ISU	3,65	4,26	3,37	5,45
ISUabs	25,55	29,84	16,15	27,65
ISUN	25,55	29,84	16,15	27,65
ISUabs2	10,96	12,77	4,90	6,26
ISUN2	10,96	12,77	4,90	6,26
CL-abs	2,84	3,32	2,03	3,20
CL-	1,15	1,34	1,02	1,82
MvtC	1,92	1,83	1,46	1,73
MvtD	0,24	0,26	0,19	0,33
Total	94,31	94,58	100,00	94,74

Table 6: Percentage occurrence of uncertainties free horizon

	MRPabs	*MRPabs_a*	*MRPrel*	*MRPrel_a*
MPS	66,48	66,48	100	70,16
Stockstartdif	51,77	51,77	38,09	51,89
Stockenddif	40,19	40,19	28,02	43,21
P-Change	2,47	2,47	1,82	2,65
Total	97,19	97,19	100	98,01

5.4 Demand Uncertainty at Prodrive Technologies

The changes from the MPS are the biggest influencers on the MRP nervousness as being found in the previous chapter. This result in combination with the characteristic that lead times of the manufactured products at PT can be longer than the period for which demand is fixed, changes in the underlying schedules can not only be caused by demand changes with a near future due date, but at lower BOM hierarchy levels by demand changes further in the future as well.

To get a detailed insight into the demand nervousness, an analysis is made upon the changes throughout the horizon for the rolling forecast principle. Figure 20 and Figure 21 give an overview of the total cumulative demand (in euro's) for a horizon of 9 weeks (2 months). Where the cumulative demand is measured 13, 9, 5 and 1 week before the start of its horizon. The analysis is conducted for a selected set of products all with lead time of more than 22 weeks, which means that every change in this horizon is within the average lead time and therefore will definitely result in disruptions somewhere in the supply chain. From this Figure in combination with Figure 38 in Appendix A.5 can be concluded that within the lead time, still many changes take place. Up till 5 weeks before the start of the planning horizon, the cumulative requirements are from the 2nd week up until the last week of the horizon still increasing, which means 6 weeks before the sales order requirement date, the total requirement value is still increasing. Only between 1 and 5 weeks before the start of the horizon, the cumulative seems to be lowered, leading to a negative relative nervousness.

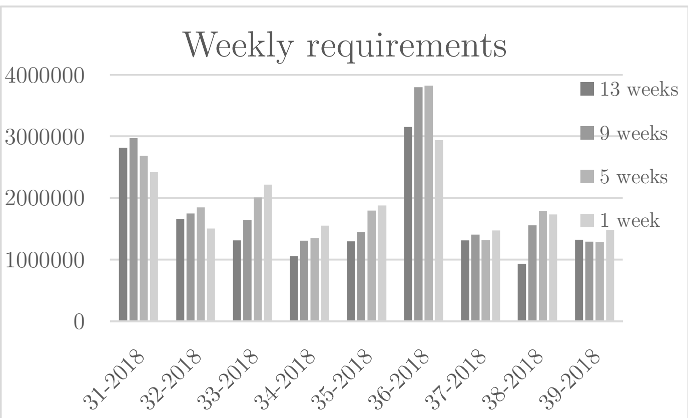

Figure 20 Overview of aggregated weekly demand

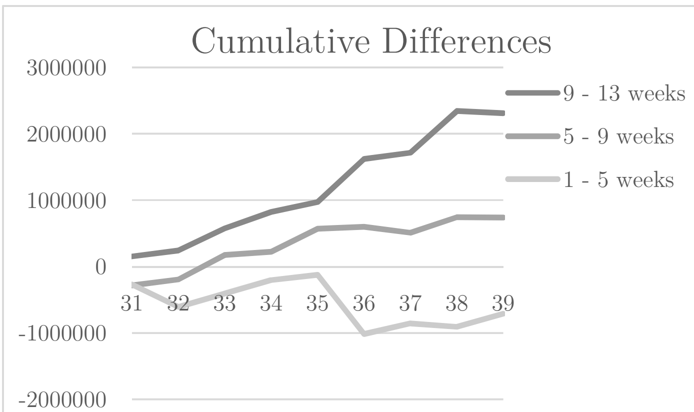

Figure 19: Cummulative value differences of demand

5.5 Regression analysis on MRP parameter influences

The MRP planning parameters can have a dampening/buffering or a strengthening effect on the relation between the requirement uncertainty and the replenishment uncertainty. This effect can be seen as a moderating effect between the independent (the requirement) and the dependent (the replenishment). This moderating effect can be tested upon by dividing the possible moderator parameters into different groups.

This analysis is done on all the MRP parameters described in the previous chapters for the aggregated nervousness measurement on the full horizon and the 'free' planning horizon. By splitting the total group of variables into four groups, the moderating influence of the parameters on the relation between the requirement and the replenishment nervousness is tested. This is justified as all the variables are discrete numerical data points. However, for the MaxLot and the MinLot variable, the testing groups are too small for dividing them into four groups, therefore for these two variables, the deviation is done in two groups; either containing a MinLot or MaxLot or not.

The occurrence of a relation is indicated in Table 19 and Table 20 in Appendix A.6 with a + for strengthening effects and a – for dampening effects. If the relation is not found to be significant, this is indicated with a dot; "." . It is also possible that a relation is not significant in all the 4 groups. As an example, this is indicated as follows: +..- , which suggests that in the first group, including the 25% of smallest values, a strengthening effect is found, in the second and third group no significant influence and that in the fourth group a positive relation is found. The results from the table are summarized as follows:

Freezing period: This study is conducted on the complete horizon, the hybrid horizon, as in the 'free' horizon. A shorter freezing period seems to have a strengthening effect on the MRP nervousness from the results of the complete horizon. For the most measurement categories, the first and/or second group of freezing variables, containing the small freezing periods, shown a strengthening influence +, in contrast with a negative influence often found in the latter categories. For the hybrid horizon, the influence of the freezing period is not as evident. On the relative nervousness (RN) the result of a longer freezing period seems to be dampening, although for the Absolute Nervousness (AN) and Absolute Nervousness with Criticality (ANC) this result is not found.

Lot Size Rule: A bigger Lot Size Rule seems to have a strengthening influence on the MRP nervousness for the Relative Nervousness with Criticality (RNC) on the complete horizon with criticality. So for big Lot Sizes close to the production delivery date, the relative changes are high. For most of the other measurements, a dampening influence is found in the second and third category, which includes the Lot Sizes between two and four weeks. Except for MRP abs >0, which is the AN on the complete horizon for a demand bigger than 0, where a dampening result is found in the first category (LS of LFL and 1 week), followed by a strengthening relation in the second (2 weeks), no significant difference in the third and a dampening result in the fourth (5 and 8 weeks)

MinLot% For the Minimum Lot Size, two categories are created. The first category contains no restriction to the minimum Lot Size and in the second category are data points assigned including a restriction to the minimum Lot Size. The result of the minimum Lot Size shows no straight conclusions upon the dampening effect on the different horizons and measurements.

MaxLot. Similar as for the MinLot, the dataset for this parameter is split into two categories as well. The table shows that the occurrence of a Maximum Lot Size for the most categories results in a strengthening effect, or a dampening effect when this restriction is not applied.

Rounding Value. The rounding value seems to have a strengthening effect on the MRP nervousness for 11 out of the 18 different measurements. However, only for the RNC the inclusion of a rounding value seems to have a dampening effect on the MRP nervousness as the categories in which a rounding value is applied show a smaller relation between the MPS and MRP nervousness.

SLT. The results from the SLT are the most interesting for the absolute changes as this parameter is not quantity based but time-based. Focusing on these values gives the impression that a longer SLT results in less production order day changes with strengthening effect in the first 2 [0 – 2 days] categories and a dampening effect in the latter [3-10] days.

SSR%. The parameter for the Safety Stock in combination with the Safety Stock rule is used as the percentage of the average Lot Size that can be used to lower the reorder level shows interesting findings. For almost all measurements with a value in the lowest category, with a percentage under <5-7%, an increasing effect on the Nervousness is found. The second and third category with values between 5 till around 35 percent, a decreasing effect is found. However, for the fourth category, both an increasing and decreasing effect is found. For demand increases in the free schedule period, this effect is decreasing on the three nervousness measurements matching these properties.

SS%. This parameter for Safety Stock is the actual Safety Stock assigned to for the product as a percentage of the average Lot Size. The increasing of this value shows a decrease in the MRP nervousness for at least one category for almost every MRP measurement. In contradiction to this finding, for the AN and ANC, during the free schedule period under negative demand change shows a strengthening effect on the MRP nervousness. This same effect is also found for the RNC under negative demand changes.

5.6 Conclusion

What are the parameter settings, net requirement changes and MRP nervousness at Prodrive Technologies?

The state of the MRP environment at PT can be described by the MRP nervousness that has been measured in combination with the occurring uncertainties as well as the influence of the MRP parameters. The MRP nervousness measurement expressed into financial relevant values gives the insight into the significant number and size of value movements. Moreover, the ABC-analysis shows that 20% of the products are responsible for the 80% of these value movements and therefore are critical in making an impact on reducing the nervousness.

The analysis on the uncertainties which are defined in chapter 4.2 shows the possible reasons for a nervous planning environment. For more than 95% of the occurrences of nervousness one of the uncertainties has been observed. The MPS/demand changes were observed most often and therefore seems to be the biggest influencer on the MRP nervousness. Although this suggests that the demand uncertainty is high, in the frozen period the change of a sales order due date and quantity can be initialized by a planner at PT as well, due to missing stock to deliver upon. Next to the uncertainty from the demand side, the uncertainty measures in initiated to capture the supply uncertainty show their influence as well. Both the component availability (ISU) and the production reliability (ISU2) shows relative quantity changes in about 5% of the nervousness measurements and absolute changes are captured in around 25%. A remarkable finding is that changing the MRP parameter settings was captured in 3% of the captured nervousness measurement on the relative nervousness.

On the free schedule horizon, the influences that can be measured is the net stock difference at the start of this horizon, the end of the horizon, direct MPS changes and MRP parameter changes. With the demand changes being captured the most, the start stock difference occurs a lot as well. This difference is the net requirement result from the frozen period. However, net every stock start difference directly results to MRP nervousness, as the decoupling point described in 3.7 does not have to be at the same date on the horizon.

The analysis on the demand uncertainty in chapter 5.4 shows us that up until 5 weeks before production order finish date, the cumulative demand keeps increasing, leading to extra demand through the whole supply chain with lead-times being longer in more than

50%. Although in the last weeks before production order start, the cumulative demand seems to decrease close to the horizon, which can originate from not being able to deal with these requirements and therefore lowering them or moving them backward on the horizon. Moreover, the forecasts can be set initially to a higher quantity to deal with uncertainties or securing that the actual demand can be fulfilled with more certainty.

The influence of the parameters on the nervousness for the different measurements, analysed with a moderation study, shows us the possible influence from these parameters on the different parts of the planning horizon under different directions of the net requirement changes. From this analysis can be seen that the influence of the parameters can differ based on the horizon and the net requirement change, which are in line with the observations from chapter 4.3.

Chapter 6

Predicting the MRP nervousness

This chapter will contain the description of the variable selection method and the test on how accurate these variables can be used to predict the MRP nervousness based on multiple prediction methods. The overall goal of this chapter is to answer the following sub-question:

Which variables and predictive model combination can be used to predict the MRP nervousness?

Figure 21 gives an overview of the complete method to answer the sub-question above. In the following sub-chapters the Data pre-processing, the feature selection and the used set of prediction models are described.

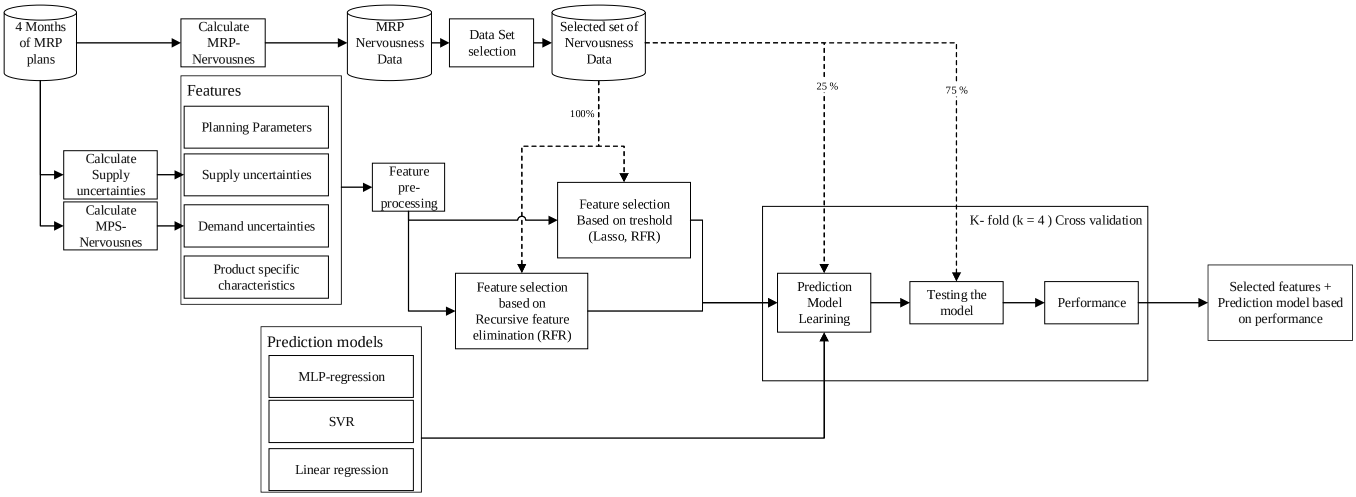

Figure 21: Model overview

6.1 Data Pre-processing

Before feature selection, the data preparation phase is required to use the raw data into the analysis. This pre-processing is done on all the features that require a normalization on product level. This is done for the Minimum and Maximum Lot Size, where the influence of this feature highly depend on the average Lot Size. Therefore are the values for these two features normalized with the average Lot Size of the specific product.

Furthermore, the product-specific characters are defined as categorical variables. The one-hot encoding technique is used to transform these categorical variables into binary variables. This is done by creating a feature for every single possible categorical variable and thereafter assigning the binary number 1 if the category value was active and a 0 if not.

6.2 Feature selection

From the complete set of features that are collected, feature selection is conducted. The feature selection is applied to fit the model with the most relevant features, decrease the running time and reduce the chance of overfitting. Table 8 shows different feature selection methods and their specifications (Guyon and Elisseeff, 2003).

Filter methods select, independently of the outcome, the variables that are most relevant based on relevance indicators. (Sánchez-Maroño, et al.,2007) Although the filter method is easy to interpret, requires short training times and reduces overfitting (James et al., 2013), it lacks on mutual dependencies between features and does not select the features upon the model that is used.

