MASTER

Forecasting and planning long-term required capacity in a make-to-build high tech industry

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Forecasting and planning long-term required capacity in a make-to-build high tech industry

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I  Abstract

This research project describes the key factors of a successful capacity planning process and the development of a model which computes various forecast scenarios for S&OP-meetings within a high tech firm defined by high demand uncertainty. The model can be used to evaluate forecast scenarios and provides insight into the reliability of a customer, the customers’ forecast and which aids in making decisions regarding the procurement of new machines. It can be concluded that the development of forecast scenarios provides great understanding of possible outcomes and is a valuable method to evaluate the future of the company and thus a valuable asset for management.
II Management summary

Introduction

This research project was conducted at the planning department, which is a sub department of the operations department of Prodrive Technologies (PT). PT is a first tier and second tier supplier to Original Design Manufacturers (ODMs) and Original Equipment Manufacturers (OEMs) in the high tech industry. Its sales programmes vary from motion and mechatronics to the internet of things. In the past fifteen years the company has undergone tremendous growth with regards to it workforce and turnover. The workforce has increased from 50 to a staggering 1,000 employees. The turnover has also followed a similar growth, increasing from 6 million Euros to over 120 million.

To keep track of the growth, PT should adjust its available resources in a timely manner. This should be conducted by means of structured Sales and Operations Planning (S&OP) meetings with which forecasted available and required capacity should be evaluated. There is currently little understanding of the S&OP-process and therefore no reliable control of the future required capacity. Regaining control in the field of long term capacity management entails gaining insight in the S&OP-process and the corresponding factors which influence this process. The manner of evaluating the forecasted required capacity against the forecasted available capacity over a time period is unstructured, static, unreliable, and unclear. This is due to the lack of insight in important forecast factors and because no theoretical background is used to evaluate the required and available capacity. In response to this problem, the objective of the project and three main research questions were designed.

The aim of this research is to develop a reliable sales and operations planning process from which a reliable forecast is developed using accurate estimations for the available and required capacity.

- What are the relevant aspects for S&OP?
- What are the capacity and decision models that affect S&OP?
- How should purchasing decisions be evaluated?

Methodology

For the outline of the research model, the framework of Mitroff et al. (1974) was used. Thus, the research model consists of the four main phases of the framework: conceptualization, modelling, model solving and the implementation. Apart from these four phases, the orientation phase was also conducted, which was included in the first three chapters of the report.

The framework begins with the conceptualization phase, which focuses on the construction of the conceptual model. Here the scope, necessary data, parameters and variables are described. Data was gathered from various information systems such as SAP and Visiprise. Data was also gathered from stored forecast worksheets and by means of interviews. The second phase, modelling, contains the mathematical
models required to solve the problem and the third phase, model solving, contains the development of the mathematical models to the tooling required to determine the optimal capacity requirements. Based on ‘what-if-analysis’ different forecasted demand scenarios were determined which was used as input for the mathematical model. For the computation of different scenarios and the required capacity, the VBA-language was used. The models were built in a manner in which they automatically interact with the ERP-system of PT; it extracts data from this system by a live connection. Finally the output of the model, in the form of required capacity over time periods, was pushed to data files which were read by AIMMS 4.19. The latter programme provided a workforce, machine plan and total cost as output. The programmes were then used to solve an optimization problem in the numerical study. The last phase of the research model of Mitroff et al. includes the actual implementation of the results of the research. So the following topics are included in this research project; a summary of the results, the conclusions of the research, the implementation of the tools in the S&OP-process, interaction with the tool with the ERP-system of PT.

Conclusions

Though the literature provides steps to the S&OP-process, it often entails cross-functional meetings. The key points of these meetings are the planning horizon, planning frequency and planning objects. In addition, the risk balancing plays an important role when the production environment is characterized by high demand uncertainties. Scenario analysis can provide a better understanding of these risks scenarios by managing demand uncertainty. Based on these scenarios, capacity should be managed. According to the literature, lead and chase strategies tend to be suitable for highly customized, low volume products as well as project manufacturing and job shops. The latter is the case for high-tech firms. Thus, a combination of lead and chase strategies seems to be the most appropriate strategy for high-tech firms to manage capacity.

As a result, these strategies were used to optimise the machine and workforce plan against minimal costs. First, to enclose demand fluctuation, various demand scenarios were established: pessimistic, most likely and optimistic. Subsequently, the output of these scenarios was used as input for the computation of the capacity requirements based on monthly infinite MRP. Common usage of aggregate demand is justified. However, aggregate demand in an environment, which includes long lead times and high BOM-levels, can create an inaccurate representation of the demand over time. Following that, the required capacity was used as input for an integer programming model; this model evaluates the required capacity against the available capacity. Lastly, the output of these scenarios was evaluated against one another to provide more insight into the risks.

The research results show that, currently, no investment is required for the procurement of new SMD machines. However, this decision should be revaluated in a monthly S&OP-meeting. In this meeting, newly generated forecast scenarios should be evaluated against the scenarios of the previous month. Moreover, the S&OP-model should serve as a backbone for this meeting. It can be concluded that the development of the scenarios provide great insight into possible outcomes and thus is a valuable asset for management.
Implications & recommendations for PT

This research project provides insights and a tool which are useful for decision making regarding the S&OP-process. They can also be used by the Operations, Supply Chain and Sales departments to determine the course PT pursues. The model is also quantitatively able to support decision making concerning the procurement of machines and the size of the workforce.

The first and most important recommendation for PT is to hold structured monthly S&OP-meetings with a clear agenda and which are led by the heads of the Operations, Sales and Planning departments.

The second recommendation entails the usage of the models for the S&OP-meetings. The developed scenarios are a valuable input to on the direction the company is growing and also provide confidence intervals by means of a pessimistic and optimistic scenario.

The third recommendation, for future improvement of the model, concerns data management. PT should save all customer forecasts. By saving this data, the forecast and forecast scenarios will also be more reliable.

The fourth recommendation is that the models should be used to evaluate the scenarios of other key production units and for all customers. This evaluation can be used to gain more insight into the behaviour of the customer and the reliability of a customer’s forecast. This is important to ensure that PT can continuously meet demand.
III Preface

This thesis is the result of my graduation project in completion of the MSc program in Operations Management & Logistics at the Eindhoven University of Technology. This research was conducted at Prodrive Technologies, a motivating company where I already worked with great dedication and satisfaction for over 3 years. Thanks to my colleagues of the planning department; Alem, Guido and Mark.

Without the help of several person, I would have never been able to finish this thesis. Therefore I want to express my gratitude to my supervisors. First of all, I would like to thank Sietze de Jong as my company supervisor. He gave me the freedom to research the problems of the planning department to the full extent and he simultaneous provided regular feedback and advice on my professional and personal skills.

Also I would like to give special thanks to my first university supervisor, Engin Topan. He was always available for a meeting and (casual) conversations. He also provided me with the structure, ideas and feedback which I required to finalize my thesis. Of course, I would also like to thank the second university supervisor, Zümbül Atan. We only had few meetings, but these meetings were constructive and to the point.

Last but not least, I would like to thank all my friends and family for their support. I would like to give special thanks to my parents and my girlfriend, Farangis, for their ongoing advice, support and love.

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1. Introduction

1.1 Prodrive Technologies

Prodrive Technologies (further referred to as PT) is a private owned company in the high-tech industry. It focuses on design, manufacturing and delivery of leading technical products and systems and was founded in Eindhoven in 1993. It is a first tier and second tier supplier to Original Design Manufacturers (ODMs) and Original Equipment Manufacturers (OEMs) in the high tech industry. PT has various sales programs: high-end computing, motion and mechatronics, power conversion, industrial automation, vision & sensing, internet of things and integrated manufacturing systems. These programs are used to gain access to various industries, e.g. the industrial, medical, automotive, infra & energy, and defence and aerospace. Figure 1 depicts information regarding the sales activities regarding the industries. For example, the industrial automation program has pro-active business development efforts in the industrial industry. However, it has passive sales efforts in the medical industry.

![Figure 1: Sales – portfolio analysis](image)

The company is growing quickly. In 2000, fifty people were employed by PT, which has since grown\(^1\) to more than 1,000. Turnover has increased from 6 million Euros in 2000 to over 120 million Euros\(^2\) today. Apart from an expansion in employees over the years, the company has also grown to become an international company with factories worldwide, from the United States to China (Appendix A).

Organizationally, the company is structured into three main departments: Development, Operations and Sales (Figure 2). The Development department mainly works on a project basis and is responsible for the development of electronic, mechanical and software solutions, whereas the Operations department is

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\(^1\) February 2016

\(^2\) December 2015
responsible for actual production. The Development and Operations departments are supported by the Sales department. Due to the scope of this research, the main focus will lie on the Sales and Operations departments.

1.1.1. Sales department

The Sales department explores the potential for new cash flows, with the purpose to commit a purchase of products by (potential) customers. The Sales department consists of three sub departments: Business Development, Sales Management and Account Management. The Business Development sub department is responsible for developing new sales programmes and programmes that focus on a specific technical field (e.g. internet of things, industrial automation and power conversion). These sales programmes are used by the Sales Management sub department to gain new customers and penetrate new industries. When they succeed in acquiring a new customer and selling a product, the contact with the customer is transferred to the Account Management sub department.

As the Sales department has limited knowledge regarding what is and what is not possible regarding manufacturing, the decision regarding a potential sale of a new product does not solely depend on the sales department. Within this process many departments are involved and each of them must approve the part of quotation for which they are responsible. Clear communication by the Sales department with the Operations and Development departments is important in aligning the sales with the operation planning and project planning.

Apart from searching for new opportunities, the Sales department also uses a technique known as farming; account management is responsible for maintaining the progress of its customers, searching for new opportunities within their customer portfolio and developing a relationship with the customer. Thus, account management functions as a bridge between the customer and stakeholders within PT.
1.1.2. Operations

The Operations department is responsible for the production, assembly, testing and life cycle management of all electronic products and systems. In order for the Operations department to work efficiently, the department is split into two groups: production and support groups. The production groups are responsible for the physical production of the material. The group manufactures cable, PCBAs, mechatronics and more. This is all done in seven sub operations departments, namely System Assembly, Conventional PCBA manufacturing, SMD PCBA manufacturing, Cable Harness Manufacturing, Magnetics, and Machining and Injection Moulding (Figure 4). The Operations department is supported by the Service, Facility, Technology, Manufacturing and Supply Chain departments. These departments ensure timely delivery of the materials to the customer.

1.1.2.1. Supply Chain department

As mentioned, the Supply Chain department is an element of the Operations department (Figure 4). The purpose of this department is to make the inventory readily available for the customer in the most efficient and cost effective manner. It strives to fulfil this goal by matching its supply with the demand through the implementation of the most expedient usage of cross-chain resources. The department also maximizes resource productivity, develops standardised processes, eliminates duplicate efforts and minimises inventory levels. These steps attempt to reduce waste, minimise costs and optimise the supply chain within PT (Chen, Defee, Gibson, & Hanna, 2011).

These goals are realised by the three sub departments of the Supply Chain department: Purchasing, Logistics and Planning. This research will focus on the Planning department, which is responsible for order planning, demand processing and contact regarding logistic questions. Thus, when the Planning sub department receives a demand, they determine the best delivery date based on the ERP-system. This system, SAP ECC 6.0, is integrated in almost all of PT’s processes and systems. Therefore, it is used to coordinate and maintain information, activities and resources in business processes, such as human resource management, billing, production planning and order fulfilment.

Planning

The Planning department plans orders and is concerned with the efficient use of the production units. A production unit is a group of resources, mostly several production lines or machines, which process production orders. To determine whether these resources are used efficiently is based on the capacity. Here a distinction is made between available capacity and required capacity. The time that a production unit is available to process production orders is referred to as available capacity and the time that a production order needs to be processed on a production unit is referred to as the required capacity. To ensure efficient use of a production unit, there should be a balance between required and available capacity. For example, when there is much more available capacity than there is required capacity, the production unit has a low utilisation and is used inefficiently. This can also imply that a production unit has been bought for no reason and thus unnecessary costs were made. However, when the required and available capacity are almost equal,
the implication is that the utilisation approaches one hundred percent and, thus, there is no time for repairs and other unforeseen problems.

The forecasted required capacity per production unit depends on the quantity of a production order which a production unit has to process. The quantity of these orders is based on two different types of forecasts: demand forecast and sales forecast. The difference in these forecasts lies in the manner of data acquisition and the time horizon in which they are used.

The demand forecast, which can be seen as short to midterm, ranges from 0 to 52 weeks and is provided to the planners on a weekly or monthly basis (Figure 3). In contrast to the demand forecast, the sales forecast is long-term; it ranges from 52 weeks to 104 weeks and is provided on a quarterly basis. The sales forecast should be used to make adjustments in future capacity by means of purchasing machines and/or hiring/firing employees. However, the forecast does not always reflect reality; the forecasted demand often deviates from the real demand. Thus, due to the unreliability of these forecasts, it is not always possible to quickly determine the amount of required capacity. This could cause PT to procure production machines too late or too soon. As a result, there can be a problem regarding the evaluation of the forecast. This means that the process of evaluating the forecast should also be analysed.

![Figure 3: Forecast range](image-url)
Figure 4: Operations department
1.2. Problem context

A fishbone cause and effect diagram is provided in Appendix B. This diagram incorporates the problems regarding the determination of sufficient available capacity in the future. PT wishes to obtain more insight into the variables and methods that influence the decision-making regarding their capacity problems. For this reason, the conclusions regarding the capacity problems were often unreliable and false. For instance, in the fall of 2014, PT forecasted an enormous on-going peak in the required capacity on two main production units in July of 2015. This peak could not be processed with the forecasted available capacity. For this reason, management decided to procure two extra production lines, one for each production unit. The total costs for these lines were over 3 million Euros. However, the peak never occurred on these production units and the required capacity in that period and the following months did not exceed the available capacity of the production units. It seemed that the procurement of the production units was unnecessary. In contrast there were also some production units where capacity problems did arise. As a result, PT misjudged the capacity problems. The context of these problems lies within the scope of Sales and Operations Planning (S&OP), which concerns with the management of capacity in the future.

For companies it is difficult to determine the future required capacity. This problem also expands when companies cope with a rather high product variety in combination with low volumes in a make-to-order and a make-to-build environment (common in high-tech firms). Such high-tech firms often have a high grade of product and process complexity, process cluttering and high demand fluctuation (Jina et al., 1997). These elements underlie the problem of incorrect required capacity estimations. Eventually it will become more difficult to absorb the demand uncertainties solely by a quick response and flexible allocation of human resources. This also implies that an unstructured manner of capacity management is not sufficient to correctly handle the uncertainty regarding the required capacity.

For most high-tech firms, it is also not possible to decline orders from customers when there is not sufficient available capacity. This is due to the fact that high-tech firms are mostly a fundamental link in the supply chain of OEMs. Thus, when PT is unable to honour the agreements, the customers face delays. For this reason, all orders have to be confirmed and produced. From this point forward, PT will be used as a case study to address the problems regarding future capacity management that high-tech firms face.
2. Research design

After numerous interviews and a comprehensive orientation within PT and the corresponding processes, a clear scope was developed regarding the aim of the research. In section 2.1, the goal of this research is defined and research questions formulated in section 2.2. Subsequently, the methodology used will be explained, which serves as a guideline for this research project. Section 2.3 and 2.4 describe the scope of the project and the deliverables which were agreed upon in consultation with PT and the supervisors from the Eindhoven University of Technology.

2.1 Research assignment

The priority of the firm lies in the timely delivery of orders to their customers. This is monitored by the Planning department by means of several key performance indicators. As comprehensively discussed in section 1, sufficient available machine capacity and efficient use of the available capacity are a necessity in order to ensure a high service level and minimise the cost of capacity. However, to accomplish this objective, a firm should manage their capacity efficiently, concerning either machines or labour.

At times when the required capacity is much lower than the available capacity, the firm should consider making employees redundant. However, when the required capacity is greater than the available capacity the firm should consider the procurement of a machine and/or hire labour as part of production planning. However, at this moment, there is little understanding of the S&OP-process and therefore no reliable control of future required capacity. Regaining control in the field of capacity management entails gaining insight into the S&OP-process and the corresponding factors which influence this process. The manner used to evaluate the forecasted required capacity against the forecasted available capacity is unstructured, unreliable, dysfunctional and unclear. This is due to the lack of understanding of important forecast factors and theoretical background used to evaluate the required and available capacity. As a result of these issues, an objective of the project can be designed:

To develop a reliable sales and operations planning process from which a reliable forecast is developed using accurate estimations for the available and required capacity.

2.2 Research questions

The main aim of this project is to develop a model for the purchase decisions of machines within PT and to aid decision-making regarding a chase or level strategy for the workforce. These decisions should be made at a sales and operation planning meeting. The application should provide a required capacity forecast as well as accurate estimations of available capacity. However, as previously mentioned, sales and operation planning is currently not in place. The model should also guide the management on whether machines should be purchased. For the construction of the model and placement of sales and operations planning, it is necessary to investigate all possible and relevant factors related to purchasing/hiring a machine.
1) **What are the relevant aspects for S&OP?**
   a) What are the forecasting methods used in S&OP with high demand uncertainty?
   b) Which strategy is used when there is high demand uncertainty?

2) **What are the capacity and decision models that affect S&OP?**
   a) How can the available capacity be calculated per production unit?
   b) Which model can be used/developed to calculate the required capacity per production unit?

3) **How should purchase decisions be evaluated?**
   a) How should the models for the capacity be implemented?
   b) How can the decision-making for purchasing/hiring a machine be incorporated in a S&OP-model?
   c) How should the outcome(s) of the S&OP-model be evaluated?

2.3 **Research methodology**

In operational research, several challenges may emerge. One of these challenges entails balancing relevance and rigor. This balance assures placement of the research in the academic field as well as in the practical field (Katzav, 2014). Van Aken et al. (2007) provides several examples of such well-balanced research. One of these cases, provided by Van Aken et al. (2007): “Developing a decision support system for the allocation of resources to research and design projects for a small, high tech company”, shows similarities with this research. As Van Aken et al. (2007) states the conducted business problem-solving case often relates to performance and efficiency of a specific business process, with the ultimate goal of increasing the profit of a company. For this research, an aggregate approach for forecasting will be used for the S&OP of PT. Such an approach is supported by Van Aken et al. (2007). They claim that when academic research is not relevant, solutions in management literature are sought.
In the field of operations management literature, there are several research methodologies ranging from qualitative to quantitative and from normative to descriptive. Depending on the research direction, certain approaches are preferable. However, it should be kept in mind that they are not mutually exclusive. Betz et al. (1974) developed a model which entails the operational research approach based on four phases with cross functional transitions (Figure 5). This framework will be used as foundation for this research project. However, to further complement this framework, the first phase of the regulative cycle (the orientation phase) will be included in this research (van Aken et al., 2007). Thus, this thesis will be structured according to the orientation phase and the framework of Mitroff et al. (1974). An outline of the framework with the reference chapters and the sections where the research questions will be answered is depicted in Figure 6.
2.3.1 Orientation Phase

The orientation phase should result in a project proposal which consists of the problem context, the problem statement, the assignment, the project approach, the cost of the project and the theoretical background. These are all required to gain more insight into the process and its problems. These aspects were covered in the Chapter 1 and the research proposal. The insight which was gained from these chapters will be covered in the third chapter of this research and the literature review.

2.3.2 Conceptualization

Conceptualization is the first stage of the framework. As the name implies, this stage focuses on the actual construction of the conceptual model which consists of the model itself, the parameters and the scope. This part also provides the input and output parameters as well as the performance parameters and any restriction to the model.

2.3.3 Modelling

This stage will convert the conceptual model into a quantitative scientific model, which will be subjected to several restrictions. The quantitative model is noted in mathematical terms for the purpose of implementation in an optimization. In this project, the mathematical model is a capacity management decision model. This model should be able to determine the optimal balance between capacity and cost of capacity as well provide insight into in the deviation of the capacity fluctuations.

2.3.4 Model solving

This phase contains the development of tools based on the mathematical models to solve the problem. Based on what-if-analysis different demand scenarios were determined which was used as input for the
mathematical model. The mathematical model has many input variables, which makes it rather complex. For this reason, the verification and validation are very important for this phase in order to be able to conclude that the model will provide reliable and valid results.

2.3.5 Implementation

Implementation is the final phase of the framework. As the name implies, this phase mainly focus on the actual implementation of the research and the corresponding results. Within this research it implies that a summarization will be provided of the results and a conclusion to the project is provided.

2.4 Deliverables

Based on the used framework discussed in this section several deliverables can be defined. The deliverables are listed below.

- Conceptual model: the conceptual model should be of added value in the scientific literature.
- Mathematical model and heuristics of the problem: The conceptual model should be transformed to mathematical equations, heuristics and/or objective function. This is required, so that the problem van computation and problem solving are possible.
- Model testing and solution method: the mathematical model is converted into tooling which is validated and a solution for the problem is provided. The solution method is intertwined in the numerical study.

2.5 Project scope

The following decisions regarding the scope are made:

- One production unit will be investigated and evaluated. This production unit is called SMD. This production unit is the most expensive and most highly utilised production unit within PT. Further information regarding these production unit will be provided in Chapter 4.
- The decision to purchase or sell machines as well as whether to hire and fire workforce is taken into consideration for the scope.
- The research will focus on the largest customer of PT. The choice was made to choose the customer which accounts for more than thirty percent of the available capacity of the production unit SMD. This customer will be referred to as Customer X.
- The period studied will be from month 0 to month 24. This is due to the fact that machines within PT should be purchased at the latest 6 months before delivery. With this scope it is possible to make timely decisions regarding the purchase of new machines.
- Parameters for products will be extracted from the ERP-system maintained by PT. These parameters consist of queue time, processing time, setup time, routings, splitting and base quantity. These terms will be further elaborated in Chapter 4.
• Only demand of existing products is taken into account. This implies that new products for all customers which are still in the project phase will not be considered. These projects often do not have any forecast.

• A chase and/or level strategy regarding the machine plan and the workforce will be one of the outcomes of the research. This concept is further elaborated in Chapter 3.
3. Sales and Operations Planning (S&OP)

One of the research questions concerns the forecasting methods used in S&OP under high demand uncertainty. An overview of available literature on the subject and important insights gained from literature are therefore addressed in this chapter. In the first part of the chapter, sales and operations planning is discussed in general. Subsequently, literature on the aspect of high demand uncertainty in S&OP will be discussed followed by S&OP-strategies.