“Wrappers utilize the learning machine of interest as a black box to score subsets of variables according to their predictive power” (Kohavi and John 1997). The main advantage of the wrapper method is the possibility to detect interactions between variables (Phuong, Lin and Altman, 2005) and that it can be linked to the prediction model. Although, there is a risk related to overfitting upon using the method for an insufficient number of observations and its computational time is significant for a large set of variables (Das, 2001).

Embedded methods have to ability to reduce to computational time for reclassification of subsets done by the wrapper methods (Chandrashekar and Sahin, 2014), which is done by including the feature selection into the learning process. By cross-validation, this method is less prone to overfitting, while resulting in similar results as the wrapper method. Embedded methods perform variable selection in the process of training and are usually specific to given learning machines.

With the shown advantages, both the wrapper and the embedded method are used as feature selection techniques.

Table 8: Feature selection method overview

	Filters	Wrappers	Embedded
Interpretation	X	X	X
Speed	X		
Effectiveness			X
Interaction between features		X	X
Influence on prediction model score		X	X
Reduce Overfitting	X		X
Learning			X

The applied embed feature selection method is based on selecting the most important features by the threshold elimination method from a RandomForestRegressor and a LassoCV model.

The wrapper method applied is a recursive feature elimination model at which at every iteration, the least important feature is eliminated. Applying the prediction model after every iteration makes it possible to find the set of features resulting in the best performance. The feature selection method in this test is the Random forest regression (RFR). After every iteration, the new set of features is fed to the prediction model to test its performance.

6.3 Prediction model

From the regression analysis some conclusions can be drawn about the mediating effect of several parameters, although in the MRP algorithm, the mutual dependencies that result in the creation of a replenishment order ask for regression models with the inclusion of this feature. This can be found in the feature of Artificial neural network such as the Multi-Layer Perceptron Regressor (MLPR) (Basheer & Hajmeer ,2000) and supervised learning algorithms as the support-vector machine regression (SVR) (Smola and Schölkopf, 2004) and linear regression methods (LR) (Seber and Lee, 2012). For the SVR, the linear kernel is used in the algorithm.

The MLPR requires the setting of several hyperparameters, such as the number of hidden neurons, layers and the number of iterations. In this research, the setting of the hyperparameters is based on trial and error. The number of hidden layers tested upon is between 1 and 2. The number of hidden neurons is set between and the number of input neurons. These choices are made upon the basic rules proposed by Heaton (2008). The number of iterations is set to 200 iterations. The solver iterates up until this number of iterations or until a tolerance for optimization is reached. This tolerance is the improvement score which should at least be reached to continue with the next iteration, which is set to 0.0001. The activation function used for the MLPR is the ReLU function (Poggio and Tomaso et al., 2017).

After the feature selection, these models are firstly trained with 75% of the data set and after that is the performance of these models tested on the remaining 25%. This is done with four different training sets and four different test sets during the k-fold cross validation phase. The feature selection method in combination with learning algorithm that gives the best average performance on the testing sets is selected and further used in this study. The results of the prediction models and the feature selection are provided in the next sub-chapter

6.4 Results of the Model

The first results shown are the comparison between the originally stated MRP nervousness measurement defined by 3.1-1 -3.2-2 and the adjusted MRP formulas defined by 3.5-1 3.6-1 and 3.6-6. The adjusted formula includes filtering out results from work-in-progress, data inconsistency and the result of a flexible horizon. The results are shown in Figure 22.

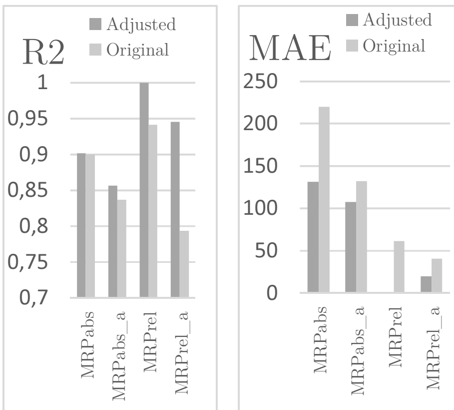

Figure 22: Overview of prediction results for MRP nervousness original and adjusted measurement

From these results can be concluded that the adjusted method give better results in predicting the nervousness and therefore in this study is continued with using the adjusted formula. The MRP relevant nervousness measurement is excluded from further studies as it is the direct translation of the MPS nervousness as the only feature with a 100 % score on the R2. For the adjusted measurement formulas for in total 27 different MRP measurements, the feature selection in combination with the prediction models is performed. The results of the feature selection methods resulting in the best performance are shown in Table 21 in Appendix A.7. The results from the feature selection show us that not for every horizon and measurement type the same features are as important. Overall the following features came out of the study to be the most relevant: Requirement changes [*MPS*], StockStartDif [*SSD*], Lotsize Rule [*LSR*] Rounding Value [*RV*], Safety Stock in combination requirement rule [*SSr*] and the Safety Lead Time [*SLT*], on the complete horizon, the internal supply uncertainties are essential as well [*ISU1* and *ISU2*].

The prediction performance corresponding to features in Table 21 are shown in Figure 23. Figure 23 shows the R2 score and the Mean Absolute Error (MAE) of the best-selected combination of feature selection and prediction method is shown in Figure 24 and 25. From these results can be seen that the prediction accuracy increases by leaving out the bigger parts of the frozen horizon. The same result can be seen in by the result in the mean absolute error. The prediction model that showed the best result was the MLPR with one or two hidden layers and with five nodes each layer. The SVR gave similar results, but was in computation time much slower. The LR gave worse results on both the R2 score and the error value. Therefore in the further study, the MLPR is preferred.

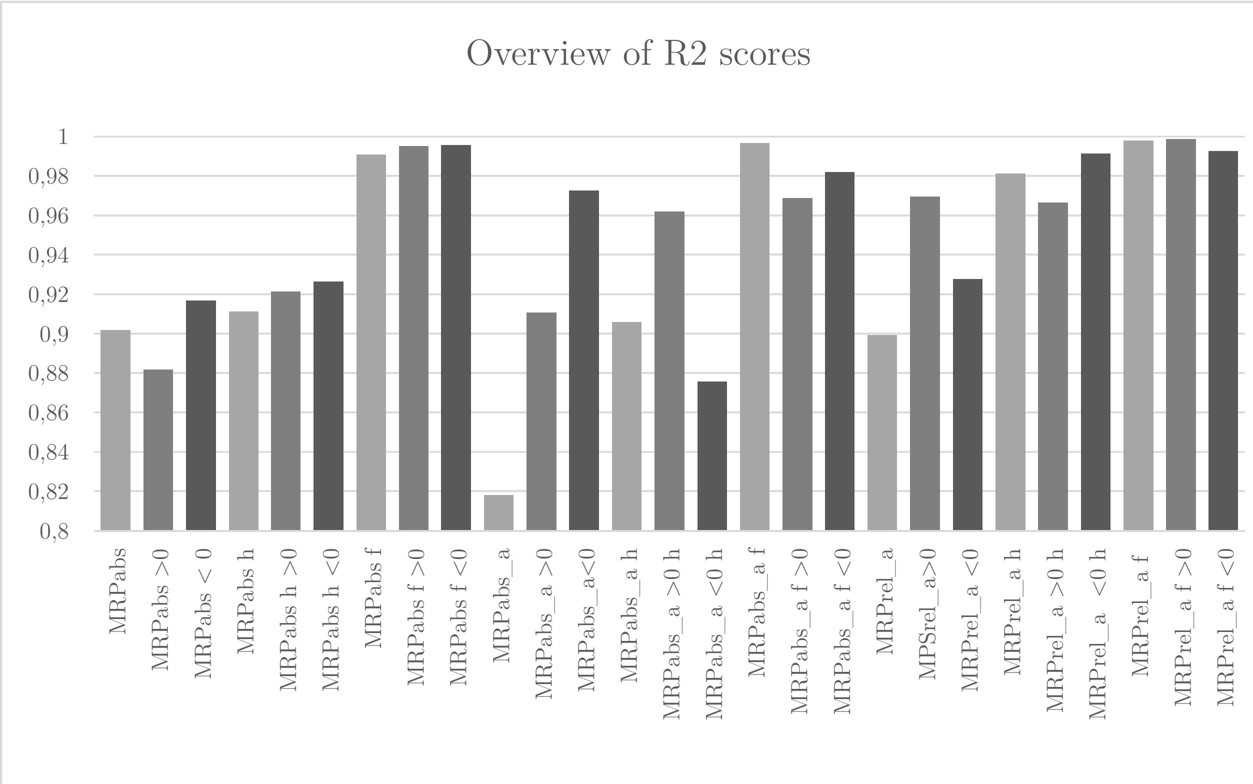

Figure 23: R2 scores of prediction models

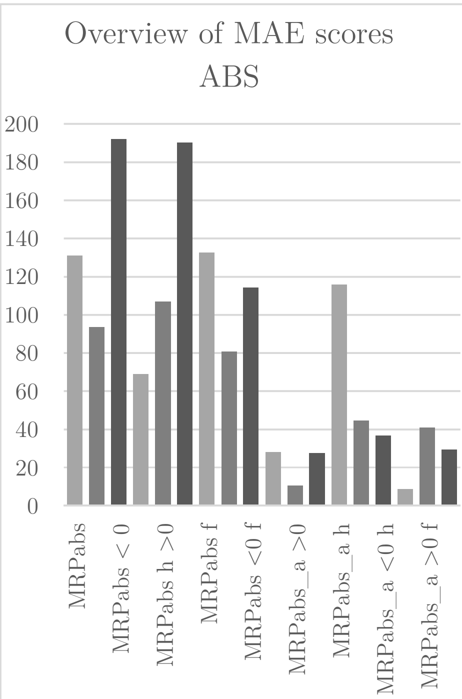

Figure 24: Overview of MAE on MRP-abs nervousness

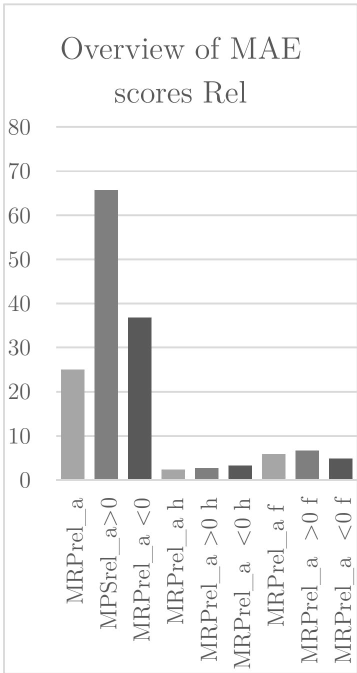

Figure 25: Overview of MAE on MRP-rel nervousness

6.5 Parameter influences

By using neural networks as regression models, the weights of the parameters into the model cannot be directly found. To find the parameter influences, a study can be done by taking the whole data set and for one change it the all different possibilities and compare the outcomes of the model. This analysis is done on the whole dataset for the hybrid horizon and the 'free' schedule horizon on all the MRP measurements as defined to be relevant for this study in chapter 4. However, the individual influences can be found with this analysis, the mutual dependencies cannot be shown.

The parameters that are selected to find their influence on are the: Lot Size (LS), the Safety Stock Rule (SSR), the Safety Lead Time (SLT) and the freezing period (FR). The figures provided show the influence of an increase in the parameters. Almost all the measurements are positives integer, for which an increasing graph shows a strengthening effect on the nervousness and a decreasing graph a dampening effect. However, the MRP rel_a <0 includes always a negative value. For these measurements, the logic is reversed and matches an increasing graph with a dampening effect and a decreasing graph in a strengthening effect.

Lot Size:

The influence of the Lot Size is captured in a range from 0.5 weeks, for the Lot-for-Lot (LFL) approach till 8 weeks.

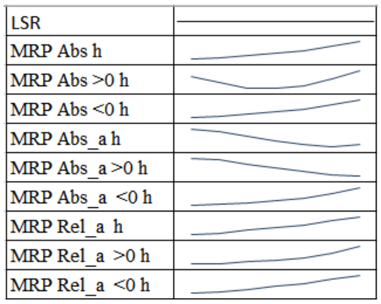

Figure 26 LSR-influence on nervousness h

On the horizon including partly the frozen and the 'free' horizon, referred to as 'h', the influence of the Lot Size parameter shows an increasing strengthening effect on the nervousness value, except for the absolute nervousness with criticality, which means that the absolute changes close to the start of the horizon are dampened.

On the 'free' schedule horizon, the influence seems to have a dampening effect on the absolute and absolute nervousness with criticality. On the relative nervousness, a strengthening effect is found for the negative requirement changes, and for the positive requirement changes a dampening effect is found up till the one before biggest Lot Size

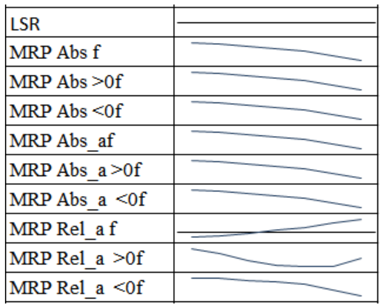

Figure 27: LSR influence on nervousness f

SSR. The influence of the SSR on the nervousness is only relevant in the period including a 'frozen' schedule and the first planned orders. This result is not seen on the horizon that only contains the 'free schedule' by the ignorance of net requirement differences at the start of the horizon. The range upon which the Safety Stock influence is tested between 0 and 200 % of weekly demand in steps of 5 %. The influence of the reorder quantity, which is the Safety Stock that is used to fulfill requirements, seems to have a dampening effect on the absolute nervousness as well as the relative nervousness including a quantity increase. On the absolute nervousness with criticality this dampening is only found on the complete requirement changes, but including the requirement change direction, a strengthening effect is found.

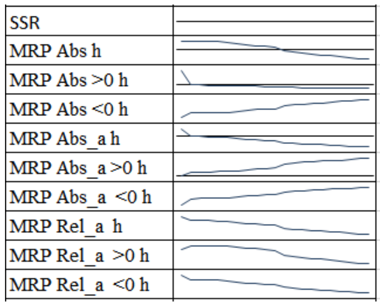

Figure 28: SSr influence on ervousness h

SLT. The result of the Safety Lead Time on the full horizon shows an increasing effect on the total number of changes. Although when a demand change occurs, both positively and negatively a dampening effect is being found. On all the other measurements a dampening effect is found, except for the MRP relative with alpha for decreasing demand. For this measurement, the graph is increasing but on negative values which means it is strengthening the negative relative MRP nervousness.