3.1 Sales and operations planning

Sales and operations planning is the long-term management of capacity. Decisions on when and how much available capacity levels should increase or even decrease are at the heart of S&OP (Olhager et al, 2001). Within PT it is also of importance to make timely decisions on when the machine plan should be altered and by how much. Detecting a capacity problem too late can result in an inability to complete orders on time. To determine future capacity problems, the process of capacity management should be clear. This section will therefore provide insight into the process used for future capacity management (S&OP-process), available strategies for forecasting under high demand uncertainty, and methods of decision-making concerning timing and quantity.

S&OP determines the long-term deployment of manufacturing resources; it keeps capacity in consideration and is based on sales and demand forecast (Olhager & Johansson, 2012). Its process normally entails monthly planning periods over nine to eighteen months. S&OP encompasses long-term production planning and predicts sales based on forecasted demands and production capacity. The Sales department and the Operations department are closely involved in decision-making.

The role of S&OP in coordinating and integrating processes, including sales and operational processes, cannot be overemphasized (Sodhi & Tang, 2011). This is because organisations must respond promptly and effectively to customers' needs (Wallace, 2004). Slow responses to customer needs may result in missed business opportunities and excess inventory; both may have costly consequences (Karlsson & Sandin, 2011). Therefore, having a cross-functional approach for balancing sales and production plans, which is the essence of S&OP, has become more crucial (Cecere et al, 2009).

S&OP can be viewed as a process of periodic, cross-functional tasks aimed at aligning supply and demand (Ivert & Jonsson, 2010), (Wang et al., 2012), (Plank & Hooker, 2014), (Lapide, 2014). Olhager et al. (2001) describe S&OP as an interfunctional attempt to develop a production plan that economically fulfils market needs while contributing to the firm’s strategic and financial objectives. Although S&OP aims to align an organization’s operational plans with its business strategy, Grimson and Pyke (2007) emphasise that the ultimate goal of S&OP is profit optimisation.

According to Karlsson and Sandin (2011), a proper balance between sales and production plans can only be effectively achieved when a number of fundamental planning parameters have been established. These include:
• planning horizon (how far into the future S&OP plans should be made, ordinarily one to eighteen months);
• planning frequency (how often plans ought to be revised, ordinarily three times per month);
• planning objects (concerns demand units in the demand plan and production volume in the supply plan);
• units of capacity (the measure by which capacity requirements are specified, such as machine hours or man hours);
• time fences for change in plans (the timeline within which the present production is linked to successive planning events).

The design of the process structure succeeds the establishment of parameters (Karlsson & Sandin, 2011). Though literature provides different steps to this process, according to Ivert & Jonsson (2010) and Karrenbauer (2015), it generally entails the following:

• data gathering (sales and market data);
• demand planning (assessing historical accuracy and generating cross-functional forecasts);
• supply planning (evaluating historical accuracy, establishing capabilities, and creating viable plans to match supply and demand);
• cross-functional meetings (for identifying conflicts, providing resolutions, and assessing plans against strategic and financial objectives);
• executive meetings (for reviewing recommendations, resolving conflicts, and further assessing plans).

These steps illustrate that S&OP is a cross-functional process that aims at balancing supply and demand. However, S&OP has evolved over the last two decades to include not only balancing demand and supply, but also balancing goals and risks. Thus, critics argue that the previously mentioned five-step process does not effectively reflect market potential and profitability. For this reason, it is important to include aspects such as the what-if analysis in S&OP-processes. While an S&OP-process can appear straightforward on paper, its implementation is often a taxing endeavour due to factors such as organizational structure and culture (Grimson & Pyke, 2007).

Correct implementation of S&OP provides important advantages to an organisation. These include better implementation of strategic objectives at the operational level, better information flow across functions and the supply chain, cost minimisation, improved lead times, optimised inventory levels, and planning and operational efficiency (Ivert & Jonsson, 2010), (Karlsson & Sandin, 2011), (Adamczak et al., 2013), (Karrenbauer, 2015). S&OP can immensely enhance an organization’s operational performance, which may in turn positively influence its financial performance.

3.2 Uncertain demand
The production environment is often characterised by many uncertainties due to factors such as demand fluctuations, inadequate forecasts, and inconsistencies between product-level and aggregate production
plans (Balachandran et al., 1997) (Thome et al., 2012). Thus, demand planning, which is one of the important stages of the S&OP-process, is often a challenging task. According to Sodhi & Tang (2011), demand planning generally goes hand in hand with three risks: unmet demand, surplus inventory and insufficient liquidity arising from demand uncertainty. Incorrect demand planning, therefore, presents a great risk for businesses. Scenario analysis can provide a better understanding of these risks scenarios.

Warren (2012) suggests that the scenario analysis (what-if analysis) can be effectively utilized in S&OP to manage demand uncertainty and other complex issues. In fact, the scenario analysis has become an important element of the S&OP-process (Karlsson & Sandin, 2011). A scenario analysis provides insight into likely changes in the business environment and the most appropriate way to mitigate them. It entails considering a variety of strategic and operational objectives and constraints, having an understanding of the issues presenting the greatest problems for the organization, evaluating various options for tackling problems and their anticipated outcomes, and selecting options that optimise outcomes (Warren L., 2012). Essentially, a scenario analysis evaluates different courses of action based on predefined objectives. Organizations never know if a single plan will be the final plan. This is due to the highly uncertain nature of the environment in which they operate. Organisations must consider several options and determine the best option based on different scenarios (Karlsson & Sandin, 2011). Some major advantages of scenario analysis are that it allows visibility into the future, enables a proactive approach to S&OP, enhances decision-making, and enhances business sustainability and profitability (Warren L., 2012). A disadvantage is that scenario analysis is mostly limited to several scenarios and does not provide a great understanding of the required capacity distribution. It is rather black and white; it simply lays out the worst-case scenario, the expected scenario and the best-case scenario.

Though scenario analysis is a valuable technique for approaching S&OP under demand uncertainty, it can be quite difficult, especially when a company has numerous product families (Sodhi & Tang, 2011). A better approach, as suggested by Sodhi and Tang (2011), is to use stochastic programming across various demand scenarios. It evaluates demand planning risks across different demand scenarios. Other studies have demonstrated the usefulness of stochastic programming in planning with demand uncertainty (Balachandran et al., 1997) (Stephan et al., 2010) (Letmathe et al., 2013) (Herbon & Kogan, 2014). Though stochastic programming provides many advantages (e.g. it is quicker and generates optimum and consistent solutions across different scenarios), many computational requirements are involved in solving stochastic models (Sodhi & Tang, 2011). More importantly, further research is needed to explore the suitability of stochastic programming in tackling S&OP under demand uncertainty.

### 3.3 S&OP-Strategies

Capacity management, especially within the manufacturing environment, entails three or four stages, including short-term capacity control and execution, intermediate capacity management and long-term capacity planning (Olhager et al, 2001). Long-term capacity management, which is of particular interest in this research, includes a manufacturing strategy perspective and an S&OP perspective (Olhager et al, 2001). A fundamental question from a *manufacturing strategy perspective* is whether available capacity should precede anticipated demand changes, or whether available capacity should be achieved after acknowledging
the matching demand level. Three strategies can be considered in this case: a lead strategy, a lag strategy or a track strategy (Olhager et al, 2001)(Figure 7). These three options centre on the timing and quantity of the available capacity versus the required capacity (Olhager & Johansson, 2012).

A lead strategy implies adding available capacity in expectation of increased demand (Olhager et al, 2001). The approach particularly aims to maintain a capacity level that can be used to guarantee flexibility in production volumes as well as reliability of lead times (Olhager et al, 2001). The problem lies in the fact that capacity should be increased to meet demand; in essence, capacity should always exceed or be equal to demand.

The lag strategy, which is the opposite of the lead strategy, is informed by a need to maintain a high deployment of resources (Olhager et al, 2001). In this case, it is important to achieve the highest level of production possible while maintaining full utilisation of capacity (Olhager et al, 2001); available capacity should never surpass required capacity. As a result, sub-contracting is sometimes necessary (Olhager & Johansson, 2012). The track option, which combines both the lead and lag strategies, consists of monitoring demand as closely as possible in order to minimise variances between demand and capacity (Olhager et al, 2001). It implies that there will be times that the available capacity has a leading behaviour and times that the available capacity has a lagging behaviour.

While the manufacturing strategy perspective seeks to balance available capacity and demand, the S&OP perspective aims to balance the level of demand in different time periods with the level of available capacity (Olhager et al, 2001). To achieve this balance, decisions must be made regarding marketing, production levels or rates, inventory levels, human resource requirements, subcontracting, etc. (Olhager et al, 2001). This includes decisions based on adjusting supply according to the sales plan (Olhager et al, 2001). Decisions relating to supply particularly aim to level production, chase sales or achieve the two

![Figure 7: Capacity Leading Demand](image-url)
simultaneously. In other words, there are three strategies for balancing the sales and production plans under the S&OP perspective: a chase strategy, a level strategy and a mix strategy.

A chase strategy essentially entails following the sales plan to match production with demand (Olhager et al, 2001). Available capacity is matched with required capacity in each planning period. This stabilizes inventory levels, thereby achieving flexibility and adaptability. However, this comes at the risk of potentially deploying too many or too few production resources and of incurring higher costs due to capacity adjustments (Olhager et al, 2001).

A level strategy involves maintaining a stable rate of available capacity, which results in varying levels of inventory (Olhager & Johansson, 2012). In this strategy, a consistent level of production is maintained over the course of a predefined period, thereby ensuring a consistent and high deployment of production resources (Olhager et al, 2001).

The mix option is a combination of the chase and level strategies; a production level is maintained for some time and then adjusted when demand requires (Olhager et al, 2001). In other words, the production rate is adjusted over the planning period. This produces a better match between production and sales as well as a steadier production environment. This makes the mix strategy better than the chase and level strategies (Olhager et al, 2001).

The difference between the two perspectives can be found in the flexibility of the required capacity or the flexibility of the available capacity. From a manufacturing perspective, the available capacity is changed over time to maintain an efficient utilisation of resources. This implies that the available capacity changes as a function of the required capacity. In contrast, the S&OP perspectives changes required capacity over time; the required capacity changes as a function of the available capacity.

The appropriateness of the strategies listed above may differ from one manufacturing environment to another. This depends on several factors such as automation, flexibility, leaness and product modularity (Olhager & Johansson, 2012). For instance, lag and level strategies tend to be suitable for standardised, high volume products as well as line production and continuous processes. Lead and chase strategies tend to be suitable for highly customized, low volume products as well as project manufacturing and job shops (Olhager & Johansson, 2012). The latter is the case for high-tech firms. Thus, a combination of lead and chase strategies seems to be the most appropriate strategy for high-tech firms. Consequently, this will be taken into account when developing a capacity planning model.
4. Conceptual models and system parameters

The conceptual model serves as a foundation for the mathematical models, which will be further discussed in Chapter 5. This section establishes and discusses the scope, the parameters and variables concerning the conceptual model. This section begins with the demand scenario capacities and is followed by a discussion regarding the input and output parameters to compute the required and available capacities.