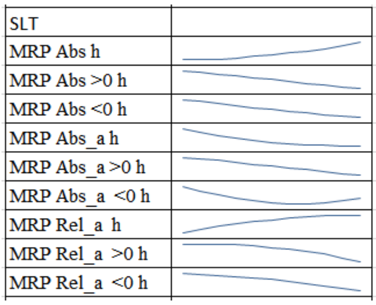

Figure 29 SLT influence on nervousness h

On the free-schedule horizon, the SLT results in a strengthening effect on all the measurements, except for the absolute nervousness measurements with positive demand changes, although this "not quantitative" parameter does not influence this nervousness in the free schedule horizon. Therefore is focused on the nervousness measurement including a time factor, which is found in the criticality. As expected does this SLT show that an increase in demand results in a strengthening effect on the nervousness, and a decrease in demand on a strengthening decreasing effect. This is the result of the gap between the MPS required date and the MRP replenishment date resulted from the SLT.

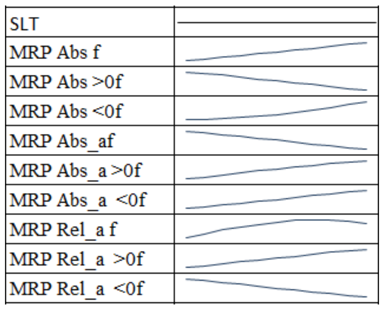

Figure 30 SLT influence on nervousness f

Rounding Value:

The influence of the rounding value is tested by either applying a rounding value factor or not. This test is only done on the dataset that has a rounding value set as their parameter setting.

On the hybrid horizon, for most the measurements a small, but dampening effect is found. The only exception is for the absolute measurements with and without alpha and on the relative measurement with criticality, with this value being negative and a decreasing slope, which shows a strengthening effect by the application of this parameter. The results on the 'free' horizon are similar to the results in the hybrid horizon, with the only difference that a dampening effect is found for demand increases on the absolute measurement, and a strengthening effect on the demand decreases.

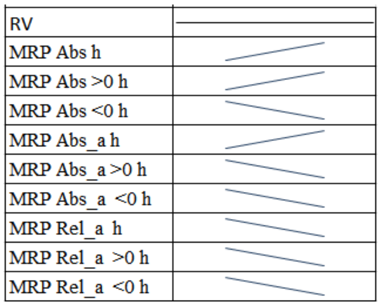

Figure 32: RV influence on nervousness h

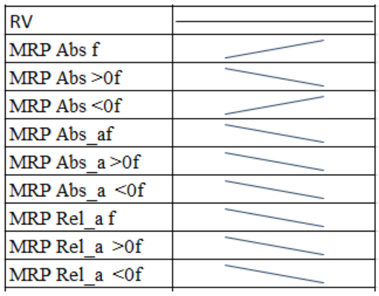

Figure 31: RV influence on nervousness f

Freezing period:

The influence of the freezing period is shown in Figure 33, from this figure can be concluded that there is a dampening effect from the length of the freezing period on the MRP nervousness on all the absolute measurements, which means that the total number of changes is dampened. On the relative measurement a strengthening effect is found, although, for quantity increases, this effect is not linear and dampens for longer freezing periods.

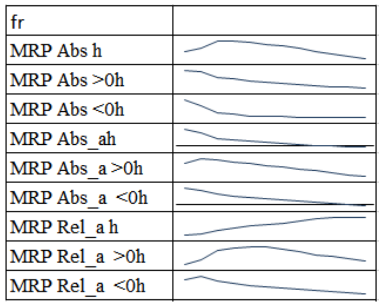

Figure 33: Fr influence on nervousness h

6.6 Conclusion.

Which variables and predictive model combination can be used to predict the MRP nervousness?

The machine learning regression methods applied in 6.3 have the possibility to include the mutual dependencies of the variables. Therefore these methods are useful in the full scope of nervousness reduction techniques. The results from the prediction models show us that including less or no frozen horizon, results in better prediction accuracy. This is due to the manual actions by the planners which occur in this frozen horizon and are hard to predict upon when they are performed not during the same replanning interval as the uncertainty or net requirement change leading to these actions. However, these actions are tried to buffer upon by the variables defined as ISU, ISU2 and the follow-ups of reschedule message. In the free schedule horizon, net requirement changes are only the result from either MPS changes or net requirement changes in the frozen period which is included as a cumulative result from this period. The hybrid period includes the transition period between the free and frozen horizon in which lots of the changes occur. Moreover, in this period the direct results from supply uncertainties upon production order delays are not included, which is left out of the scope in this research. Therefore this period is chosen as the period on which MRP parameterization under cost considerations will be applied upon.

The variables that can predict the MRP nervousness most accurate depends on the horizon that is included in the MRP nervousness. From the variables that describe the uncertainties, the MPS uncertainties are always included. In the frozen horizon and hybrid horizon, the Internal supply uncertainties (ISU's) needs to be implemented to define the manual actions performed by planners upon the supply uncertainties. Moreover, the reschedule message follow-ups are included in the hybrid and complete horizon, as these are manual actions that lag behind net requirement changes on quantity and date. On the hybrid and free horizon, the net start stock requirement changes should be added as an influencer of the net requirement changes at the start of these horizons.

For the MRP parameters, the Lot Size rule, the Safety Stock in combination with the net requirement rule, the rounding value and the Safety Lead Time are selected as the most important features. The inclusion of the frozen horizon length is also found as being from vital importance. Upon the material specifications, some specific vendors and material groups are selected upon. The influence of the customers is probably related to their demand pattern and their uncertainty. For one of these customers the usage of consignment stock has been found, in which the transition from a demand forecast to the sales order is postponed till the delivery of product and thus results into more nervousness with a high criticality factor.

In the regression methods, some conclusions are made upon the mediating effect of the MRP parameters on the relation between the MPS and MRP nervousness, upon the full, 'hybrid' and the 'free' horizon. Most of the effects found are similar between this regression study and the graphs shown on the parameter influence. Important to keep in mind is that for several parameters their influence on the nervousness depends on the sort of measurement, the presence of a net demand change and on the horizon on which this parameter is studied upon.

Upon the Lot Size, a strengthening effect is measured in the free and hybrid horizon for the relative factor with criticality during the regression analysis. This is in line with the results from the prediction model. From the literature, described in 4.1.1, upon the nervousness the LFL method is not recommended leading to more nervousness, while in the literature the nervousness is only measured upon the absolute changes it cannot be compared with the finding upon the relative measurement. However, on the absolute measurement, the same result as in the literature is found in the free horizon, although in the hybrid horizon the contrary result has been found.

Upon the Safety Stock used to fulfill requirements in the frozen horizon, a dampening is found on both horizons in both the regression analyses and the perdition model. These two findings are in line with the results from 4.1.2.

Moreover, the rounding value shows a strengthening effect on the Nervousness and for the Minimum and Maximum Lot Size this effect depends on the nervousness measurement factor. For the planning technique of applying a frozen horizon length, the regression analysis showed a moderating effect on the absolute changes with criticality, with exclusion from the group with minor frozen horizons. Whereas these regression methods show some results that can be used in the research of reducing the MRP nervousness, the mutual dependencies of these parameters is not tested upon.

Chapter 7

Proposing MRP parameters under cost considerations

In this chapter, the focus is on creating a costing model that can be used in reducing the total costs including costs of the MRP nervousness by MRP parameterization. With this costing model answers can be given to:

Which MRP parameter settings minimize overall costs of the MRP system?

7.1 Building the model

Prescribing MRP parameters leading to Nervousness reductions can be done by applying a brute force technique on the prediction model proposed in 6.3. This technique includes the creation of the complete set for combinations of these parameters and test them into the nervousness model. The combination of parameters that, with the uncertainty values gives the lowest overall cost is optimal in the MRP nervousness optimization within the boundaries of the created model.

In chapter 3, different MRP nervousness measurements techniques are shown, with deviations between the absolute or relative changes, different horizons and the addition of criticality.

The most relevant nervousness to reduce at PT by focusing on the top-level products is the relative changes with criticality, which imply net demand changes over the planning horizon, as well as the absolute changes implying the total stability of the system. On the relative MRP nervousness, a change will directly lead to changes of requirements in the complete horizon, influencing the whole supply chain. Moreover, the changes leading to a positive value of this nervousness are more critical than with a negative value. Therefore, in this chapter, the reduction of the positive relative MRP nervousness with criticality is leading.

On the other hand, the total number of requirements as described with the absolute nervousness will result in lack of stability, overview and performance based on focus and data integrity and cleanliness of the planning system. Therefore, this nervousness measurement is included as well.

The focus of this MRP nervousness reductions is on the 'hybrid' schedule horizon. The reason for excluding the first three weeks of the horizon, based on the 'frozen' period, is to exclude the nervousness from supply uncertainties and focus on the control of the planning system at PT driven by the direct customer demand on the final products. Moreover, it can be concluded from the previous chapter that the uncertainty on this horizon can be predicted with better accuracy and therefore will show more accurate prescriptions upon nervousness reduction techniques.

The MRP parameters that are varied are the Lot Size Rule, the Safety Stock rule multiplied with the Safety Stock level, and the Safety Lead Time. The scope on which combinations between these variables can be tested is equal to the scope on which there is a variability in the input parameters of the model. Therefore the Lot Sizing rule is either LFL or POS with periods between one week and eight weeks. For the Safety Stock parameter, the rule that is applied is in the set [0; 0,5; 1] multiplied with the SS value in the range between [0 and 100%] of the weekly demand] in steps of 5, rounded up to whole integers. Moreover, the SLT is varied between one and ten days.

7.2 Cost considerations

The cost considerations for the MRP parameterization are split into holding cost, production set-up cost and a penalty cost for the nervousness.

7.2.1 Holding cost

The holding cost includes the expected inventory level multiplied with the costs for holding the product. Cost for actually holding the product includes the cost for actually holding the product as for the Return On Investment (ROI). This cost is being set on 10% of product value per year. This results in a factor of 0.03% of the value per day. The expected inventory level is derived from the average weekly demand in combination, with the Safety Stock level, the Safety Lead Time and the Lot Size rule that will be applied. Independent of the setting of the parameters, there will be a holding cost based upon the manufacturing lead times and the safeties applied on lower levels of products in the bill of materials. These holding costs are independent and therefore left out of the scope in this cost calculation. The expected holding cost formula applied will take into account the expected daily demand

and in combination with the Lot Size rule, the expected inventory will be calculated. Calculating the expected inventory with the expected daily demand assumes that the demand is proportionally distributed over the Lot Size period. However, this is only righteous if, within the period of supply from a lot, multiple requirement points are existing. Therefore, for calculating the expected stock level, a factor, *LSF*, is used to show the relation between the numbers of requirement points divided by the expected number of replenishment orders. When this value is larger or equal to two, the formula as proposed with the expected average daily demand is rectified. This value being smaller than one assumes that the requirement lines are directly fulfilled with the replenishment orders and therefore does not include extra holding cost. If this factor is between 1 and 2, it is reduced with one, and this factor is multiplied with the expected stock over the period of supply of the lot. These calculations upon the expected inventory level are shown with equation 7.2-2. The calculation upon the *LSF* is based upon the number of requirement orders, *NMPS,* divided by the number of expected number of setup, *E[S],* orders for planning cycle k. The expected number of setups is based upon the original number of setups at a planning cycle multiplied with the factor of the new LSR and the original LSR rule as described by equation 7.2-5. If the original or new LSR is the LFL and therefore being indicated with 0.5 this, the value is round up to 1.

The Safety Lead Time is added as it includes the extra days of this inventory being at stock. The Safety Stock level will be added to the expected inventory quantity. The holding cost is calculated based upon the information from the MRP plan if this plan is active for more than one day, the costs are multiplied with the active days.

$$C_{h,i,k} = h_i * E[I_{k,i}] * (M_{k+1} - M_k) \qquad 7.2\text{-}1$$

$$E[I_{k,i}] \begin{cases} ((SLT_i) * E[D_i] + SSi) & if\ LSF_{k,1} \leq 1 \\ \left(\left(\frac{LSR_i}{2} * (LSF_{k,i} - 1) + SLT_i\right) * E[D_i] + SSi\right) & if\ 1 < LSF_{k,i} \leq 2 \\ \left(\left(\frac{LSR_i}{2} + SLT_i\right) * E[D_i] + SSi\right) & if\ LSF_{k,1} \geq 2 \end{cases} \qquad 7.2\text{-}2$$

$$LSF_{k,i} = \frac{NMPS_{k,i}}{E[S_{k,i}]} \qquad 7.2\text{-}3$$

$$E[S_{k,i}] = \frac{LSR_{i,o}}{LSR_{i,}} * \frac{E[S_{k,o}]}{h_k} \qquad 7.2\text{-}4$$

$$h_i = P_i * \frac{0.1}{365} \tag{7.2-5}$$

M_k = *The beginning of the planning cycle k*

h_i = *The holding cost of product i per day*

$E[I_{k,i}]$ = *Expected inventory at schedule k for product i*

$E[D_i]$ = *Expected daily demand*

SSi = *Safety Stock of product i*

SLT_i = *Safety Lead Time of product i*

P_i = *Product value of product i*

LSR_i = *Lot size rule of product i in days*

LSR_i = *Lot size rule of product i in days*

$E[S_{k,1}]$ = *Expected number of set-ups for product i in planning cycle k*

$E[S_{k,o}]$ = *Original number of set-ups for product i in planning cycle k*

$NMPS_{k,i}$ = *Number of requirement orders in cycle k for product i*

7.2.2 Nervousness cost

The cost of rescheduling is introduced by Carlson et al. (1979). They described that the disruption of a previously established schedule results in additional costs somewhere in the whole system. Pujawan (2004) suggested that the schedule change cost depends on the criticality of the period in which the change took place. Therefore, the MRP nervousness measurements including criticality can be used to follow up Pujawan his proposed method. Adding a cost factor to the measured nervousness would include the cost that is made for 'escalation costs', 'cost of premium components', 'holding cost of components' and all the other extra work that is the result of a schedule change. There is a difference between the cost for an RPNC and RNNC. The cost of the RPNC is related to the escalation costs and possible, component and capacity issues throughout the whole supply chain. To minimize this disruption, for this nervousness a 'penalty' cost of 2 % of the product value is assigned. On the other hand, the cost for the RNNC includes the extra holding cost in combination with dead stock possibilities. For the negative nervousness, the same cost as the holding cost is applied, which is 10% on a yearly base, the further away on the horizon, the less the value. With the alpha factor decreasing with 0.1 per week, a negative alpha factor of 0.1 means that one product is one week longer on stock. Therefore the cost factor that can be assigned is 10% times the value of the product divided by 52. Which is equal to the value of the product times approximately 0.005, equal to 0,5% of the product value. This value being closer to zero on the longer horizon is equal to the assumption that the percentage of components being on stock, will get lower on a further horizon. For the A, there is no difference between the positive and negative nervousness. Therefore, a general penalty cost can be applied for this factor. This value will be set to 0.002 which is equal to 0,2% of the Product value.

$$C_{n,i,k} = C_{n,i,k_{absa}} + C_{n,i,k_{rela}} \quad \text{7.2-6}$$

Relative nervousness costs with criticality:

$$C_{n,i,,krela} = C_{n,i}^{+} * \mathrm{RPNC}_{k,i} + C_{n,i}^{-} * RNNC_{k,i} \quad \text{7.2-7}$$