4.1 Conceptual models

This research focuses on the long-term capacity management (S&OP) of a production unit. Based on the literature study and PT, the chase strategy was used to optimise the machine and workforce plan against minimal costs. Firstly, demand scenarios were determined to account for fluctuations in demand. The determination of the different scenarios was done by means of the Demand-Scenarios-Model. Following that, the output of these scenarios was used as an input for the ‘Required-Capacity-Estimations-Model. To calculate the capacity requirements, the monthly-based infinite MRP was used. This implies that demand is planned without taking existing available resources into account.

Normally the use of aggregate demand is justified for the usage for sales and operations planning. However, the use of aggregate demand gives a wrong representation of the demand distribution when a company produces products with high BOM-levels and long lead times. This is also the case for PT. Products of PT can have over five hundred sub-assemblies with more than eight BOM levels. All of these BOM levels may also have a rather high lead time. The total production lead time over the entire BOM can be, as a result, over six months. This means that a large customer order in month \( t \) does not cause a large required capacity peak in month \( t \) but for example in month \( t - 3 \). The use of aggregate demand can therefore give an unrealistic visualisation of the demand distribution over time. To incorporate these lead times and other parameters which affect the demand distribution (such as lot sizes), MRP is used to determine the demand distribution. Based on this demand, the required capacity will be computed.

This required capacity is then used as input for the IP-Model, which is an integer programming model. In general, the model evaluates the required capacity against the available capacity. The evaluation entails checking the required and available capacity against several constraints (section 4.3.6). If the constraints are not satisfied, the workforce, machine plan and/or shifts are adjusted. The goal of the IP-Model is to minimise total investment costs and to satisfy all constraints. The IP-Model provides the total costs and the monthly machine and workforce plan of each scenario. The outputs of these scenarios are then evaluated against each other to provide more insight into the investment risks and problems which could arise when investing in the wrong scenario. An abstract representation of the models is provided in Figure 8. The remaining part of this chapter further elucidates the input parameters of the model.
In consultation with PT, the focus of this research rests on a production unit of the PCBA department, which can be divided into two production units, namely: the surface-mounted device line (SMD) and the conventional assembly line (CAL). SMD is a fully automated production line. Apart from the setup of the machine and machine maintenance, no manual labour is required for operating the production line. In contrast, CAL is a semi-automated production line. This means that production is partially manual and partially automated. In general, products are initially processed by SMD and afterwards further processed by CAL. The products are temporarily buffered between SMD and CAL before being further processed by CAL (Figure 9). Within PT, SMD is the highest utilised production unit. For this reason, the focus of this research is the production unit SMD.
4.2 Demand scenarios

As mentioned in section 3, the forecast of the near future is, in general, more certain than the end of the time studied. This research assumes that this uncertainty can be represented as a random use of distributions. Because the uncertainty differs per time period, the distribution (parameters) can also differ per time period. An example of a single period forecast of demand probability distribution is illustrated in Figure 10. To cope with the uncertainty that accompanies demand, different demand scenarios are computed, which is referred to as the Demand-Scenarios-Model. These scenarios will be based on a chosen confidence interval; the outer ranges of this interval represent the most pessimistic and optimistic scenarios and the mean represent the most likely scenario. It must be noted that the determination of the confidence interval is a managerial decision. Choosing a rather high confidence interval accounts for higher fluctuations, thus incorporates more uncertainties. Consequently, it leads to a more optimistic and a more pessimistic scenario. Figure 11 illustrates the scenario forecasts actual demand over time. However, this research is concerned with the relative change as opposed to absolute change. A relative change can be seen as a percentage or ratio. For example, with a relative change it can be said that the demand in month 14 of the optimistic scenario is two times higher (two hundred percent) than the forecasted demand. The use of relative changes makes it possible to use the distribution on different scales (e.g. daily, weekly or monthly). An example of this concept is further illustrated in section 5.2.1.

![Figure 10: Probability distribution of single-period forecast](image)

![Figure 11: Demand scenarios over time](image)

After the determination of the demand scenarios, this demand is converted to the capacity requirements of a production unit. To calculate the capacity requirements, a monthly-based infinite MRP is used. This means that demand is planned without taking existing available resources into account.

4.3 Input and output parameters for the capacity estimations

To manage and evaluate the capacity of a production unit, it is necessary to know the available capacity and the required capacity. To compute the required and available capacities, several input parameters are necessary. These input parameters, except for the demand, are stored in the ERP system, which are discussed in section 4.3.2 and 4.3.3.
4.3.1 Production unit

A production unit is an organisational unit that defines where operations must be performed to manufacture an order. SMD is an example of a production unit. To manufacture a product, several operations are performed in a specific sequence, which is referred to as a routing. A routing is unique per product. These operations represent production units on the floor and each routing’s production unit has predefined parameters (see section 4.3.2). A routing is therefore a representation of the process flow on the production floor. When all these operations are completed, the product is completed and can be sent to the customer or stocked. An example of a routing consisting of a production unit SMD and a production unit CAL is depicted in Figure 12. The routing is used to check if a production order follows a specific production order; if this is the case, it is used as an indicator that capacity is required for the production order. The capacity required to produce an order depends on several factors such as setup times, process times, base quantities, production quantities and splitting. Each of these parameters are unique per production unit, per routing and per product. All of these parameters are maintained in the ERP system used by PT and are briefly discussed in this section. When necessary, an example of the parameter, which uses the production unit SMD as an example, is provided.

![Figure 12: Example of a production order routing](image)

4.3.2 Required capacity of a production unit – parameters

Setup time

The setup time at PT is defined as the time required to prepare a machine for the production of an order plus the difference of the time between when the product first enters the production unit and when it exits (Figure 13). The setup time is unique per production unit and is independent of the order quantity. In the example in Figure 13, the setup time is the preparation time (PPU), \( t_2 - t_1 \) plus the time until the first product leaves the production line (PTFPU) \( t_3 - t_2 \). Thus, the total setup time consists of \( PPU + PTFPU = (t_2 - t_1) + (t_3 - t_2) = t_3 - t_1 \). In this Setup time, the machines cannot be used. For this reason the setup time can be seen as required capacity on a production order. This setup time is also required to compute the total lead-time.

![Figure 13: Setup time at PT](image)
Process time

The process time at PT is equal to the difference in time of two consecutive end times of a product of an order on a production unit (Figure 14). The process time of the example is \( \frac{(t_3-t_2)+(t_4-t_3)+(t_5-t_4)}{3} = \frac{t_5-t_2}{3} \).

This processing time is used to compute the required capacity on a production unit and the processing times of each material is maintained in the ERP system of PT.

![Figure 14: Processing Time](image)

Splitting

With splitting, the production order is divided across several identical production units. This is generally used to reduce the lead time of production units that consist mainly of labour. For example, when the splitting quantity is equal to four, it means that four machines/employees will process the order simultaneously. If a production unit has to process one hundred units with a splitting quantity of four, then four identical machines/employees will each process twenty-five units. However, when splitting is used, each machine/employee has a set up; thus, each machine/employee has a setup time. Although splitting is generally faster, it also requires more capacity. An example is provided in Figure 15. If splitting is not used, the total required capacity of the production unit is equal to eighteen hours. However, if splitting is used, the total required capacity is equal to twenty-four hours. The option to split orders is used by some products on a production unit at PT.

![Figure 15: Splitting](image)
Base quantity

Base quantity is an important parameter for the calculation of the required capacity of a production unit. A base quantity is unique per production unit. The term is used to indicate the quantity required per processing time on a production unit. For example, if a production order of eighty pieces has a base quantity of four, it means that the process time will be executed twenty times (Figure 16).

4.3.3 Available capacity of a production unit - parameter

For a production unit to process a product, it must have available resources, which are expressed in available labour hours and machine hours per production unit. Roughly, the capacity for a time period consists of three main factors: operational days, machines/workforce and shifts in a period.

Operational days

To be able to process a production order, the production unit must be available for order processing. A day when a specific production unit is available is referred to as an operational day, which is unique per production unit. For example, production unit 1 might have thirty operational days in a month, while production unit 2 has twenty-four operational days. The operational days for the production unit SMD per month are presented in Table 1.

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
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<tbody>
<tr>
<td>Year 1</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>27</td>
<td>26</td>
<td>26</td>
<td>26</td>
<td>25</td>
<td>26</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>Year 2</td>
<td>25</td>
<td>27</td>
<td>26</td>
<td>26</td>
<td>27</td>
<td>26</td>
<td>26</td>
<td>25</td>
<td>26</td>
<td>24</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Operational Days per Month

Workforce and machine level

The workforce and machine level plays an important role in the available capacities of a production unit. A large workforce and high machine levels ensure more available capacity per production unit. Taking SMD as an example, its production unit has five production lines. The number of machines is thus equal to five. Both the machine plan and workforce plan have initial values. For the machine plan, the values are five for SMD and, for the workforce plan, the values equals 31.
Shifts

A shift is a time frame on an operational day when the production unit is available to process an order. A shift always has a specific duration that can, but does not always, vary per shift. A shift is unique per individual capacity per production unit. Each unique shift also never overlaps with other shifts on the same day of the production unit. PT maintains three shifts, each with a duration of eight hours. In general PT aims to fill the first two shifts. However, if this is not feasible due to capacity restrictions, the third shift is also used. If PT uses the third shift, it is seen as overtime.

4.3.4 Demand

Product demand is based on two different types of forecast: demand and sales. The difference between these forecasts is the accuracy and the time horizon in which they are provided. The demand forecast mostly ranges from zero to twelve months and is depicted as demand per week (Figure 17). The sales forecast, however, has a longer range; it mostly entails the range from thirteen to twenty-four months and is recorded as demand per month. Next to the computations of the final demand, the demand of the sub-assemblies must also be computed. This is done with help of the BOM, the lead time and scrap percentages.

Demand scenarios

As mentioned, due to uncertainties of future orders, future demand has a higher degree of uncertainty than short-term demand. This implies that demand in the future can differ from what is expected. To incorporate this uncertainty, several scenarios of the forecast were developed. The sales and demand forecast provided by Customer X is depicted in Table 2. This forecast was used to compute the demand scenarios and used as an input for the IP-Model. The demand of Customer X exists of two end products. This demand is divided equally between end product 1 and 2. However, when the demand is uneven, this is always in favour of the demand of product 1. Therefore, in the case of month 2, the demand for product 1 is equal to 6 and 5 for product 2. The latter was based on historical data and information provided by the planners.
Table 2: Forecast of a products per month provided by Customer X

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<td>Demand Year 1</td>
<td>14</td>
<td>11</td>
<td>11</td>
<td>16</td>
<td>10</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>12</td>
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<tr>
<td>Demand Year 2</td>
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<td>9</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

**Bill of material**

The bill of material (BOM) consists of all components and sub-assemblies to produce the final assembly. The BOM depicts a tree-like structure of the product and its sub-layers. Each branch represents the relationship between a predecessor product and a successor product and the corresponding ratio between each predecessor and the successor. PT stores every BOM in its information system, which also contains every ratio of successors and predecessors (Figure 18).