Absolute nervousness costs with criticality:

$$C_{n,i,k,absa} = C_{n,i} * ANC_{k,1} \quad \text{7.2-8}$$

With

$$C_{n,i}^{a+} = P_i * 0.05 \quad \text{7.2-9}$$

$$C_{n,i}^{a-} = P_i * 0.002 \quad \text{7.2-10}$$

$$C_{n,i}^{absa} = P_i * 0.002 \quad \text{7.2-11}$$

$C_{n,i}^{+}$ = *Nervousness+ cost percentage of product i*

$C_{n,i}^{-}$ = *Nervousness- cost percentage of product i*

$C_{n,i}^{abs}$ = *Nervousness abs cost percentage of product i*

7.2.3 Production setup cost

The set-up cost is related to the cost of starting up a batch. This set-up time can be split into the time for picking the required components and tools and setting up the needed machinery. As this data is available for every product. These directly required hours are translated into a set-up cost by multiplying the set-up time with the average labor cost a 50 euros an hour. The setup cost will be multiplied with the expected number of setups for a production plan. This number is derived from the expected number of setups in the horizon for the original schedule times the multiplier between the old and new Safety Stock. The number of set-ups cannot be larger than the number of requirement orders. Therefore, this number of setups is the maximum of the expected number of setups and the number of required orders. The expected number of setups is and divided by the horizon length in days, which results in the expected number of setups per day. This expected number of setups per day is multiplied with the active number of days of the MRP schedule.

$$C_{s,i,k} = s_i * E[S_{k,1}] * \ (M_{k+1} - M_k) \qquad 7.2\text{-}12$$

$$E[S_{k,1}] = \frac{Max\left(\frac{LSR_{i,o}}{LSR_{i,}} * E[S_{k,o}], NMPS_{k,i}\right)}{h_k} \qquad 7.2\text{-}13$$

$$s_i = t_{s,i} * lc \qquad 7.2\text{-}14$$

s_i = *Set- up cost for product i*

$t_{s,i}$ = *Set-up time for product i*

lc = *Labor cost per hour=50€*

h_k = *Horizon length*

7.2.4 Costing formula

The costing formula including the Holding, Nervousness and Setup cost look as follows:

$$C_{i,k} = C_{h,i,k} + C_{n,i,k} + C_{s,i,k} \qquad 7.2\text{-}15$$

$$Total\ cost\ i = \sum_{\forall k>1} C_{i,k} \qquad 7.2\text{-}16$$

With Objective:

$$MIN\ Total\ cost\ i = \sum_{\forall k>1} C_{i,k} \qquad 7.2\text{-}17$$

7.3 Results of the model with MRP nervousness predictions

For the selected set of 15 products resulting from the ABC-study prescribed MRP parameters are to be found. The calculations are done as described with formula 7.2-16. The nervousness factor is predicted with the methods as described in the previous chapter. The parameter setting resulting in the lowest total cost can be used as the prescribed parameter setting.

The results related to the minimization of the total costs from the combination of holding cost, the setup cost and minimizing the absolute as well as the relative nervousness with criticality is shown below. The results of the parameter settings can be found in this table. In this table, the original values are indicated with a [old] and the new proposed values are indicated with [new]. When only focusing on the minimization of the MRP nervousness, the proposed shown in the last three columns of Table 9 are obtained.

While the influence of the SLT is hard to validate in the frozen horizon, the results with excluding the SLT is calculated upon as well. The parameters that have been found by minimizing the expected total costs without the inclusion of the SLT are shown in Table 10.

The results show us that a lot of costs can be minimized while lowering the periods of supply of the Lot Sizes for products with a low set-up cost. For these products, the expected MRP nervousness costs seem to be drastically lowered, as well as the holding cost that added while having bigger Lot Sizes. From these findings can be learned that for products with high LS and a small ratio between set-up and holding cost the most cost minimization can be realized. Moreover can be learnt that the additional holding cost that is added while making use of SS can be worth in reducing the expected nervousness costs. Finally can be learnt that with the additional holding cost and the increase in nervousness on the 'free' horizon for the SLT, this parameter only must be set while facing high lead time uncertainties.

Table 9: prescribed MRP parameters

PN	LS new	SSR new	SLT new	LS old	SSR old	SLT old	% Total cost Dif	LS MRP	SSR MRP	SLT MRP
p1	2	0	1	2	3	4	-47,74	1	0	1
p2	0,5	0	1	2	0	4	-50,90	0,5	0	1
p3	0,5	0	1	1	8	2	-15,87	0,5	0	1
p4	0,5	0	1	1	0	2	-7,81	0,5	0	1
p5	1	93	1	1	425	4	-27,40	0,5	553	1
p6	0,5	0	1	1	13	2	-8,76	0,5	0	1
p7	1	82	1	0,5	80	2	-2,51	0,5	82	1
p8	0,5	0	1	1	1	4	-34,48	0,5	0	1
p9	4	0	1	4	0	4	-4,18	0,5	8	1
p10	4	8	1	4	40	4	-22,38	0,5	79	1
p11	8	0	1	4	0	4	-7,25	0,5	0	1
p12	0,5	0	1	1	0	2	-3,93	0,5	0	1
p13	1	0	1	0,5	10	2	-11,98	0,5	0	1
p14	0,5	6	1	1	10	2	-2,06	0,5	21	1
p15	8	0	1	4	1	4	-60,17	0,5	0	1

Table 10: prescribed MRP parameters without SLT

PN	LS new	SSR new	LS old	SSR old	% Total cost Dif	LS MRP	SSR MRP
p1	0,5	0	2	3	-17,89	0,5	0
p2	0,5	0	2	0	-43,18	0,5	0
p3	0,5	0	1	8	-13,97	0,5	0
p4	0,5	0	1	0	-0,20	0,5	0
p5	1	93	1	425	-25,36	0,5	369
p6	0,5	0	1	13	-7,51	0,5	0
p7	1	82	0,5	80	0,05	0,5	82
p8	0,5	1	1	1	-4,96	0,5	1
p9	4	0	4	0	0,00	0,5	8
p10	4	8	4	40	-16,69	0,5	79
p11	8	0	4	0	-7,26	0,5	0
p12	0,5	0	1	0	-0,02	0,5	0
p13	1	0	0,5	10	-3,49	0,5	0
p14	0,5	6	1	10	0,00	0,5	21
p15	8	0	4	1	-50,27	0,5	0

7.4 Results of the model from MRP nervousness findings

Next to the results from of the nervousness prediction model, the parameters are proposed by rules of thumb. These rules of thumb are proposed based upon the finding during the data analysis, the detailed research and the literature study. This set of rules should deliver the basic guidelines for the MRP parametrization in a situation where the brute force approach and parameter predictions are not applicable or as a test upon the results of the brute force method. This process should contain the analysis upon historical or expected nervousness, customer arrangements and production risks, resulting in proposals for the LSR, the SSR, the Freezing Period and the SLT. For this research, a simplified process is proposed for determining the LSR and the SSR. For products without historical data, an aggregated set of data should be used of products with similarities in demand and supply uncertainties and upon demand patterns. The process contains three clear steps.

Step 1. First is started with the calculation upon the optimal LSR based upon the cost calculation formula for the holding cost vs. the setup cost. In this chapter, this is based on historical data, with the formulas defined by 7.2-15 without the inclusion of the part of the nervousness cost.

Step 2. Afterwards, the historical MRP nervousness results are analyzed based upon the matrices proposed in chapter 3.7. This process is started with the nervousness that occurs in the frozen period. The average gross requirement changes in this period (MRP-rel) is chosen as the reorder quantity level, the Safety Stock that can be used to fulfill gross requirements. This rule is similar to the finding of Kadipasaoglu and Sridharan (1995) which determined the SS quantity to be equal to the standard deviation of the forecast error.

Step 3. With the found result that requirement changes in the free-schedule period can lead to lots of MRP nervousness while using big periods of supply. The Period of Supply defined in step 1 should be analyzed upon the risk of requirement changes. Using historical MRP nervousness data, the focus should be on the RN and RNC. If these two nervousness measurements show significant changes, the optimal Periods of Supply showed be lowered. For the RN this value is set upon 1% of the total schedule value. For products having a bigger value than 1% of the average RN, a smaller POS is advised, as this increase is always brought forward to the start of the lot in the POS it occurs. For the RNC, this value is divided with the MPSrel with criticality. The resulting factor (F) shows the strengthening or dampening effect upon the RNC of the original POS. If the original POS is equal to the proposed POS and F is bigger than one, a smaller POS is suggested. If the original POS is smaller than the proposed POS and the factor being bigger than one, an even smaller POS can be suggested, although the consideration upon increasing set-up cost should be made. If the original POS is bigger than the proposed, and the factor is smaller than one, this bigger POS is suggested, as it dampens the influence of the MPSrel with criticality. Although, when F is bigger than one, a decision is made upon the value of the average RN.

The results from this three-step approach can be found in Table 11

Table 11: Parameter proposals from the three steps approach

Step 1	LSR
p1	**2**
p2	**1**
p3	**1**
p4	**0,5**
p5	**1**
p6	**0,5**
p7	**1**
p8	**1**
p9	**4**
p10	**4**
p11	**8**
p12	**0,5**
p13	**1**
p14	**1**
p15	**8**

Step 2	LSR	SSR
p1	2	0
p2	1	0
p3	1	**1**
p4	0,5	**2**
p5	1	360
p6	0,5	**41**
p7	1	0
p8	1	0
p9	4	0
p10	4	**2**
p11	8	**24**
p12	0,5	**79**
p13	1	0
p14	1	**3**
p15	8	0

Step 3	LSR	SSR
p1	2	0
p2	1	0
p3	1	**1**
p4	0,5	**2**
p5	1	**360**
p6	0,5	**41**
p7	1	0
p8	1	0
p9	**2**	0
p10	**2**	**2**
p11	**4**	**24**
p12	0,5	**79**
p13	1	0
p14	1	**3**
p15	**4**	0

For products that do not have the historical data used as an input in this three-step approach, Step 2 and Step 3 should be modified. For Step 2, if possible, data of similar products upon production and demand uncertainty in the first period can be used. For Step 3, equal to Step 2, the historical data of products showing similarity upon demand uncertainty can be used, and can even be extended with the customer agreements that are in place upon flexibility.

Chapter 8

Validating the proposed MRP parameters

To find the result of the prescribed planning approach as concluded in the previous chapter, a simulation is executed. This simulation should answer to:

What are the simulated cost minimizations from the proposed MRP parameters?

To validate if the proposed MRP parameters in the previous chapter result in cost minimizations a simulation study is created. In this simulation, the MRP logic as in place at PT is recreated. Based upon the requirements and the frozen production orders in historical MRP plans, replenishment orders are created by the MRP algorithm with the set of proposed MRP parameters given as input. This recalculation of MRP plans is done for a period of four months. The simulation includes calculation of the MRP schedules with the proposed set of MRP parameters, the nervousness is measurement and the costs are calculated with the formulas provided in the previous chapter. The primary goal of this study is to validate if the expected cost minimizations found in the previous chapter indeed result in these minimizations.

The simulation includes changes the Lot Size rule, the Safety Stock rule and the Safety Lead Time.

In the first part of this chapter, the results from chapter 7.3 are tested. These results are shown in chapter 8.1. In 8.2 the simulation study is executed for the results obtained in 7.4 which includes the MRP proposals from the method based upon the literature and detailed MRP study. The results of this chapter are wrapped up in the conclusion section.

8.1 Evaluation of the model with MRP nervousness prediction

The results of the planning adjustments are shown by the differences in total costs as calculated with the proposed cost model. The results are shown in Table 12 to Table 15. Table 12 shows that the proposed parameters give a better result in 80% (12/15) with a cost-benefit of at least 1 percent comparing to the old parameters. The cost improvements are between 1.1 and 40%. For 13% (2/15) the results are equal within a 1 percent margin. For 1 product the proposed parameter gave worse results related to total costs, which was around 4% worse than the original settings of parameters. Upon the MRP nervousness reduction, the results are 47% (7/15), 14% (2/15), 40% (6/15) for better, equal and worse results between the proposed and originally implemented values.

Next to the analysis of the results of the three proposed parameters, an analysis on the ignorance of the SLT changes is done as well, are shown in Table 13. This exclusion is analyzed with the reason that their influence on the frozen period cannot be tracked into the simulation study, but only their negative influence in the free period on holding costs as well as nervousness costs. The ignorance of the SLT value proposed by the model gives better results for 47% (7/14) and equal results for 47% (7/15) of the proposed parameter settings as well. The improvements are between 3.9% and 40%. For the same two products as with the inclusion of the SLT, only worse results have been found. Upon the MRP nervousness reduction, the results are 35% (4/15%), 53 % (8/15) and 20% (3/15) for better, equal and worse results between the proposed and initially implemented values.

The third analysis, shown in Table 14 and Table 15, is related to the parameter setting which from the model is expected to result in minimum MRP cost. Including or excluding the Safety Lead Time resulted in Nervousness reductions for 60 % (9/15), equal results 20% (3/15) and worse for 20% (3/15).