![Figure 18: Bill of material](image)

**Lot size**

When the customer sends forecasts, the demand is often determined on a weekly basis. However, the proposed demand plan of the customer is often in non-economic production quantities. Customers' demand plans obviously do not correspond with PT’s optimal production order quantity. PT has used several calculation models to determine the optimal lot size for production orders. The lot size methods used at PT is the fixed cycle rule (Dellaert, 2012). By applying trade-offs between inventory and production, PT ensures that it holds efficient and economically-desirable lot sizes (Hoppe, 2007). All the fixed lot size cycles are maintained in the ERP system. For example, a fixed cycle of four means that a production order
will consist of demand in the present up to four weeks ahead. An example of the fixed cycle of three is presented in Figure 19.

<table>
<thead>
<tr>
<th>Week</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>12</td>
<td>15</td>
<td>10</td>
<td>14</td>
<td>22</td>
<td>11</td>
<td>0</td>
<td>12</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Production order</td>
<td>37</td>
<td>0</td>
<td>0</td>
<td>47</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>35</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 19: Fixed periodic lot size of three

**Scrap percentage**

During production, it often occurs that some products are defective beyond repair. This is due to errors in the production process. To cope with these defective products, a scrap percentage is linked to each material. This scrap percentage indicates the percentage of the products that will be unusable after completing the production process. To produce the correct amount of working products from an order, the order should correspond with this scrap percentage. This means that a production order will produce additional products to cope with the scrapped products. For example, if 99 products are required, but the scrap percentage equals 10 for a production order, the production order will consist of \( \left( \frac{99}{0.9} \right) \) 110 products. If these 110 products are produced, 10% will be scrapped due to defects and 99 usable products remain.

**Lead time**

For a production order, the lead time resembles the time required to process the order. The lead time consists of several times, including queue time, setup time and floats. The collection of these times gives the total lead time for an order. Due to the minimal impact of the processing time of an order in small batches, this time can be neglected. For this reason, the processing times are not taken into account for the lead time calculations. Thus, the lead time can be calculated by adding all floats, setup times, queue times and processing times of an production order.

**4.3.5 Costs**

**Workforce-related cost**

Several costs are associated with the workforce. The cost of hiring an individual is one thousand Euros, and the cost of firing an employee is three thousand Euros. At PT, the cost of labour depends on the assigned shift. The third shift is the most expensive shift, costing sixty Euros per hour for each employee. The first two shifts cost forty-eight Euros per hour for each employee.
Machine-related cost

There are also costs associated with machines, which are based on the number of production units. The cost corresponding to the SMD line exists of fixed and variable costs. The fixed costs per hour have to be paid even when the machine is not used while the variable costs only have to be paid when a machine is used. These costs include repairs, maintenance and the purchase costs of the machine. The fixed costs are equal to two hundred Euros and the variable cost depends on the shift. The third shift is the most expensive shift, costing one hundred Euros per hour per machine. The first two shifts cost fifty Euros per hour per machine. The cost related to purchasing machines also differs and the cost of purchasing an SMD line is two million euros. Machines can also be sold, but typically only ten percent of the purchase value of the machine is recovered. Thus the selling value equals two hundred thousand Euros. These costs were obtained from the finance department.

4.3.6 Utilisation

Several constraints are defined for the IP-Model and the corresponding decisions. These constraints ensure that the machine and workforce plans align with the company's objectives. This section presents the main constraint.

"Utilisation" is the proportion of the available time that the production unit is operating. The utilisation will be expressed in percentages; it always lies between 0% and 100%. The utilisation is an important indicator of the use of a production unit. A utilisation that approaches 0% means that the production unit is hardly used and may be redundant. In contrast, a utilisation of 100% means that a machine has almost reached its maximum capacity. For PT, it is important for the utilisation of the machines and workforce to remain lower than 85%. By choosing a utilisation of 85%, PT accounts for machine down time and back orders. Other constraints are also applicable; these constraints relate to the conservation of the workflow and the filling of shifts (see section 5.2.4.3).
5. Modelling

The model that is constructed in this research project uses the scope, input and output parameters of section 4 as a foundation to construct the mathematical model. To compute the demand for different scenarios, a stochastic probability distribution based on historical data is calculated by means of the Demand-Scenarios-Model. The demand is then used as an input parameter for the Required-Capacity-Estimation-Model. Finally the required capacity serves as an input for the IP-Model. This section discusses assumptions necessary for the model, the project design and the mechanism. Abbreviations used in this section are included in Appendix G. This section is followed by verification and validation of the outcomes.

5.1 Assumptions

The following assumptions are made for the computations:

- Demand over a period can be approached according to a probability distribution.
- The same probability distribution is used over all time periods. However, the parameters may differ.
- Deviation of the demand over a time horizon can be extrapolated over time. For instance, when a normal distribution is present and the period 1, 2, 3 and 4 respectively, $\sigma$ is 1, 2, 3 and 4, then it is assumed that in period five, $\sigma = 5$. However, this can only be done when there are fourteen or more measurements. This to ensure that the extrapolated data is reliable.
- Due to the fact that not all historical data for all customers is stored and because of the time limitations of the project, not all demand fluctuations of all customers can be taken into account. For this reason, the forecasted demand that does not belong to Customer X was seen as a fixed demand without any fluctuations ($\mu = 1, \sigma = 0$). Consequently, a customer that seized roughly thirty percent of the capacity of the production unit SMD was chose for investigation.
- When a scrap percentage is maintained by PT, this percentage is always eliminated. This means that when a scrap percentage of ten percent is maintained in the system, ten percent of the products (rounded to the closest integer) will be eliminated.
- Process time may be neglected in calculating the lead time. This is due to the minimal impact of the process time in comparison to the other lead time parameters.
- PT can also be in production on a holiday.
- PT is closed on Sundays.
- Maintenance, repair and down time are incorporated in the maximum set utilisation of 85%.
- Machine cost does not differ over time. They always stay the same over the time horizon.
- Cost of labour remains the same.
- Demand in each scenario is rounded to the closest integer.
5.2 Design

5.2.1 Generation of demand scenarios

The forecast of the demand provided to planners does not always reflect reality. It seems that the reliability of the forecast diminishes over time, and the degree of reliability also varies per customer. For each customer, different demand scenarios are applicable. It is not possible to determine the precise demand, but it is possible to estimate it. To estimate a demand, it is important to know the time frame's distribution. As mentioned, a forecast in the short–term is often more certain than a forecast in the distant future. The distribution differs per time period, thus the demand for the planning horizon can be represented as a distribution over multiple time periods. Obtaining a distribution for the periods is practical, as such a distribution can be determined based on historical forecasted demand compared to the actual produced demand. In this research, distribution is based on the ratio of the forecasted demand against the actual demand. In mathematical terms, the forecast provided in month \( k \) of the forecasted demand of a month \( l \) is denoted as \( FD(k, l) \), the actual demand is denoted as \( AD(l) \), and the ratio is denoted as \( R^x_k \). The latter formula can be computed using Eq. 1:

\[
R^x_j = \frac{AD(x + k)}{FD(k, x + k)} \tag{Eq. 1}
\]

For example, if the forecasted demand is 130 and the actual demand was 100, then the ratio will be \( \frac{100}{130} = 0.77 \). If a set of ratios is computed for a \( x \)-month forecast, a distribution is fitted on this set of ratios. This distribution is later used to determine the demand deviation of a \( x \)-month forecast. This set of ratios consists of the same \( x \)–month forecast compared to the actual demand. The set of the 1-month forecast consists of 1-month forecasts (thus the forecast which was sent every month) compared to actual demands. Based on the distribution, three scenarios are computed. These scenarios are based on a chosen Confidence Interval; the outer ranges of this interval represent the most pessimistic and optimistic scenarios, and the mean represents the most likely scenario. In Figure 20, for example, the pessimistic, most likely and most optimistic scenarios are based on the boundaries of a 80% confidence interval. In the case of the example, the pessimistic case is equal to 0,75, the most likely case is 1,00 and the optimistic case is 1,25. This ratio is then multiplied with the forecasted demand. Thus, for the forecasted demand of 130, a pessimistic view of the demand would be equal to \( 0,74 \times 130 = 97,5 \); the most likely demand would be 131,3, and the most optimistic case would be 163,5. In the numerical study, demand is rounded to the closest integer.
To illustrate this method, assume that Customer Y has a rolling forecast of one hundred units every month from month one to month twenty-four. Customer Y always provides a monthly rolling forecast of twenty-four months (Appendix D). The historical forecasted demand can be evaluated against the actual demand. A small part of the forecasted demand is depicted in Table 3.

The leftmost column represents the month in which the forecast is provided. The horizontal row represents the forecast provided in the month in the first column. For example, in month 1, the forecast for month 2 was 112,72 and the forecast for month 3 was 127,51. The diagonal axis represents actual demand. To take a random example, in month 3, the actual demand was 120. By comparing the actual demand and the forecasted demand, it is possible to determine the demand realisation ratios. For example, in month 1, the two-month forecast was set at 127,51. However, the actual demand in this period was 120. The demand was therefore a factor $(\frac{120}{127,51}) = 0.94$ of the predicted demand. This logic applies to all periods. Based on Eq. 1, the total sets of ratios were computed through to the twenty-fourth month forecast ($1 \leq x \leq 24$). A part of the data of a 1, 3, 6 and 12 month forecast is provided in Table 4 and the remainder of the data can be found in Appendix D. These sets are plotted in Figure 21.
If there are less than fourteen measurements of a set of ratios, it becomes difficult to reliably fit a distribution and to determine their parameters. Thus, the parameters of the previous distribution are extrapolated for the other months. When a distribution is fit on the results, it seems that the demand has a rather normal distribution. The parameters of all the twenty-four months have a mean of 1 \( (\forall t : \mu(t) = 1) \). The standard deviation of the demand ratios \( (\sigma) \) of all twenty-four months is provided in Table 5.

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) Year 1</td>
<td>0,01</td>
<td>0,02</td>
<td>0,03</td>
<td>0,04</td>
<td>0,05</td>
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<td>0,08</td>
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<td>0,1</td>
<td>0,11</td>
<td>0,12</td>
</tr>
<tr>
<td>( \sigma ) Year 2</td>
<td>0,13</td>
<td>0,14</td>
<td>0,15</td>
<td>0,16</td>
<td>0,17</td>
<td>0,18</td>
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<td>0,21</td>
<td>0,22</td>
<td>0,23</td>
<td>0,24</td>
</tr>
</tbody>
</table>

Table 5: Standard Deviation of the Forecast over Time Periods

The probability distribution are plotted over time to give a representation of the distribution of the demand ratios (Figure 22). As can be seen, the deviation towards the end is much bigger than in the beginning.
Based on the distribution and the confidence interval, the scenarios can be determined. The optimistic and pessimistic scenarios for a confidence interval of 80% and 90% are provided in Table 6. These values are computed by multiplying the initial forecast of a month with the outer ranges of the 80% and 90% confidence interval. Due to the fact that \( \mu \) is equal to 1, the most likely scenario is always 100. The full list of the table is provided in Appendix D.