Table 12: Results of total minimum cost model with SLT

1	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p1	3656,74	4897,83	-1241,10	-25,34	3043,22	3878,26	-835,05	-21,53
p2	10324,72	17241,23	-6916,50	-40,12	9375,68	13124,20	-3748,52	-28,56
p3	5229,07	5367,03	-137,96	-2,57	4394,48	4288,30	106,18	2,48
p4	5684,76	5797,93	-113,17	-1,95	5257,22	5194,78	62,44	1,20
p5	6236,27	7938,17	-1701,90	-21,44	5184,28	6300,72	-1116,44	-17,72
p6	24622,72	25258,41	-635,68	-2,52	23269,54	23637,53	-367,99	-1,56
p7	11795,09	11880,23	-85,13	-0,72	8989,55	8753,41	236,13	2,70
p8	5270,97	7037,81	-1766,84	-25,10	4827,29	6336,46	-1509,18	-23,82
p9	8410,00	8666,42	-256,42	-2,96	4566,94	5062,90	-495,96	-9,80
p10	6030,34	6700,92	-670,58	-10,01	2454,38	2646,22	-191,84	-7,25
p11	5667,72	5442,81	224,91	4,13	4168,65	3875,50	293,16	7,56
p12	15198,44	15410,07	-211,64	-1,37	14737,24	14737,24	0,00	0,00
p13	5355,11	5519,25	-164,14	-2,97	5061,49	5061,49	0,00	0,00
p14	14940,60	14903,13	37,46	0,25	12360,71	12160,02	200,69	1,65
p15	4143,80	5094,44	-950,64	-18,66	1894,44	1836,26	58,18	3,17

Table 13: Results of MRP nervousness minimum cost model excluding SLT

2	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p1	3631,51	4897,83	-1266,32	-25,85	2887,16	3878,26	-991,11	-25,56
p2	10324,72	17241,23	-6916,50	-40,12	9375,68	13124,20	-3748,52	-28,56
p3	5229,07	5367,03	-137,96	-2,57	4394,48	4288,30	106,18	2,48
p4	5684,76	5797,93	-113,17	-1,95	5257,22	5194,78	62,44	1,20
p5	7228,39	7938,17	-709,78	-8,94	5800,01	6300,72	-500,71	-7,95
p6	24622,72	25258,41	-635,68	-2,52	23269,54	23637,53	-367,99	-1,56
p7	11834,49	11880,23	-45,74	-0,38	8989,55	8753,41	236,13	2,70
p8	5270,97	7037,81	-1766,84	-25,10	4827,29	6336,46	-1509,18	-23,82
p9	8410,00	8666,42	-256,42	-2,96	4566,94	5062,90	-495,96	-9,80
p10	8619,42	6700,92	1918,50	28,63	4075,06	2646,22	1428,83	54,00
p11	5440,02	5442,81	-2,79	-0,05	3331,78	3875,50	-543,72	-14,03
p12	15198,44	15410,07	-211,64	-1,37	14737,24	14737,24	0,00	0,00
p13	5300,36	5519,25	-218,89	-3,97	5061,49	5061,49	0,00	0,00
p14	15398,92	14903,13	495,78	3,33	12475,56	12160,02	315,54	2,59
p15	11023,02	5094,44	5928,58	116,37	1183,20	1836,26	-653,06	-35,56

Table 14: Total and MRP cost differences excluding SLT

1	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p1	4125,53	4897,83	-772,30	-15,77	2943,51	3878,26	-934,75	-24,10
p2	11345,98	17241,23	-5895,24	-34,19	9733,93	13124,20	-3390,27	-25,83
p3	5195,79	5367,03	-171,25	-3,19	4276,87	4288,30	-11,44	-0,27
p4	5752,39	5797,93	-45,54	-0,79	5194,78	5194,78	0,00	0,00
p5	7515,95	7938,17	-422,22	-5,32	6213,28	6300,72	-87,44	-1,39
p6	25133,26	25258,41	-125,15	-0,50	23637,53	23637,53	0,00	0,00
p7	11820,26	11880,23	-59,97	-0,50	8753,41	8753,41	0,00	0,00
p8	6703,90	7037,81	-333,91	-4,74	6003,51	6336,46	-332,95	-5,25
p9	8666,42	8666,42	0,00	0,00	5062,90	5062,90	0,00	0,00
p10	6397,47	6700,92	-303,45	-4,53	2576,34	2646,22	-69,89	-2,64
p11	6538,26	5442,81	1095,45	20,13	3676,77	3875,50	-198,73	-5,13
p12	15357,53	15410,07	-52,55	-0,34	14737,24	14737,24	0,00	0,00
p13	5569,91	5519,25	50,66	0,92	5160,97	5061,49	99,48	1,97
p14	14933,59	14903,13	30,45	0,20	12172,71	12160,02	12,69	0,10
p15	4210,36	5094,44	-884,08	-17,35	1901,01	1836,26	64,74	3,53

Table 15: Total and MRP cost differences excluding SLT

2	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p1	4125,53	4897,83	-772,30	-15,77	2943,51	3878,26	-934,75	-24,10
p2	11345,98	17241,23	-5895,24	-34,19	9733,93	13124,20	-3390,27	-25,83
p3	5195,79	5367,03	-171,25	-3,19	4276,87	4288,30	-11,44	-0,27
p4	5752,39	5797,93	-45,54	-0,79	5194,78	5194,78	0,00	0,00
p5	7598,86	7938,17	-339,31	-4,27	6213,28	6300,72	-87,44	-1,39
p6	25133,26	25258,41	-125,15	-0,50	23637,53	23637,53	0,00	0,00
p7	11882,36	11880,23	2,14	0,02	8753,41	8753,41	0,00	0,00
p8	6703,90	7037,81	-333,91	-4,74	6003,51	6336,46	-332,95	-5,25
p9	9108,97	8666,42	442,55	5,11	4927,29	5062,90	-135,61	-2,68
p10	8682,89	6700,92	1981,97	29,58	3868,14	2646,22	1221,92	46,18
p11	5954,80	5442,81	511,99	9,41	3676,77	3875,50	-198,73	-5,13
p12	15357,53	15410,07	-52,55	-0,34	14737,24	14737,24	0,00	0,00
p13	5514,27	5519,25	-4,98	-0,09	5160,97	5061,49	99,48	1,97
p14	15393,54	14903,13	490,41	3,29	12287,57	12160,02	127,55	1,05
p15	11188,87	5094,44	6094,43	119,63	1198,84	1836,26	-637,42	-34,71

8.2 Evaluation of the model from MRP findings

The parameter prescription by the steps defined in 7.4 is evaluated in the same way as prescribed in 7.1. The results are shown in Figure 35 and Figure 34 and in Table 16 till Table 18.

After step one, 53% (8/15) of the proposed parameters showed cost reduction within 1,25% and 32 %. For 34 (5/15) the total costs were equal to the original situation and for 13 % (2/15), worse results are obtained from the parameter setting. After applying the negative reorder quantity in step two, this distribution is 60% (9/15), 33 % (5/15) and 7% (1/15). After the LSR addition in step three, the same distribution is found. Between the first and the second step, the total cost for two out of eight is decreased, the other modifications did not have any significant result in the total costs. Between the third and the first step, for two products the total cost is decreased drastically (15 and 17 %), and for the one product, the total cost is increased (8%).

When only is focused on the reduction of MRP nervousness costs after step one, 33 % (5/15) shows better results, 40% (6/15) shows equal results and 37% (4/15) resulted in worse results, under the same conditions as defined in 7.2 for MRP nervousness reduction. After step two the same results occur upon the number of better, similar and worse findings occurs. After the last step 40% (6/15) shows a decrease in MRP costs, for 47% (7/15) percent a similar result is obtained and for 13 percent (2/15) a worse result is obtained. After the second step, for one product, the MRP nervousness is decreased by 5 % and one is decreased by 20%. Upon the other products, no significant changes have been found. After the third step, the results upon the nervousness costs is that for two products this cost has been dropped with more than 18% and for the other two products the results are equal to the results from the first step.

Lowering the SLT gives 100 % results in lower costs but by not measuring the direct influence of the SLT as buffering effect om the exception messages do not clarify this result the frozen period, where the result would be reversed.

The results of the ‘simplified’ rules of thumb proposed upon finding the values of the Safety Stock and the Lot Size rule with costs assigned to holding costs, setup costs and the addition of MRP nervousness cost show the perspective to be efficient in MRP nervousness reduction under cost considerations.

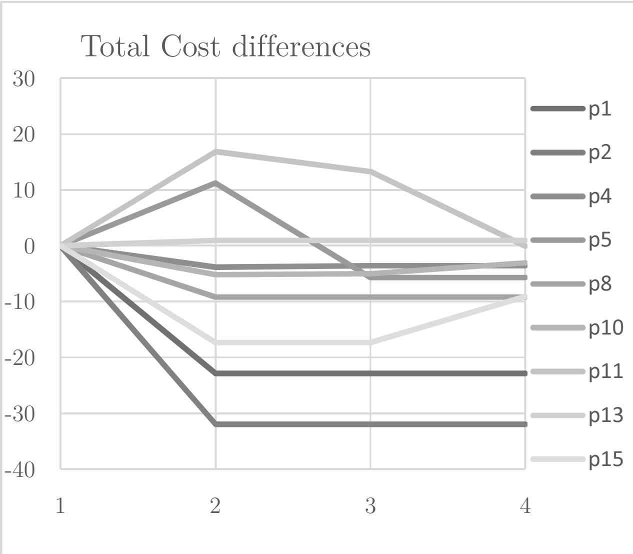

Figure 35: Total cost result from the three step approach in %

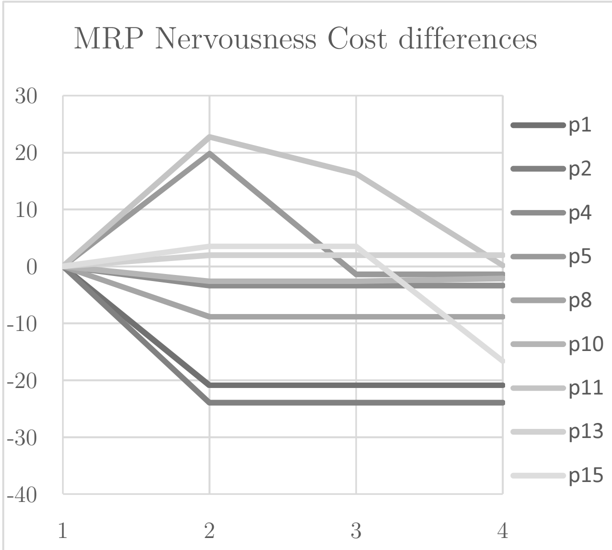

Figure 34: MRP cost result from the three step approach in %

Table 16: Total and MRP cost differences after step 1

1	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p1	3777,58	4897,83	-1120,25	-22,87	3068,15	3878,26	-810,12	-20,89
p2	11727,57	17241,23	-5513,65	-31,98	9978,59	13124,20	-3145,61	-23,97
p3	5195,03	5367,03	-172,00	-3,20	4276,87	4288,30	-11,44	-0,27
p4	5575,43	5797,93	-222,50	-3,84	5018,93	5194,78	-175,85	-3,39
p5	8829,76	7938,17	891,58	11,23	7548,63	6300,72	1247,91	19,81
p6	25133,26	25258,41	-125,15	-0,50	23637,53	23637,53	0,00	0,00
p7	11731,65	11880,23	-148,57	-1,25	8752,40	8753,41	-1,01	-0,01
p8	6390,97	7037,81	-646,84	-9,19	5774,61	6336,46	-561,85	-8,87
p9	8665,77	8666,42	-0,65	-0,01	5062,44	5062,90	-0,45	-0,01
p10	6353,54	6700,92	-347,38	-5,18	2576,34	2646,22	-69,89	-2,64
p11	6359,74	5442,81	916,93	16,85	4755,95	3875,50	880,46	22,72
p12	15357,53	15410,07	-52,55	-0,34	14737,24	14737,24	0,00	0,00
p13	5570,52	5519,25	51,27	0,93	5162,01	5061,49	100,52	1,99
p14	14809,55	14903,13	-93,58	-0,63	12164,55	12160,02	4,53	0,04
p15	4210,36	5094,44	-884,08	-17,35	1901,01	1836,26	64,74	3,53

Table 17: Total and MRP cost differences after step 2

2	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p3	5216,86	5367,032	-150,18	-2,80	4276,87	4288,30	-11,44	-0,27
p4	5591,50	5797,927	-206,43	-3,56	5018,93	5194,78	-175,85	-3,39
p5	7510,05	7938,17	-428,12	-5,70	6213,28	6300,72	-87,44	-1,39
p6	25372,58	25258,41	114,17	0,45	23588,91	23637,53	-48,62	-0,21
p10	6364,53	6700,921	-336,39	-5,02	2576,34	2646,22	-69,89	-2,64
p11	6166,04	5442,809	723,23	13,29	4505,44	3875,50	629,94	16,25
p12	15530,94	15410,07	120,87	0,78	14737,24	14737,24	0,00	0,00
p14	14882,83	14903,13	-20,30	-0,14	12164,55	12160,02	4,53	0,04

Table 18: Total and MRP cost differences after step 3

3	New Cost	Old cost	Cost dif	Cost dif %	MRP new	MRP old	MRP dif	MRP dif %
p9	8838,31	8666,42	171,89	1,98	5062,44	5062,90	-0,45	-0,01
p10	6496,13	6700,92	-204,79	-3,06	2589,63	2646,22	-56,59	-2,14
p11	5440,00	5442,81	-2,81	-0,05	3882,00	3875,50	6,50	0,17
p15	4630,62	5094,44	-463,82	-9,10	1531,00	1836,26	-305,26	-16,62

8.3 Conclusion

What are the simulated cost minimizations from the proposed MRP parameters?

The result of the proposed MRP parameters on the cost considerations shows that the parameters do have a major influence on the three different costing pillars. Both of the two models to propose the MRP parameters under cost considerations showed the possibilities of cost improvements. The inclusion of the MRP nervousness into the costing formula makes it possible to obtain cost minimization upon holding and setup cost with the constraint of stability in the production planning.

The results of the brute force method upon total cost improvements show equal (7/15) or better (7/15) results for 93% of the product group. The expected cost simulations show improvements between 3.9% and 40%. Moreover, excluding the holding cost and setup cost showed the improvements upon the MRP nervousness by the proposed parameters for 60%, 9 out of 15 products, while equal results are found for 4 out of the 15 products, 33% and for only one product worse results are found.

The results from the rules of the three-step approach show equal results upon the total number of parameters for which the total costs are minimized or equal. However, its percentage of total cost minimizations are slightly less than with the brute force approach. Upon the MRP cost minimization, the results show a decrease of 40%, equal results for 47% and worse results for 13%.

Although the models are only tested upon 15 products, for these products, the model seemed to be effective on the biggest portion of products. For the product defined with P9, the cost model does not show the results as expected, while for P10 the results upon MRP nervousness reductions are not in line with the expected. This result is probably caused by a too big Lot Size, because in 7.2 cost reductions are found for smaller periods of supply. For these set of products a smaller Lot Size often resulted in less MRP nervousness cost, although the resulting increase in the set-up costs did not always make this improvement the most cost-efficient one.

From the results of the two methods can be concluded that the brute force method performed best upon total cost minimization and MRP cost minimization, although when this method is not possible due to the lack of historical data, the three-step approach shows significant cost improvements as well.

Chapter 9

Final Conclusions

In this study, extensive research of the influence of MRP parameters on the MRP nervousness is executed to find how these parameters can be used into dampening and buffering the net requirement changes on both supply and demand uncertainty. After finding the most relevant parameters, its influence upon the relation between the uncertainties and the nervousness is researched on. A costing model is created that propose MRP parameters resulting in the minimization of costs including a penalty cost for the MRP nervousness. After validation the proposed parameters the research loop is closed and the main research question can be answered:

How can MRP parameters be determined to reduce the nervousness of the Material Requirement Planning under uncertainties and minimal costs?

The answer to this research question can be given by the combination of results found by answering the defined sub-questions. After providing the answers to the sub-questions, the final research question can be answered. Upon this result, practical recommendations will be given for Prodrive Technologies, the limitations of the research are elaborated and future research directions upon this topic are proposed.

9.1 Revisiting the research questions and the overall goal

9.1.1 MRP Nervousness

The planning horizon at PT can be split into a frozen and a free schedule horizon. In the frozen schedule horizon, replenishment orders are fixed upon quantity and date and in the free schedule horizon, the replenishment order creation is done by the MRP algorithm where net requirements are translated into planned order based upon the MRP parameters. The replenishment orders, as well as the requirement orders, can be shown in the MRP schedule as partly delivered upon. This possibility in combination with the two different horizons require modifications to the existing MRP nervousness formulas. Moreover, next to the absolute measurement, the relative nervousness measurement is introduced, because cumulative quantity requirement changes over the horizon are identified as being extremely important. Lastly, the addition of the criticality factor is included into the MRP nervousness measurements to make it possible to give importance based upon the point in the planning horizon.

9.1.2 Expected parameter influences

The features that influence the MRP nervousness are split into the MRP parameters, supply and demand uncertainties and the product-specific characters. The first group influences the real creation of the MRP plan, the second gives the input for the calculation of the MRP plan and the third does not specifically influence the production plan, but makes aggregations over the different products possible. The influence of the MRP parameters upon the MRP nervousness is expected to be based upon the planning horizon and the directions of the net requirement change. From detailed research upon the parameters, most of the parameters can have a strengthening and dampening effect upon the MRP nervousness. Next to the difference in influence upon the frozen and free planning horizon, a net requirement increase or decrease from a demand or supply change, it also depends on how the MRP nervousness is measured to find if the influence is dampening or strengthening. The mutual dependence upon the parameters is of an influence on these results as well. From this analysis, the risk of not assigning a certain level of safety stock and the risk of a big POS upon the MRP nervousness are the main findings for the MRP parameters. Although, when the POS can be aligned upon customer agreements a dampening effect can be created. Other small findings are based upon, the increase of Nervousness by the SLT on the free planning horizon and its possible dampening effect on the frozen horizon by manufacturing time uncertainties. The length of the frozen horizon is also found to be effective to dampen the nervousness close to the planning horizon start. The planning method in which forecast orders are converted into sales order, results directly in nervousness if the time horizon differs between both. Moreover, the uncertainty of the forecast orders is much higher than the sales orders, where the latter has the characteristic of being fixed. Therefore, this conversion being executed further in the planning horizon has a decreasing effect on the MRP nervousness.

9.1.3 MRP Environment State

The state of the MRP environment is given with the descriptive statistics upon the planning parameters, the MRP nervousness and uncertainties. The expression of the MRP nervousness into value changes, makes comparison between products possible. The results show that many value shifts are occurring and that the causes of these shifts can be captured with the defined uncertainties. With the MPS uncertainty being the primary influencer of the MRP nervousness, a detailed analysis is done upon this factor. Results show that the cumulative requirements of demand are still increasing within five weeks before the delivery date, while lead-times in the MRP environment are overwritten for more than 70% of the components. Another frequent cause of the nervousness is the supply uncertainties and manufacturing problems. The former is probably not only be a cause of the MRP nervousness, but a consequence of the requirement changes as well. Therefore, a circular cause and consequence exist between the MRP nervousness and the supply uncertainties. The uncertainties leading to reschedule requirements in the frozen horizon are not performed automatically, but require manual replanning. This leads to the lagging implementation or no implementation at all of frozen replenishment orders changes.

9.1.4 MRP Nervousness Prediction

The MRP nervousness prediction is performed to create a model that upon net requirement changes on different moments of the planning horizon can predict the MRP nervousness with the influence of the MRP parameters. With the use of a supervised neural network regression model, the MLP regressor, the MRP nervousness can be predicted most accurately. Upon the frozen horizon, the accuracy of the prediction results is lower due to the manual replanning activities, which makes it hard to link the direct cause and effect of the MRP nervousness in the frozen period of the planning horizon. This result and the circular consequence occurring the first weeks of the planning horizon let to the decision to exclude these weeks in further research. Without letting out these first weeks, the prediction results are better and acceptable to include in further research. However, the MRP nervousness in the first weeks is excluded, the net stock result from the first weeks is included. This is summarized as the cumulative quantity change at the start of the hybrid period and the free schedule period. The hybrid period gives the opportunity to predict the MRP nervousness including the transition period between the free and frozen horizon, in which a lot of MRP nervousness is captured. However, partly including the frozen period makes its prediction results not as good as on only including the free planning horizon. The features that are included in the prediction models are the set of MRP parameters with the exclusion of the Minimum and Maximum Lot Size and floating times. The former two only occur in a small set of products and therefore are not significant on the variance. Moreover, the floating times have the biggest influence on the start of the frozen period and therefore excluded on the two other horizons. The influence of the MRP parameters upon the MRP nervousness prediction is found to give a complete set of possible MRP parameters as input into the trained regression model. The influence of the parameters gives divergent results on the two horizons, the hybrid and the free horizon, and on the different MRP nervousness measurements.

9.1.5 Proposing MRP parameters under cost considerations

The results from the Nervousness prediction model shows us that in reducing the MRP nervousness by parameter settings, the importance of the different nervousness measurements should be predefined with a cost factor. Moreover, the MRP settings come with a cost as well. To give a complete view upon proposing MRP parameters on cost minimization, the setup cost and the holding are included next to a penalty cost for the MRP nervousness. The MRP nervousness measurements included are the relative and absolute MRP nervousness with criticality. The first measurement includes the nervousness upon quantity requirement changes, where the second is more focussed upon the stability of the MRP plan. The values of the MRP nervousness can be predicted with the trained regression prediction model and including a penalty cost for the different MRP measurements gives the nervousness cost for parameter settings. With a brute force method to test upon all the different MRP parameter settings for the three different cost pillars, the best-expected set of MRP parameters can be selected and be proposed upon. Another method that is designed is the MRP parameter proposal upon a three-step approach, where firstly the settings leading to cost optimization are selected, whereafter upon historical MRP nervousness into a second step the Safety Stock and a third step a change to the Lot Size is proposed. The results from these methods upon the three selected parameters are as follows: the Safety Lead Time in the free horizon only results in a strengthening effect on the MRP nervousness and results in extra holding cost, the Lot Size rule is proposed to be small while facing requirement changes over the free planning horizon and the Safety Stock is added to dampen relative net changes in the frozen horizon.

9.1.6 The result of proposed MRP parameters

Evaluating the proposed MRP parameters is done by rerunning historical MRP plans with the new set of MRP parameters. The results show that the proposed parameters for the biggest group of products indeed result in Total cost savings up to 40 %, as well as MRP nervousness cost savings up to 35 %. Moreover, the effect of the Safety Lead Time cannot be tested upon in the frozen horizon and therefore no direct conclusion can be made upon this parameter. The expected influence of the Lot Size and the Safety Stock rule can be validated from the simulation study and are therefore effective in the MRP nervousness reduction under cost considerations. Concluding, both methods show its effectivness upon cost minimization. However, the parameter proposals of the brute-force method show better results upon cost minimizations than the three-step approach. On the other hand, the latter shows its opportunity to be applicable in situations where product specific historical MRP data is lacking.

9.1.7 Final conclusion

How can parameters be used in reducing the nervousness of the Material Requirement Planning under uncertainties and acceptable costs?

The answer to this question is given by findings for four important MRP parameters.

Focus on small periods of supply in Lot Sizing: From a classical point of view, the Lot Sizing period of supply length is the result of the trade-off between the set-up costs and the holding costs. When adding the penalty cost on MRP nervousness to this costing model, the result between the Lot Size and its resulted MRP nervousness on different MRP measurements is included. While upon the relative Nervousness with criticality a strengthening effect is found for the Lot Size rule, a smaller period of supply is advised to exclude quantity increases being brought forward into the schedule. The simulation study validated the dampening effect from the smaller lots and therefore showed its cost minimization effect. The only drawback of this inclusion is their increased cost of set-up, and the missing possibility of dampening quantity shifts from different requirements within the same period of supply.

The inclusion of Safety Stock used to fulfil requirements upon the risk of net quantity changes in the frozen horizon: Net quantity differences in the frozen horizon can lead to rescheduling-in frozen production orders and the first planned order to prevent the net stock going below zero. This can result in a big batch of products being rescheduled to this point on the horizon. When it is acceptable to let the net stock drop below a certain predefined negative reorder-point, which can be done with this type of Safety Stock, the first planned order is not rescheduled in and the negative stock will be fulfilled in the next planned order. A drawback of this method is the holding cost that is included with this Safety Stock. Moreover, when this negative reorder point is exceeded, the complete lot is still rescheduled. Therefore, when this quantity is too large, this can still result in lots of nervousness. Moreover, this Safety Stock should not be close to the size of an individual requirement line. In this case, this Safety Stock is not only used to dampen the requirement changes into the frozen horizon, but to fulfil complete requirements lines as well.

Safety Lead Time for high production time uncertainties only. The Safety Lead Time has a strengthening effect upon the nervousness on the free schedule horizon, therefore it is important that this safety time is only implemented for high uncertainties into the internal manufacturing time upon the end-level production orders.

Accept a range of frozen production orders. The length of the frozen horizon is defined by the range of planned orders that are converted to production orders. This conversion prevents the replenishment orders to be rescheduled automatically by the MRP algorithm, which gives the opportunity to dampen the nervousness at the beginning of the planning horizon. The drawback of this solution is that while changes are required to be made upon these frozen orders, a lot of manual work is added, while the benefits of this manual decision include a consideration to go along with the proposed rescheduling.

Concluding, the MRP parameters can be used in reducing the MRP nervousness, although the mutual independence of the parameters, the net stock at every point in the frozen horizon, the supply or requirement changes on quantity and time difference does not make it straightforward to prescribe the most optimal set of parameters for every situation. Therefore, awareness and following-up the proposed recommendations are the first step into the nervousness reduction, but the awareness upon the changes leading to net requirement changes is essential as well.

9.1.8 Research goal

Research goal: *The creation of a method to propose multiple planning parameters from a wide range of possibilities focused on minimization of the holding, set-up and MRP nervousness costs in a computationally feasible manner with the use of historical data.*

With the use of the costing model as proposed in 7.2 whilst using the prediction model from 6.3 the goal of the research is achieved. Based upon four months of historical data, for the Periods of Supply in the Lot Size Rule and the Safety Stock that can be used to fulfill requirements parameter proposals can be made. The goal upon the computational feasibility is that with the trained prediction model within less than a second, the proposals can be generated.

On the novelty can be concluded that the tailored MRP nervousness measurements are required to measure the nervousness correctly in the MRP environment at PT. The quantitative research, as well as the detailed research on the uncertainties and the MRP parameters, give PT lots of insights on both the causes of nervousness as well as on the influence of the parameters. The prediction of the MRP nervousness on the entire planning horizon by manual modifications that not easily can be related to a cause, occurring in earlier MRP plans, gives the difficulty upon accurately predicting the nervousness in the frozen horizon. The exclusion of the first three weeks of the horizon still delivers the novelty to predicting the nervousness, with much higher scores upon the prediction accuracy. The nervousness costs, as being an extension to current costing models, shows the benefit of including multiple nervousness measurements and assign different costs upon its importance.

9.2 Recommendations

From the findings during the research, the following recommendations are proposed.

9.2.1 Performance indicators upon MRP nervousness

The findings upon and the insights it can deliver, give the opportunity to use the different MRP nervousness measurements as performance indicators of the (in)stability of the material planning of individual products. Increasing efficiency in the complete supply chain and increasing delivery performance urges for reporting upon MRP nervousness and continuously maintaining a certain level of stability. When finding certain predefined levels of stability cannot be met, direct actions should be performed to return to stability and causes should be analyzed to prevent this nervousness from happening again. To introduce this recommendation tooling should be introduced which daily updates the MRP nervousness level. Moreover, specific performance levels should be determined on the different parts of the horizon and nervousness measurements.

9.2.2 A small Period of Supply as Lot Sizing Rules for top-level products with uncertain demand

The second recommendation is related to the Lot Sizing period of top-level products. With the finding that the quantity changes from the MPS of the customers have a major influence on the MRP nervousness and that these changes are amplified through the start date of the lot, small lots are recommended for the products that encounter high demand uncertainty. If possible the brute force approach can be applied and otherwise the three-step approach. For the latter, first optimal Lot Size is calculated upon holding and setup costs, where after the historical findings upon MPS nervousness can be used upon the proposal the lower the Periods of Supply as Lot Sizing Rule. For this issue, the Relative measurement with criticality and without criticality upon the free schedule horizon is advised.

9.2.3 A small level of Safety Stock for top-level products with uncertainties on the frozen horizon

The third recommendation is related to the level of Safety Stock level that is used in fulfilling requirements. To buffer against MRP-nervousness upon net requirement changes by supply issues or close to due date demand changes, a small level of Safety Stock can be introduced to prevent the necessity of rescheduling fixed production orders or automatic rescheduling in planned orders. Similar to the previous recommendation, both approaches upon parameter proposals can be used. The three-strep approach proposes the Safety Stock level upon the historical findings of MRP nervousness measurements, with its value based upon the average Relative nervousness measurement in the frozen horizon.

9.2.4 Define fixed levels of freezing periods

The freezing period is the period in which all the replenishment orders are fixed upon quantity and due date. Freezing the orders prevents the automatic rescheduling of these order upon net requirement changes. The length of the freezing period is essential in decreasing high critical MRP nervousness. This period should be equal to the horizon length in which changes upon quantity and date cannot be solved or result into such high levels of nervousness upon lower parts into the bill of material that a manual review should be executed before specific following up actions are executed. The length of the freezing period should at least be equal to the internal manufacturing time plus a certain length in which no changes can be made the most critical parts based upon lead time and.

9.2.5 Introducing and upholding Customer Sales flexibility restrictions

Although for various customers customer sales restrictions are defined, monitoring and upholding these rules is not in place or poorly performed. When promising high service levels to customers, it is essential that alignment upon the requirements can be met. Therefore it is crucial that, if not in place, restrictions upon flexibility for cumulative quantity increases or due date changes within Manufacturing and supplying lead time have to be defined. Upholding these restrictions to prevent cumulative quantity increases upon a defined horizon should be rolled-out by the introduction of a model that can be used in checking changed or new requirements upon these restrictions and after that accept or reject the change considering historical changes as well.

9.3 Implementation plan

The recommendations proposed in the previous sub-chapter require a proper implementation plan to be deployed at PT. The recommendations partly overlap upon stakeholders required for the deployment as well as the process in which they need to be implemented.

The implementation of the MRP nervousness indicators as performance indicators require a daily run in which the old MRP plan is compared with the new MRP plan. The formulas as used in this research should be used upon the measurement of the Nervousness. This execution should be triggered automatically and follows the nightly MRP run. The results from this performance indicator need to be collected and stored into a database, which is under the supervision of the data management team. Next to the collection and the storage, a view should be created by the data science team into the business intelligence software used at PT. In this view sorting upon the product and the responsible planner should be possible as well as on the different horizons and the appropriate different nervousness measurements. Moreover, triggers should be generated while exceeding the boundaries of acceptable nervousness. These triggers should include the causes of the MRP nervousness results by showing the differences upon replenishment orders between two succeeding MRP plans which contributed to this nervousness.