<table>
<thead>
<tr>
<th>80% Confidence Interval</th>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>…</th>
<th>6</th>
<th>…</th>
<th>12</th>
<th>…</th>
<th>18</th>
<th>…</th>
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<td>100</td>
<td>&quot;</td>
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<td></td>
<td></td>
<td></td>
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<td>0.97</td>
<td>0.96</td>
<td>&quot;</td>
<td>0.92</td>
<td>&quot;</td>
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<td>&quot;</td>
<td>0.77</td>
<td>&quot;</td>
<td>0.69</td>
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<td>1.04</td>
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<td>&quot;</td>
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<td>&quot;</td>
<td>1.23</td>
<td>&quot;</td>
<td>1.31</td>
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<td>Demand</td>
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<th>3</th>
<th>…</th>
<th>6</th>
<th>…</th>
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<th>…</th>
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<th>…</th>
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</thead>
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<tr>
<td>Demand Forecast</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.98</td>
<td>0.97</td>
<td>0.95</td>
<td>&quot;</td>
<td>0.90</td>
<td>&quot;</td>
<td>0.80</td>
<td>&quot;</td>
<td>0.70</td>
<td>&quot;</td>
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<td>1.03</td>
<td>1.05</td>
<td>&quot;</td>
<td>1.10</td>
<td>&quot;</td>
<td>1.20</td>
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<td>1.30</td>
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<td>1.39</td>
</tr>
<tr>
<td>Demand</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pessimistic</td>
<td></td>
<td>98</td>
<td>97</td>
<td>95</td>
<td>&quot;</td>
<td>90</td>
<td>&quot;</td>
<td>80</td>
<td>&quot;</td>
<td>70</td>
<td>&quot;</td>
<td>61</td>
</tr>
<tr>
<td>Optimistic</td>
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<td>103</td>
<td>105</td>
<td>&quot;</td>
<td>110</td>
<td>&quot;</td>
<td>120</td>
<td>&quot;</td>
<td>130</td>
<td>&quot;</td>
<td>139</td>
</tr>
</tbody>
</table>

Table 6: Example of Demand Scenarios

5.2.2 MRP-Computations

This section presents planning schemes. As discussed in the previous section, monthly demand is computed and converted to a required capacity for a production unit. Subsequently, the machine and workforce plans are determined.

The ERP system used by PT, SAP ECC 6.0, uses material requirements planning to schedule its products (MRP scheme), create demand and determine the required capacity for a production unit. This section discusses the material requirements planning logic used by PT’s system. This logic is mimicked across several computations in order to process the product demand and the resulting capacity needs. The products used for this MRP scheme have a high BOM level. The upper level of BOM level 0 is denoted as final assembly (FERT) and all levels where the BOM level is greater than zero are sub-assemblies (HALB). The MRP scheme is used to allocate planned production orders to production units at specific time periods. The logic starts with the creation of FERT demand in the system. It then computes when all of the HALBs required to produce the FERT are available. If this is not the case, the HALBs are planned for production. To produce a HALB, other HALBs are required. If these are not available, HALBs are also planned for production. This is continued until all HALBs are planned to be produced or/and procured. The planned production orders for the FERT and HALB therefore require some capacity for the unit to be produced. A simple example of an MRP scheme is provided in section 5.2.4.5.

5.2.2.1 MRP-Scheme update procedure

The MRP scheme procedure is depicted in Figure 23. First, the requirements for the upper BOM level are determined \( (i = 0) \); as mentioned this is done based on the demand scenarios. These requirements are
denoted by gross requirements and are necessary for producing a production order or delivering the order to the customer (in the case of FERT). Based on the gross requirements and the stock level, the net requirements are determined; these are the requirements that cannot be fulfilled directly from stock. Following that, the stock is updated. Then the requirements are evaluated, and when necessary, a planned production order is created to fulfil the net requirements. The procedure for the same BOM level is then repeated for the next time period. When the time period reaches its horizon \( t = T \), the requirements for the next BOM levels are evaluated \( i = i + 1 \) and the same process repeats itself. This continues until all levels of the BOM have been evaluated for the total time horizon \( i = l \) and \( t = T \) (Figure 23). The next section will provide a mathematical model for computing the MRP scheme. For clarification, the model will be followed by example calculations.

\[
\begin{align*}
\text{Determine requirements BOM i} & \quad \rightarrow \quad \text{Update inventory positions Level i} \\
\text{Update inventory positions Level i} & \quad \rightarrow \quad \text{Evaluate inventory positions Level i} \\
\text{Evaluate inventory positions Level i} & \quad \rightarrow \quad \text{Create Planned Production orders BOM level i} \\
\text{Create Planned Production orders BOM level i} & \quad \rightarrow \quad \text{Stop}
\end{align*}
\]

Figure 23: Computation Logic of the MRP-Logic

### 5.2.3 MRP formulation

To apply MRP, several additional terms, definitions and equations typical in MRP are introduced to compute the MRP scheme. The full list of terms can be found in Appendix G. An example is also provided in section 5.2.4.5. When an order is scheduled before the evaluated time period \( t < 0 \) and becomes available in the time period \( 0 < t < T \), this is denoted as the scheduled receipt of product \( n \) \( (SR_n(t)) \). The projected on-hand stock of product \( n \) \( (OH_n(t)) \) is the former on-hand stock plus any scheduled receipts minus the gross requirements of product \( n(D_n(t)) \). The gross requirement is the direct requirement of the product \( n \) in time period \( t \). Because the on-hand stock is physical stock, it can never be negative (Eq. 2).
\[ O\!H_n(t) = \text{Max}(O\!H_n(t - 1) + SR_n(t) - D_n(t); 0) \quad \text{Eq. 2} \]

The net requirement of product \( n \) \((NR_n(t))\) is the requirement which cannot be fulfilled directly from the projected on-hand stock for time \( t \). If the net requirement can be fulfilled directly from on-hand stock, the net requirement is equal to zero (Eq. 3).

\[ NR_n(t) = \begin{cases} 0, & O\!H_n(t) > 0 \\ D_n(t) - O\!H_n(t - 1) - SR_n(t), & O\!H_n(t) = 0 \end{cases} \quad \text{Eq. 3} \]

If the scheduled receipt of product \( n \) \((SR_n(t))\) at time \( t \), plus the stock of the product \( n \) \((S_n(t))\) at \( t - 1 \), minus the gross requirements of the product at time \( t \) is negative, there is not enough quantity to fulfil demand. For example, if an order is planned to be completed at time \( t \), but its quantity becomes available at time \( t \), the net requirements can be fulfilled. the net If requirements of product \( n \) exist \((NR_n(t) > 0)\), it is a trigger for a planned order to be completed; however, the quantity of the planned order is not per definition the same as the net requirements. This is because the quantity of the planned order of product \( n \) \((POD_n(t))\) is specified by means of the periodic lot size indicator of product \( n \) \((LS_n)\) (always expressed in weeks). Thus, due to the use of periodic lot sizes, the planned order is the sum of the gross requirements (Eq. 4) of period \( t \) until \( t + LS_n \) minus the former stock (Eq. 5).

\[ D_n(t, t + LS_n) = \sum_{w=t}^{t+LS_n} D_n(w) \quad \text{Eq. 4} \]

\[ POD_n(t) = \begin{cases} 0, & S_n(t - 1) + SR_n(t) - D_n(t) \geq 0 \\ D_n(t, t + LS_n) - S_n(t), & S_n(t - 1) + SR_n - D_n(t) < 0 \end{cases} \quad \text{Eq. 5} \]

To ensure that the planned order is available at the correct time, the order should be released at the right moment and with the correct production order quantity. The production order quantity of product \( n \)(POQ_\(n\) (\( t \)) is not the same as the production order of product \( (POD_n(t))\). This is due to the fact that the production order quantity has to be corrected for the scrap percentage \((SCR_n)\); this is the percentage of the products that will be scrapped due to production faults. The production order quantity is therefore always greater or equal to the production order (Eq. 6). The scrap percentage is always unique per product and is maintained in the master data of the ERP-system.

\[ POQ_n(t) = \frac{POD_n(t)}{1 - SCR_n} \quad \text{Eq. 6} \]

This \(POQ_n(t)\) has to be released at the correct time. This is to ensure that there is enough time to produce the production order – denoted as the planned order release of product \( (POR_n(t))\). To know when to release
the planned order, the lead time of the production order due \((L_n)\) must be determined. The planned order release is on \(t - L_n\). Thus, the planned order release is equal to \(POR_n( t - L_n)\).

\(L_n\) consists of the following factors: setup time, queue time, and float before and after production. The process time is negligible compared to the other times; this is due to the fact that PT mostly produces rather small batches.

Float before production \((FLS_n)\) or float after production \((FLE_n)\) can be seen as a safety time that is set before the start of the production order and at the end of the production order. Floats are always expressed in whole days. When a production order begins, it follows a routing. For each step of a routing, a production unit has its own parameters (see section 4.3.1). Each production unit \(j\) has a queue time, which equals the time an order has to wait at the production unit before it is processed \((QT_{j,n})\). The queue time is unique per production unit per product and is expressed in days. Next to the queue time, the lead time of a production unit also has to be computed by means of the setup time \((ST_{j,y,n})\). In general, a production unit has both labour times \((y = 2)\) and machine times \((y = 1)\). The total formula for the lead-time can be computed by summing the floats, the queue times and the setup times of all production units of a production order (Eq. 7).

\[
L_n = FLS_n + FLE_n + \sum_{j=1}^{j} (QT_{j,n} + \max(ST_{j,1,n}; ST_{j,2,n})) \quad \text{Eq. 7}
\]

Once the \(L_n\) is calculated, the \(POR_n(t)\) can be determined. Finally, the stock can be updated (Eq. 8).

\[
S_n(t) = S_n(t - 1) + POD_n(t) + SR_n(t) - D_n(t) \quad \text{Eq. 8}
\]

To build order \(POR_{n_i}(t)\), gross requirements of all predecessors of product \(n_i\) are required \((n_{i+1} \in Pre(n_i))\). For the creation of one product of \(n_i\), a specific amount of \(n_{i+1}\) is required. This ratio is denoted as \(QBOM_{n_{i+1},n_i}\). For example, if \(QBOM_{n_{i+1},n_i}\) is equal to four, it means that for the production of one product \(n_i\), four products of \(n_{i+1}\) are required \((D_{n_{i+1}}(t))\) (Eq. 9). This demand will in turn apply as input for the calculation of the required capacity.

\[
\forall n_{i+1} \in Pre(n_i): \quad D_{n_{i+1}}(t) = POR_{n_i}(t) \times QBOM_{n_{i+1},n_i} \quad \text{Eq. 9}
\]

Calculating required capacity

Required capacity includes the required capacity of the machine (Eq. 10) and the required capacity of labour (Eq. 11). The required capacity for a production unit is computed by calculating all the required capacities of individual production orders on a production unit. Here, the required capacity for individual orders can
be computed by adding the total setup time and the total processing time. The total setup time consists of a single setup time multiplied with the split quantity, and the total processing time consists of the production order quantity divided by the base quantity and multiplied by the processing time. The computed required capacity serves as input for the IP-Model.

\[
R_{reqCap, j, 1}(t) = \sum_{n=1}^{N} ST_{j, 1,n} \times SPLIT_{Q, j, n} + \left(\frac{POQ_n(t)}{BQ_{j, n}} \times PT_{j, 1,n}\right) \quad \text{Eq. 10}
\]

\[
R_{reqCap, j, 2}(t) = \sum_{n=1}^{N} ST_{j, 2,n} \times SPLIT_{Q, j, n} + \left(\frac{POQ_n(t)}{BQ_{j, n}} \times PT_{j, 2,n}\right) \quad \text{Eq. 11}
\]

### 5.2.4 IP-Model

#### 5.2.4.1 Decision variables

The model has several decision variables that are altered to satisfy the constraints (section 5.2.4.3) and the objective function (section 5.2.4.4). These decision variables include the alteration per time period of the workforce \((WF_j(t))\), machine plan \((Mach_j(t))\), and the amount of hours worked per shift \((SH_{j,z}(t))\). If the workforce is too small, additional employees should be hired or extra shifts should be added. If the machine capacity is too low, the company should procure (an) additional production machine(s). There is therefore an option to increase the individual capacities for labour or machines for a shift. When a machine is bought, the available capacity takes a larger discrete step (Figure 7); in contrast the workforce can be altered on a more refined manner. This is due to the fact that when a machine is bought, it is then continuously available.

The decision variables in this model are:

\[
WF_j(t) = \text{The Workforce of a production unit } j \text{ for time } t \quad \text{Eq. 12}
\]

\[
Mach_j(t) = \text{The Machine plan of a production unit } j \text{ for time } t \quad \text{Eq. 13}
\]

\[
SH_{j,z}(t) = \text{Total hours worked in shift } z \text{ of production unit } j \text{ for time } t \quad \text{Eq. 14}
\]

#### 5.2.4.2 Parameters and variables

The model has several parameters that are used as input to compute several values. As previously mentioned, the customer’s demand is computed and used as an input variable. This demand is converted to required capacity for the workforce \((ReqCap_{j, 2}(t))\) and for the machines\((ReqCap_{j, 1}(t))\). A list of the parameters is given in Table 7 and a total list of all decision variables, parameters and other variables is provided in
Appendix H.

### Table 7: List of parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ReqCap_{j,1}(t)$</td>
<td>Required Machine Capacity of production unit $j$ of period $t$ in hours</td>
</tr>
<tr>
<td>$ReqCap_{j,1}(t)$</td>
<td>Required Labor Capacity of production unit $j$ of week $w$ in hours</td>
</tr>
<tr>
<td>$SD_{j,z}$</td>
<td>Length of shift $z$ of production unit $j$</td>
</tr>
<tr>
<td>$FT$</td>
<td>Full time job in hours per month</td>
</tr>
<tr>
<td>$MD_j$</td>
<td>Available hours of a Machine per day</td>
</tr>
<tr>
<td>$OD_j(t)$</td>
<td>Operational Days of a production unit $j$ per time $t$</td>
</tr>
<tr>
<td>$Util_{j,1}$</td>
<td>Maximum set utilisation of machine capacity of production unit $j$</td>
</tr>
<tr>
<td>$Util_{j,2}$</td>
<td>Maximum set utilisation of labour capacity of production unit $j$</td>
</tr>
<tr>
<td>$C_{j,F}$</td>
<td>Cost of Firing an employee</td>
</tr>
<tr>
<td>$C_{j,H}$</td>
<td>Cost of Hiring an employee</td>
</tr>
<tr>
<td>$C_{j,P}$</td>
<td>Cost of purchasing a machine for a production unit $j$</td>
</tr>
<tr>
<td>$C_{j,S}$</td>
<td>Cost of selling a machine for a production unit $j$</td>
</tr>
<tr>
<td>$C_{j,z,2}$</td>
<td>Cost per hour of labour for shift $z$ of production unit $j$</td>
</tr>
<tr>
<td>$C_{j,m}$</td>
<td>Cost per hour of holding a machine of production unit $j$</td>
</tr>
<tr>
<td>$C_{j,z,1}$</td>
<td>Cost per hour of using a machine in shift $z$ of production unit $j$</td>
</tr>
</tbody>
</table>

Based on the decision variables and the parameters, several values were computed that were necessary for the objective function. The available machine capacity (Eq. 15) and the available labour capacity (Eq. 16) were computed based on the machine and workforce plans, multiplied by the availability in hours of an individual machine or employee per month.

\[
AvCap_{j,1}(t) = Mach_j(t) \times OD_j(t) \times MD_j
\]

Eq. 15

\[
AvCap_{j,2}(t) = WF_j(t) \times FT
\]

Eq. 16

As mentioned earlier, to produce an order, a specific amount of machine and labour hours are required. The ratio between these amounts is called the labour-machine capacity ratio ($RLMC$) (Eq. 17). This ratio is used in the constraint to ensure that the workforce is evenly and correctly distributed across shifts.

\[
RLMC_j(t) = \frac{ReqCap_{j,2}(t)}{ReqCap_{j,1}(t)}
\]

Eq. 17

The importance of this ratio is clarified by means of an example (Figure 24). Assume that the required machine capacity for a production unit with one machine is twenty hours a day and the required labour hours is eight hours. The $RLMC$ is equal to $\left(\frac{8}{20} = 0.4\right)$. This means that, for every machine hour, 0.4 labour
hours are required. With this ratio, the correct number of labour hours will be allocated to the shift. If this ratio is not in place, all the labour capacity is allocated to the first shift (labour 2 in the Figure 24). If this ratio is used (labour 1 in the Figure 24), the resources are allocated correctly across the shifts.

![Figure 24: Ratio between machine hours and labour hours](image)

To compute the total hours of labour that can be worked in a shift for a production unit $j$ for time $t$ ($Z\text{Cap}_{j,z}(t)$), the available machine time per shift per time period should be multiplied by the RLMC (Eq. 18).

$$Z\text{Cap}_{j,z}(t) = SD_j \times Mach_j(t) \times OD(t) \times RLMC_j(t)$$  \hspace{1cm} \text{Eq. 18}

Based on the decision variables, the machine plan and workforce can alter over time. The alterations of the plans per time period indicates that employees have been hired (Eq. 19) or fired (Eq. 20) or that machines have been purchased (Eq. 21) or sold (Eq. 22).

$$H_j(t) = WF_j(t) - WF_j(t-1)$$  \hspace{1cm} \text{Eq. 19}

$$F_j(t) = WF_j(t-1) - WF_j(t)$$  \hspace{1cm} \text{Eq. 20}

$$P_j(t) = MACH_j(t) - MACH_j(t-1)$$  \hspace{1cm} \text{Eq. 21}

$$S_j(t) = MACH_j(t-1) - MACH_j(t)$$  \hspace{1cm} \text{Eq. 22}

The total cost of a production unit $j$ over the time horizon (Eq. 23) consists of the sum of the cost of labour, the cost of operating a machine, the cost of firing and the cost of hiring, minus the profit of selling a machine.

$$\text{TotCost}_j = \sum_{t=0}^{T} \left( c_{\text{m},z}^{\text{mu}} \text{AvCap}_{j,z}(t) + c_{j,z} P_j(t) - c_{j,z} S_j(t) + c_{j,z} H_j(t) + c_{j,z} F_j(t) + \sum_{z=1}^{Z} \left( \frac{SH_{j,z}(t)}{RLMC_j} c_{j,z,1} + SH_{j,z}(t) c_{j,z,1} \right) \right)$$  \hspace{1cm} \text{Eq. 23}
5.2.4.3 Constraints

Several constraints are defined for the IP-Model and the corresponding decisions. These constraints ensure that the machine and workforce plan align with the company’s objectives. The first set of constraints regards the utilisation of the machines (Eq. 24) and the workforce (Eq. 25). The required capacity per time period should never exceed the predetermined utilisation.

\[ \forall t : \frac{\text{ReqCap}_{j,1}(t)}{\text{AvCap}_{j,1}(t)} \leq \text{Util}_1 \quad \text{Eq. 24} \]

\[ \forall t : \frac{\text{ReqCap}_{j,2}(t)}{\text{AvCap}_{j,2}(t)} \leq \text{Util}_2 \quad \text{Eq. 25} \]

The second set of constraints regard the conservation of the workforce (Eq. 26) and the conservation of the machine plan (Eq. 27). These constraints ensure that it is not possible for an employee or machine to leave the system without notice. For the workforce, this indicates that the workforce for period \( t \) consists of the workforce of period \( t - 1 \) and the employees that were hired or fired. The same reasoning applies for the machine plan.

\[ \forall t : WF_j(t) - WF_j(t - 1) - H_j(t) + F_j(t) = 0 \quad \text{Eq. 26} \]

\[ \forall t : Mach_j(t) - Mach_j(t - 1) - P_j(t) + S_j(t) = 0 \quad \text{Eq. 27} \]

Based on the RLMC, a restriction is set for the maximum hours that can be worked in a shift (Eq. 28). Allocating more working hours to the shift would not make sense since there would not be enough work to do during the shift.

\[ \forall z, t : SH_{j,z}(t) \leq ZCAP_{j,z}(t) \quad \text{Eq. 28} \]

PT aims at filling the first shift first and then the second shift, followed by the third (Eq. 29).

\[ SH_{j,1}(t) \geq SH_{j,2}(t) \geq SH_{j,3}(t) \quad \text{Eq. 29} \]

This, of course, also indicates that the second shift can only be filled when the first shift is full, and the third shift can only be filled when the second shift is full (Eq. 30). To relegate this to an IP problem, the constraint has been rewritten as an if-then construct. In this case, \( M \) must be large enough that \( ZCAP_{j,z}(t) - SH_{j,z}(t) \leq M \) and \( SH_{j,z}(t) \leq M \) hold for all values that satisfy the other constraints in the problem.

\[ z = 1, z = 2, \forall t : \]

\[ ZCAP_{j,z}(t) - SH_{j,z}(t) \leq M(y - 1) \quad \text{Eq. 30} \]
\[ SH_{j,z}(t) \leq My \]
\[ y = 0 \text{ or } 1 \]

The last set of constraints concerns the sign constraints.

\[ \forall t: H_j(t) \geq 0 \quad \text{Eq. 31} \]
\[ \forall t: F_j(t) \geq 0 \quad \text{Eq. 32} \]
\[ \forall t: P_j(t) \geq 0 \quad \text{Eq. 33} \]
\[ \forall t: S_j(t) \geq 0 \quad \text{Eq. 34} \]
\[ \forall t: Mach_j(t) \geq 0 \quad \text{Eq. 35} \]
\[ \forall t: WF_j(t) \geq 0 \quad \text{Eq. 36} \]
\[ \forall t: SH_{j,z}(t) \geq 0 \quad \text{Eq. 37} \]
\[ \forall t: AvCap_{j,1}(t) \geq 0 \quad \text{Eq. 38} \]
\[ \forall t, z: ZCap_{j,z}(t) \geq 0 \quad \text{Eq. 39} \]

### 5.2.4.4 Objective function

The objective function is to minimise total cost of capacity over the time horizon of a production unit (Eq. 40) \((Costs_{pu}^{pu})\) while satisfying all constraints for a scenario. This model is solved using AIMMS and discussed by means of a case study in section 0. The total IP-Model is reported in Appendix I.

\[ Costs_{j,sc} = \text{Minimize}(TotCost_j) \quad \text{Eq. 40} \]