The implementation upon the improvements that are given in 9.2.2 and 9.2.3 depend upon the data availability of the products. When for these products, historical MRP plans are available and it is likely that the demand and supply pattern and uncertainties of the historical data will be similar to the future, the brute force method can be used as proposed in chapter 7.3. For products that are newly introduced or for which the historical uncertainties that are faced do not match the future expectations the three-step approach proposed in chapter 7.4 is applicable.

The model that includes MRP nervousness predictions proposes Lot Size and Safety Stock parameters. The neural network that is used in nervousness predictions can be constantly trained by feeding it with new data. Therefore this deployment consists of two parts. From one side the model should be updated once in a while with the new availability of data, which can be done automatically while implemented in a data environment triggered by timestamps. The data science team should execute this part at PT. The second phase of the implementation is based upon the practicality for the planners at PT. Next to periodically training the model, the costing model used in 7.3 can be periodically run as well and reviewed upon the current parameter settings. The calculation and reviewing part can be automatically executed and a report can be distributed with planners upon the newly proposed parameters.

The model proposed in 7.4, defines the MRP parameters upon three steps. To execute these three steps, data about historical and/or expected future demand, the set-up costs and the expected uncertainties upon demand and supply are required. For the first part, the expected average demand is required, which can be based upon between historical demand patterns and trends or upon customer framework contracts. The second is the determination of the level of Safety Stock based upon expected relative nervousness in the frozen period. This can be determined from its historical nervousness data or upon historical nervousness data exists from similar products, based on complexity, customer, supply risks and production risks. For complete newly introduced products without any similarity, another strategy should be defined. To be practically implemented, nervousness measurement should be available into the business intelligence environment. In this environment upon product number and the data range, the nervousness should be displayed. To collect the data from multiple products, the selection of those should result in an average upon the relevant measurement. The next step could be a mapping upon product similarities which can be used in automatically performing the selection of similar products. The third step requires the decision upon the Lot Size adjustment. If no explicit restrictions upon the MPS changes are made or can be maintained and historical demand or expected demand is expected to be uncertain a lower Lot Size than resulted from the ratio between holding and setup costs should be chosen.

The proposed parameters resulting from the two methods should be reviewed and a transition plan should be defined in the follow-up of these parameters. This transition plan is required as MRP parameter changes can result in MRP nervousness as well. For the increase of the Safety Stock level, the extra requirement should be added to build up this stock far enough in the horizon and not directly create supplying issues. This decision should be made by the planner in combination with the responsible purchasers of the components. A decrease in the Safety Stock level does not require this consideration. For the Lot Size, similar considerations should be done. The increase of a Lot Size can result in similar requirement changes which need a review before implemented. This increase of the Lot Size can be deployed by first freezing the period over which Lot Size increase is not required and afterward changing the Lot Size in the material master.

The implementation of a defined frozen period requires an adjustment to the planning process on the conversion horizon of planned orders into production orders. The length of this horizon requires an analysis upon the critical period for the specific product based upon internal and external supply lead time, uncertainties and risks.

Implementing and upholding customer sales flexibility restrictions firstly require the initiation of contractual restrictions by the account managers of PT in consultation with the responsible purchases of the customer. The statement should be that demand flexibility/uncertainty comes with a cost, which can either be accepted in the sales price or can be prevented by the initiation flexibility restrictions. The former gives the opportunity to create buffers upon requirement changes and the second requires the upholding of the initiated rules. Upholding the initiated rules requires the introduction of a model that can be used in checking changed or new requirements upon these restrictions and after that accept or reject the change considering historical changes as well

9.4 Limitations of the research

The limitations of this research are in first place with the availability of clean data. For this research, a dataset of four months has been used on the final products at PT. If more data can be fed to the model, it is likely that a higher level of accuracy can be reached.

Additionally, the nervousness that occurs in the frozen period is hard to directly link or not possible to link to uncertainties, with the property that these changes are manually done and therefore can lag on the expected nervousness result or not occurring or occurring while not expected. During this research is focused on the input from the higher level requirement upon the lower level components and this scope in combination with the hard to define uncertainties in the start of the frozen production plan, the first three weeks of the MRP plan are being left out of the scope on to nervousness measurements. However, the net requirement change from these three weeks has been taken into account during this study. This limited the research to nervousness reduction focused on translating the requirement changes into the replenishment orders and control from the top-level products, other than measuring the result of this control on the production order release level and component availability.

Moreover, the focus has been on parametrization upon top-level products for MRP-nervousness reduction. This approach excludes the nervousness-reduction which can be achieved on lower levels in the BOM.

Another limitation is that the proposed model is only tested upon the products in group A from the ABC-analysis. These products all have a significant contribution to the total nervousness. While the model seemed to be valid for the biggest group of these products, it cannot be concluded that for the products in the other group the same results would be received.

Lastly, a limitation of the research is upon the prediction models that are used. Whereas there is a broad range of regression algorithms that can be applied to the proposed problem, this research is limited to the LR, SVR and the MLP regressor. For the MLP regressor a trial and error method upon the hyperparameterization is applied, for which only a limited set of hyperparameters is tested.

9.5 Further research

Further research can be done on the parameterization of multi-level MRP nervousness in finding relations between the parameter settings on different BOM levels and their influence on the MRP nervousness under demand and supply uncertainties. This research will give the opportunity not only to try to dampen and buffer all the nervousness on the top-level, but find this in relation to its lower level components. This approach can be more effective upon total cost reductions as well as on the complete MRP nervousness. The cost reductions can be achieved while holding costs are more capital intensive on the top level than on subassembly and component level. Moreover, the circular consequences of top-level MRP nervousness back to the nervousness originated from supply uncertainties can be reduced if the top-level nervousness is attenuated by dampening and buffering parameters on the lower levels. So, therefore, it is interesting how MRP nervousness on the top level rippled through the lower levels, where on the lower levels the top-level nervousness is equal to their required demand nervousness. This approach would allow nervousness on the top-level if it can be dampened in the lower levels, although this research is very complex based upon component commonalities and extensive bill-of-materials leading to the difficulties of finding allocations between specifically required demand nervousness and the relating supply nervousness.

With the finding that MPS changes are the leading cause of the nervousness, further research should be focused on agreements with customers in MPS nervousness restrictions. Based on these arrangements the MRP parameters can be more efficiently aligned. Some example of parameters based on customer arrangements is only letting quantity changes occur within the Lot Size and not over the lots. However, if these quantity changes are unavoidable and therefore not restricted on, in the potential of over forecasting lays an opportunity to deal with these issues.

Next to focus on agreements with customers, the reduction of the bullwhip effect between the end-product of the customer and PT its end product can be an efficient MRP nervousness reduction strategy by better containment and integral MRP communication.

Another focus of research can be done upon the creation conditions to either accept or decline the MPS changes of a customer. By calculating the ‘financial’ impact of the change before the implementation can be decided against at which costs these changes will still be accepted. Next to the calculation of the financial impact, the calculation of the impact before implementing a demand change should be discussed upon with the relevant stakeholders in the supply chain. To make this possible, a simulative MRP run needs to be carried out and the result upon the availability of the lower levels components should be tested upon criticality to deliver within lead time. This test should not only be upon the top-level product that initiates this change, but upon the supplying risk for other dependent requirements that have mutual components as well.

Next to the research upon the scope of the MRP parameterization can also be focused upon the increase of the accuracy of the prediction model. This both includes further research upon the data input as well as on the prediction models and their hyperparameters. On the former, data input can be extended with additional features or cleaner data can be used. An example of cleaner data is based upon the MPS changes, which can be both initiated from PT as well as from the customer. Where this initiation from PT is a result of the lack of, for example, available stock and therefore not being a cause of the MRP nervousness but a result. Upon the MRP nervousness from the frozen horizon, which can lag from the uncertainties resulting in this change, a method should be found to relate the uncertainties to the nervousness more accurate. Upon the prediction models, further research can be done upon other machine learning regression models and upon the hyperparameters that result in better accuracy.

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Appendix

I. A.1

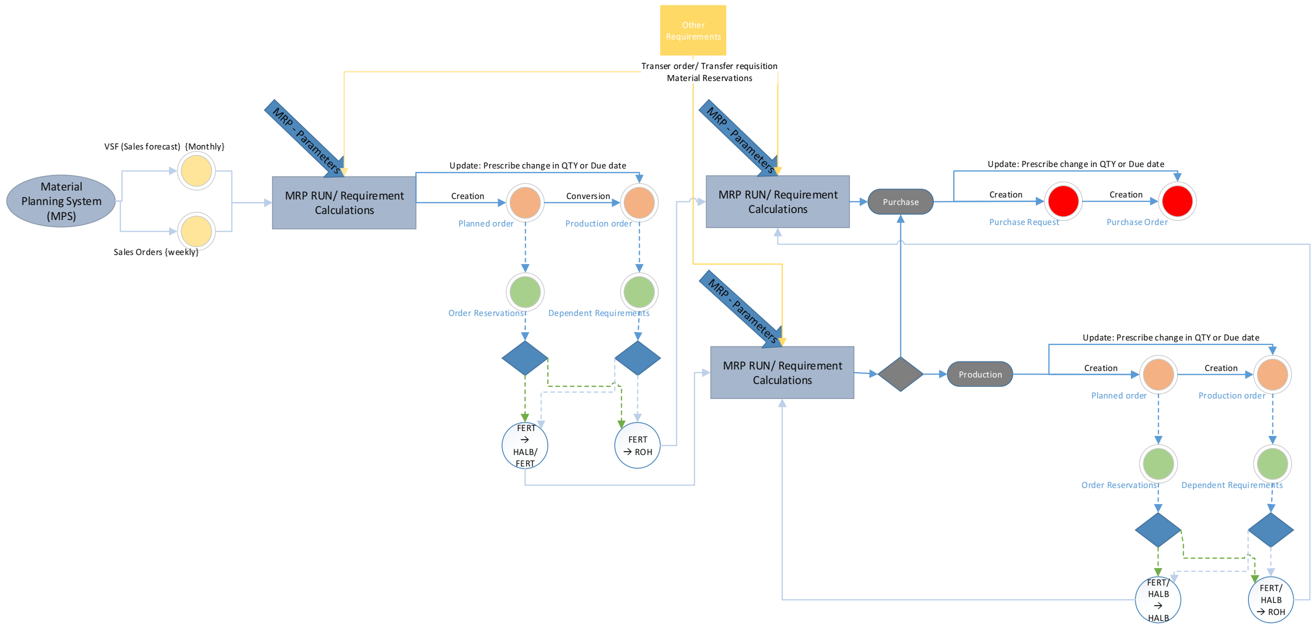

Figure 36: MRP way of working at PT

II. A.2

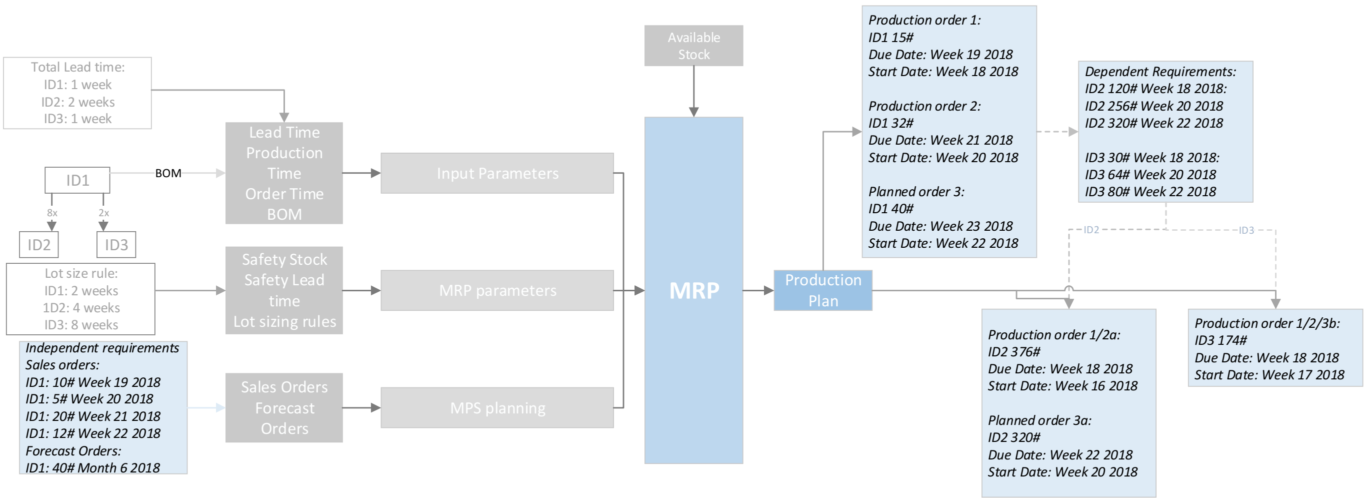

Figure 37: MRP calculation logic

III. A.3

Mathematical formulation of the MRP algorithm

The MRP algorithm contains of a loop until all of the scheduled demand is met with planned orders, where the date and quantity of these planned orders is determined by the demand quantity and date and the setting of MRP parameters.

Variables:

$GQ_{x,t,k}$ is the gross required quantity for order x with due date t during planning cycle k

$x \quad \in [so, vsf]$

so : Sales order

vsf: Forecast order

$SQ_{y,t,k}$ is the scheduled receipt quantity by order y with available date t during planning cycle k

$y \quad \in [p, pl]$

p: Purchase order

pl: $Planned\ order$

S_k: Net available stock at schedule period k

$N_{t,i,k}$: Net available stock at schedule period k for order i with due/available date t

$RQ_{i,t,k}$ required quantity at schedule period k for order I with due/available date t

$$if\ i = x, \qquad RQ = GQ_{xt,k} \rightarrow, RQ < 0$$

$$if\ i = y, \qquad RQ = SQ_{xt,k} \rightarrow, RQ > 0$$

k: schedule period

t: due date time

$SQd_{p,k}$ Delivered quantity from production order p during planning cycle k

$GQd_{s,k}$ Delivered quantity on sales order so during planning cycle k

MRP parameters

SL: safety leadtime

SS: Safety Stock

SR: Safety Stock rule

Mn: Minimum Lot Size

Mx: Maximum Lot Size

RV: Rounding value

Sc :scrapping percentage

LR = Lot Size Rule

Logic:

MRP logic with no scheduled receipts:

Sort all order according to their due date

$T = \max(t_i)\ \forall i$

Start I = 1

$While\ t_i < T$

$t_0 \leq t_i \leq t_{i+1} \leq T\ \forall i\ \in I_k$

$N_{t,i,k} = N_{t,i-1,k} + RQ_{i,t,k}\ \ \forall i$

if $N_{t,i,k} < -(SR * SS)$

If $LSR = 'LFL'$

$with: rq1 = -N_{t,i,k}$

$rq = r1 * (1 + sc)$

$t = t_i - SL$

$Sq = \max(\min\left(rq\ + \left(rq - RV\left\lfloor\frac{rq}{RV}\right\rfloor\right)\ , Mn\right), Mx)$

$SQ_{y,t,k} = \frac{sq}{1+sc}$

$if\ LSR\ \neq 'LFL'$

$L = \max(t_j)\ \forall j\ with\ t_i \geq t_j \leq ti + LSR$

$with: rq1 = -N_{L,i,k}$

$rq = r1 * (1 + sc)$

$t = t_i - SL$

$sq = \max(\min\left(rq + \left(rq - RV\left\lfloor\frac{rq}{RV}\right\rfloor\right)\ , Mn\right), Mx)$

$SQ_{y,t,k} = \frac{sq}{1+sc}$

else: -

next i

MRP logic with scheduled receipts:

While scheduled receipts for production orders $SQ_{p,t,k}$ will remain similar to $SQ_{p,t,k-1}$ without manual adjustments, planned orders $SQ_{pl,t,k}$ will be remove and calculated over again. Although production orders will not be adjusted in time and quantity again, they will get a reschedule message to either be rescheduled in or rescheduled out with their order quantity. The adjustment to above logic is only the implementation of generating these reschedule messages. They logic behind the reschedules messages is as follows:

$Tp = \max(t_i)\ \forall p\ \in P_k$

$T = \max(t_i)\ \forall i$

$rt_i = t\ \forall i\ \in I_k$

$Start\ p = 1$

$N_{t,i,k} = N_{t,i-1\,,k} + RQ_{i,t,k}\ \ \forall i$

$RN_{t,i,k} = N_{t,i,k}$

$While\ p_i < T_p$

$rt_0 \leq rt_i \leq rt_{i+1} \leq T\ \ \forall i$

$RN_{t,i,k} = RN_{t,i-1\,,k} + RQ_{i,t,k}\ \ \forall i$

Remove p from schedule:

$RN_{t,i,k} = RN_{t,i-1\,,k} + RQ_{i,t,k}\ \ \forall i$

Start I = 1

$While\ t_i < T\ or\ \ re_k = 0$

if $RN_{t,i,k} < -(SR * SS)$:

$rt_k =\ t_i - SL$

$if\ rt_k > t_k$:

$M_{p,t,k=}Re - Out$

$if\ rt_k < t_k$:

$M_{p,t,k=}Re - in$

$$re_k = 1$$

Next i

Next p

$t_0 \leq t_i \leq t_{i+1} \leq T \ \forall i \ \in I_k$

$N_{t,i,k} = N_{t,i-1\,,k} + RQ_{i,t,k} \quad \forall i$

After the creation of reschedule messages the MRP logic as described on the previous page is applied for the creation of planned orders.

IV. A.4

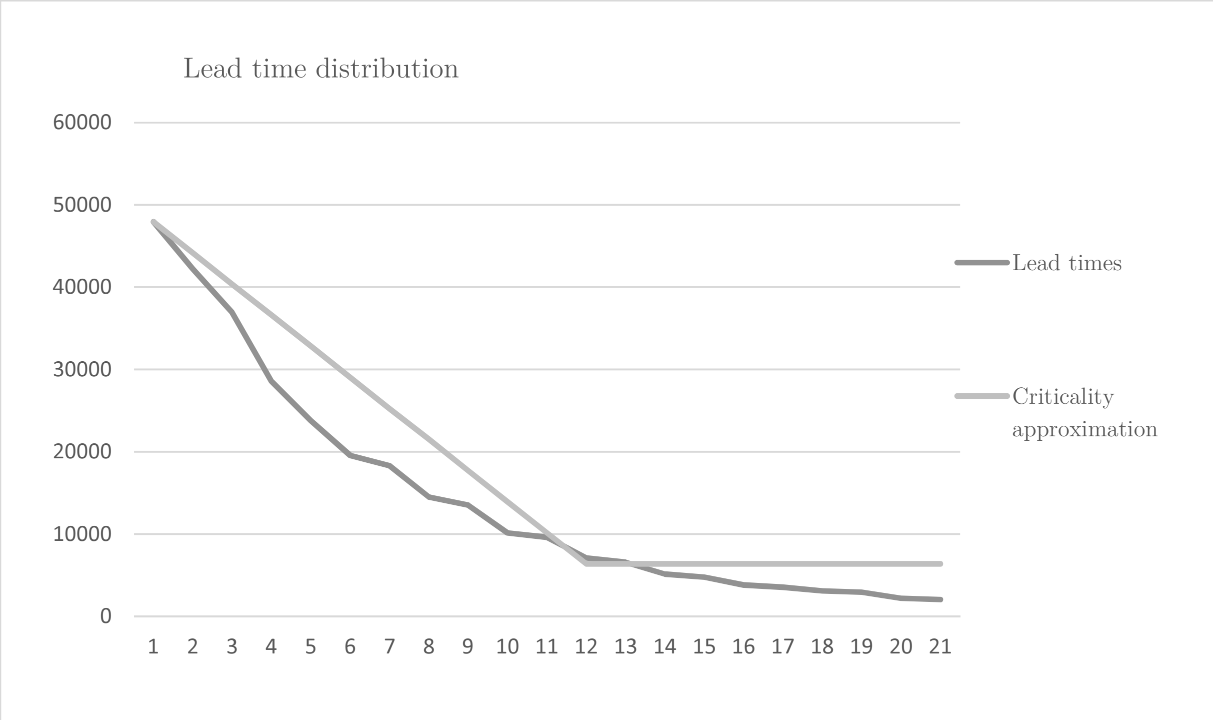

Figure 38: External Lead Time distribution of components

V. A.5

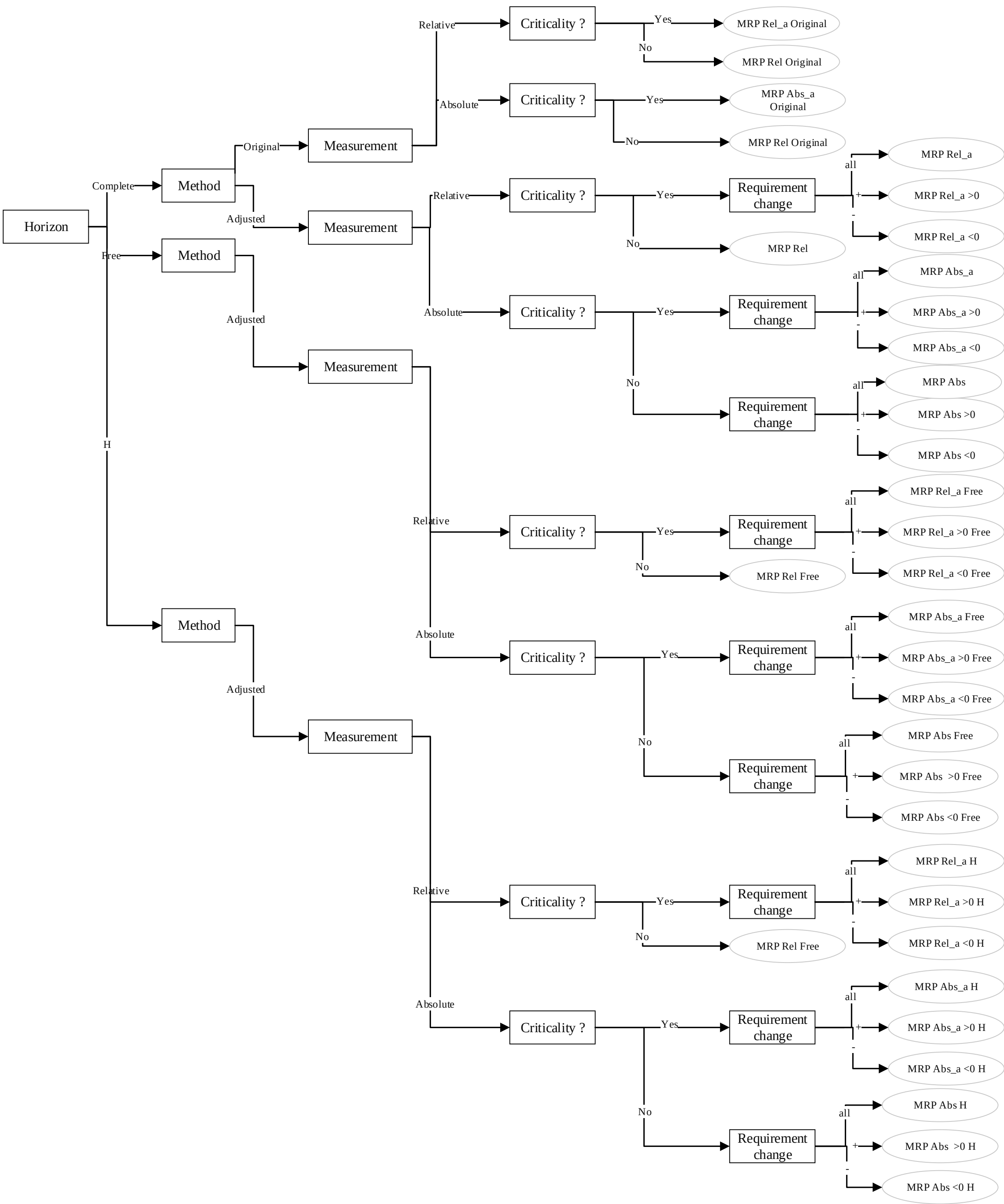

Figure 39: MRP nervousness measurements overview tree

VI. A.6

Table 19: Overview of mediating effect from MRP parameters between MPS and MRP nervousness 1

Freezing period	. . . .	. + - .	. . . .	. . . .	+ - . -	N/A	N/A	N/A	. . . .	. . + .	. + . -	. . . -	. - . .	. - + .	. - . .	N/A	N/A	N/A
LotSizeRule	. - . .	- . . .	. - . -	- + - .	. . - .	. + . .	. . - .	- . . .	. - . .	. - . .	+ . . -	. - . -	. + - .	. . - -	. . - .	+ . - .	. . . .	. . . .
MinLot%	. .	. -	. .	. +	- +	. +	+ .	. .	. .	+ -	+ -	+ -	- +	- .	. +	+ .	. -	+ .
Maxlot%	. .	. -	. .	+ -	- +	- .	- +	. .	. +	. .	. -	. .	- .	- .	- .	. .	. .	- +
RV	. . . .	- + + .	. . . .	- . - .	- . - .	. - . .	- . + .	- - . .	. . . +	. . . +	. . + .	- - . .	. . - .	. . - .	. - . .	- . + .	- - + .	. . . +
SLT	. . . .	. . . .	. + . .	+ + - -	. + - .	+ + - -	. + - -	+ . - .	. . . -	. . . .	. . . .	. . . -	. + . -	. . . .	. + . -	. . . .	+ . - .	. - + .
SSr%	. . - +	. . - +	. . - +	+ . . -	+ - . -	. . - .	+ . - .	. . . -	. . + .	. . - .	. . - .	. . - .	. . . .	. - . .	. . - +	. . - .	. . . -	+ - + .
SS%	. . - .	. . . .	. . - .	+ . . -	+ . . -	+ . . .	+ . . -	. . . -	. . . .	. . - .	. . . .	. . - .	. . . .	. . . .	. - . +	. - . .	. . . -	. . . .
Features / Nervousness Measurements	*MRP Abs*	*MRP Abs >0*	*MRP Abs <0*	*MRP Abs h*	*MRP Abs h >0*	*MRP Abs h <0*	*MRP Abs f*	*MRP Abs >0 f*	*MRP Abs <0 f*	*MRP Abs_a*	*MRP Abs_a >0*	*MRP Abs_a*	*MRP Abs_a h*	*MRP Abs_a >0*	*MRP Abs_a<0*	*MRP Abs_a f*	*MRP Abs_a >0*	*MRP Abs_a<0 f*

Table 20: Overview of mediating effect from MRP parameters between MPS and MRP nervousness 2

Freezing period	+ + + -	+ + - .	+ + + -	+ . - -	. + - .	. + . .	N/A	N/A	N/A
LotSizeRule	- . + +	- . . +	- . + +	+ - . .	. . + +	+ - - .	. - . +	. - . +	+ - . .
MinLot%	. .	+ .	. +	. .	- +	+ -	+ -	. .	- .
Maxlot%	- +	. +	- .	. .	- +	. .	. -	. -	. .
RV	+ - . .	. . . -	+ - - .	. + . .	. . . -	. . - .	- . . +	. - . .	- + . +
SLT	- + + .	. + . .	- + + .	+ - . -	. . . .	. + . -	. . - .	. . . .	+ . . .
SSr%	+ - . +	+ . + .	+ - + +	+ . . -	. + - .	. - . +	+ - . -	. - . -	+ . - .
SS%	- . . .	+ . . .	- . - +	. - . -	. . + .	. - . +	. . . -	. . . -	+ . . .
Features / Nervousness Measurements	*MRP Rel_a*	*MRP Rel_a >0*	*MRP Rel_a*	*MRP Rel_a h*	*MRP Rel_a >0*	*MRP Rel_a <0*	*MRP Rel_a f*	*MRP Rel_a >0*	*MRP Rel_a <0*

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Avq_D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Customer	X			X	X	X						X	X	X	X	X	X	X				X	X	X	X	X	X
CL-	X		X							X	X	X							X	X	X						
ESU	X											X							X	X	X						
EUS2												X															
Flt Be									X							X	X	X									
Flt Af									X											X					X	X	
Freezing period	X										X	X							X	X	X						
ISU	X	X	X							X	X	X								X	X						
ISU2	X		X							X	X	X							X		X						
LotSizeRule	X			X	X	X	X		X			X	X	X	X	X	X	X	X	X		X	X	X	X	X	
MVTd												X															
MVTc												X							X	X							
MinLot												X		X		X											
Maxlot																											
Quantiy start dif	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Mrpg									X			X	X	X	X								X	X			
MPS	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X
Re-in Follow-up	X											X				X	X	X	X	X							
Re-out Follow-up	X											X							X								
RV				X	X	X			X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
SLT					X	X			X			X	X	X	X	X	X	X				X	X	X	X	X	
SSr	X	X		X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Features / Nervousness Measurements	MRP Abs	MRP Abs >0	MRP Abs <0	MRP Abs h	MRP Abs >0 h	MRP Abs <0 h	MRP Abs f	MRP Abs >0 f	MRP Abs <0 f	MRP Abs_a	MRP Abs_a >0	MRP Abs_a <0	MRP Abs_a f	MRP Abs_a>0 f	MRP Abs_a<0 f	MRP Abs_a<0 h	MRP Abs_a<0 h	MRP Abs_a<0 h	MRP Rel_a	MRP Rel_a >0	MRP Rel_a <0	MRP Rel_a h	MRP Rel_a >0 h	MRP Rel_a <0 h	MRP Rel_a f	MRP Rel_a >0 f	MRP Rel_a <0 f

Table 21: Results of feature selection