### 5.2.4.5 Simple example MRP scheme

Assume that there is a simple FERT, referred to as Product A. The intention is to investigate the required capacity on a specific production unit to produce product A and all its HALBs. To produce product A, several other products are necessary (Figure 27), and all of these products have unique parameters (Figure 28) with regard to the production unit. The demand for the FERT is given from week 42 through week 49. Further, assume that there is a schedule receipt of one hundred thirty units of product A on week 43 \((SR_A(43) = 130)\), and the on-hand stock is one hundred \((OH_A(41) = 100 \text{ and thus } S_A(41) = 100)\). Based on Eq. 2, it can be determined that the on-hand inventory of time 42 equals 10 \((OH_A(42) = \max(100 - 0 - 90; 0) = 10)\). Because the on-hand stock is greater than zero, based on Eq. 3, the net requirements are also zero \((NR_A(42) = 0)\). Subsequently, the stock is computed, which equals ten \((S_A(42) = 100 + 0 + 0 - 90 = 10)\) (Eq. 8). When all calculations are complete for one time period, the next \(t\) is analysed \((t = t + 1 = 43)\). In the next time period, the scheduled receipt arrives \((SR_A(43) = \)
The value remains the same and result in $OH_A(43) = 50$, $SA(43) = 50$. In the next period, $t = 44$, more changes occur. Based on Eq. 2, the on-hand stock is zero ($OH_A(44) = \max(50 + 0 - 90; 0) = 0$), and the net requirement is forty ($NR_A(44) = 90 - 50 - 0 = 40$) (Eq. 3). Checking the planned orders based on Eq. 5, it is determined that this equals 130 ($POD_A(44) = (90 + 90) - 50 = 130$). Based on the scrap percentage of 18.75%, the production order quantity for one hundred thirty units of product should be one hundred sixty ($POQ_{pn}(44) = \frac{130}{1-0.1875} = 160$). As denoted in the parameters, this quantity will be produced with a production lead time of one week; thus, the product should release in week 43. The production order would therefore release on week 43 and should contain a quantity of one hundred sixty ($POR_A(43) = 160$). Finally, the inventory can be calculated with Eq. 8; this equals ninety ($SA(44) = 50 + 130 - 0 - 90 = 90$). Continuing these calculations provides the MRP scheme for product A. Now the requirements of product A can be translated in gross requirements for products B and C. This latter product can be translated into requirements for product D. The total MRP scheme of all products A, B, C and D is provided in Appendix E. The quantities per product that must be processed by the production unit is depicted in Figure 25.

Finally, these requirements are translated into capacity requirements; this is done based on the parameters of Figure 28. For example, the capacity of week 42 of product D can be computed as follows: $\text{Setup time} + \frac{\text{production quantity}}{\text{Base quantity}} * \text{processing time} = 5 + \frac{3000}{40} * 1.5 = 117.5$ (Figure 26).

<table>
<thead>
<tr>
<th>Period</th>
<th>41</th>
<th>42</th>
<th>43</th>
<th>44</th>
<th>45</th>
<th>46</th>
<th>47</th>
<th>48</th>
<th>49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>160</td>
<td>180</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product B</td>
<td>160</td>
<td>180</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product C</td>
<td>320</td>
<td>360</td>
<td>320</td>
<td></td>
<td></td>
<td></td>
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<td>Product D</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 25: Production Quantity for the production unit

<table>
<thead>
<tr>
<th>Period</th>
<th>41</th>
<th>42</th>
<th>43</th>
<th>44</th>
<th>45</th>
<th>46</th>
<th>47</th>
<th>48</th>
<th>49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>106</td>
<td>118</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product B</td>
<td>35</td>
<td>39</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product C</td>
<td>194</td>
<td>218</td>
<td>194</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product D</td>
<td>117.5</td>
<td>229</td>
<td>106</td>
<td>229</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 26: Required Capacity for the Production Unit
Figure 27: BOM-structure

Figure 28: BOM parameters
6. Validation and verification

In this section the created model is checked for coding and conceptual errors by verification and the validation. This is the final check before the computation and optimisation can take place. This check is the threshold for reliable and valid results.

6.1.1 Verification

The Required-Capacity-Estimation-Model (computation of the MRP-run and the required capacity) were programmed in VBA language. The coding was checked separately on coding errors. To add an additional layer to the verification, the computed MRP-scheme of section 5.2.4.5 was again computed. However, this time it was not computed manually, but with the use of the VBA-code. The outcome of the manual computations and the computation of the VBA-code is presented in Table 8. The outcome of both models is equal; there is no difference between the two computations. It was verified that the formal (mathematical) model was translated correctly into VBA.

<table>
<thead>
<tr>
<th>Month</th>
<th>41</th>
<th>42</th>
<th>43</th>
<th>44</th>
<th>45</th>
<th>46</th>
<th>47</th>
<th>48</th>
<th>49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Computation</td>
<td>117.5</td>
<td>229</td>
<td>106</td>
<td>257</td>
<td>118</td>
<td>229</td>
<td>106</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>VBA-computation</td>
<td>117.5</td>
<td>229</td>
<td>106</td>
<td>257</td>
<td>118</td>
<td>229</td>
<td>106</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8: Verification Computation Model

Subsequently, the IP-Model was checked. The IP-Model was modelled in AIMMS. The IP-Model was separately checked on coding errors. To add an additional layer to the verification, two extreme scenarios were checked on the IP-Model. The first scenario, EX1, shows that the required capacity doubles in the last twelve months in comparison to the first twelve months (Table 9). The second scenario, EX2, presents a scenario where the total required capacity on a certain point almost drops to a 0-point (Table 9). The expectation is that, in scenario EX1, the machine plan (Mach_pu) almost doubles (2 * Mach_pu) in comparison to the first 12 months. However, due to the fact that the machines are not fully
utilised, the machine plan will most likely be a bit lower ($2 \times Mach_{pu} - 1$). The expectations for the machine plan of scenario $EX2$ will most likely drop to one machine for the low demand period. The outcome of these results is provided in Table 9. The expected outcome is indeed equal to the outcome of the IP-Model. Thus, it was verified that the model has no coding errors and that the decision variables, parameters, constraints and objective function were correctly implemented in AIMMS.

<table>
<thead>
<tr>
<th>Machine</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<th>11</th>
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<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
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<td>2000</td>
<td>1500</td>
<td>1000</td>
<td>1500</td>
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<td>2500</td>
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<td>9000</td>
<td>9500</td>
<td>10000</td>
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<td></td>
</tr>
</tbody>
</table>

Table 9: Verification IP-Model extreme scenarios

In addition, whenever the models did not behave as expected, the error was located, the models were debugged and the Required-Capacity-Estimation-Model and the IP-Model were run again. This loop was executed until the models behaved correctly and as expected.

### 6.1.2 Validation

After having verified the models, the validation process was conducted. Validation is the process of determining whether the model is an accurate representation of the system. However, validation cannot be assumed to result in a perfect model, since the perfect model would be the real system. A distinction is made between face validity and historical data validity. Historical data validation is an ideal manner to check if the Demand-Scenarios-Model behaves as the real system. Therefore the models were checked for validity by performing a face validity and/or historical data validity test.

Furthermore, in order to add additional layers to the validation, the Demand-Scenarios-Model, the Required-Capacity-Estimation-Model and the IP-Model were individually validated through an example. For the Demand-Scenarios-Model, historic data validity was used. Historical forecast (Table 10) was taken from Customer X and converted to different scenarios using a stochastic distribution with an 80% confidence interval.
Based on the obtained distribution of the forecast, the realised demand falls between the ranges of the forecasted demand was verified (Figure 29). It also seems that the realised demand follows the most likely demand quite accurately. As these results are within the boundary of the confidence interval, it demonstrates the accuracy of the data procedures as carried out by the Demand-Scenarios-Model.

For the verification of the Required-Capacity-Estimation-Model, a product was created with four BOM-levels, setup times, process times, queue times and floats for the production unit SMD. Following that, demand was set in the ERP-system of PT for month one up to month six. Based on an MRP-run, the demand of the FERT and HALBs were determined. Next, this demand was converted into required capacity. The outcome of the required capacity per month of the ERP system was compared to the outcome of the required capacity of the Required-Capacity-Estimation-Model (Table 11). The BOM, setup times, process times and lead times are provided in Appendix J. The sum of the total required capacity was the same in the ERP-system and the Required-Capacity-Estimation-Model. The allocation of the capacity on a monthly basis was roughly the same as the ERP-system. This indicated that there was a difference in month three and four. This difference was due to the fact that the ERP-system had a different number of operational days because of national holidays. Thus, a part of the required capacity of month four shifted to month three. Therefore, the Required-Capacity-Estimation-Model is verified and validated.

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
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<td>105,6</td>
<td>105,6</td>
<td>105,6</td>
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<td>633,6</td>
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<td>ERP PT</td>
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<td>121</td>
<td>90,2</td>
<td>105,6</td>
<td>105,6</td>
<td>633,6</td>
</tr>
</tbody>
</table>

Table 11: Validation Required-Capacity-Estimation-Model
For the IP-Model, the realised historical required machine capacity of the production unit SMD, from 01.06.2015 up to 31.05.2016, was used to validate the IP-Model. This realised required capacity was inserted into the IP-Model and the outcome of the machine plan was validated by means of historical data validity and face validity; individuals knowledgeable about the system (planners in the Planning department) were asked whether the outcome of the model was reasonable. The output and the behaviour of the purchase (and selling) decisions of the system were analysed (Figure 30 and 32).

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Plan Realized</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Machine Plan IP-Model</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 30: Machine Plan Validation

PT installed their SMD-machine in July of 2015 (the second month). However, the IP-Model suggests that the machine should have been procured in December of 2015 (the seventh month). According to the planners of the Planning department, the fifth SMD-machine should indeed have been procured later. Based on the face validity and the historical data validity, it is determined that the IP-Model is verified and validated.

After an extensive verification and validation phase, it can be concluded that the developed model is ready to generate reliable and valid results.
7. Numerical study (model solving)

Reliable and valid results are now able to be generated to aid in answering the research questions. To implement the models, a case study was conducted at PT. After determining the values of parameters, different scenarios and IP models were created to generate results. It should be noted that, due to the scope, not all customers were taken into account. However, the demand of the largest customer, Customer X, was analysed in this case study.

7.1 Experiments

In order to effectively provide answers to the research questions, experiments were conducted. Sub questions were developed to clearly define the scope. All sub questions were based on the production unit SMD. The sub-questions are:

1. Which probability distribution fits the demand of Customer X?
2. What are the demand scenarios for the coming twenty-four months based on an 80% confidence interval?
3. How does the IP-model function based on actual historical data?
4. What is the corresponding machine plan and workforce plan for the production unit SMD for each scenario?
5. What kind of insight is gained using these models?

7.1.1 Past purchase decisions

This section illustrates the problems regarding PT’s forecast. The forecast used in this section was created two years ago and was compared to the realised required capacity. The focus was on the machine plan due to the fact that it is much more difficult to procure or sell a machine compared to hiring or firing employees in the short term. The old forecast served as an input for the IP-model. Based on this model and the old forecast, it was possible to determine the machine plan. Following that, the machine plan was again determined. However, in the second time, the realised required capacity served as input for the IP-model.

Table 12 provides the realised required capacity (RRC), the forecasted required capacity (FRC), the corresponding realised machine plan (RMP) and the forecasted machine plan (FMP). This data shows that the realised required capacity was much higher than the forecasted required capacity.

<table>
<thead>
<tr>
<th>Week</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC</td>
<td>1263</td>
<td>1283</td>
<td>1292</td>
<td>1209</td>
<td>1310</td>
<td>1299</td>
<td>1308</td>
<td>1299</td>
<td>1308</td>
<td>1312</td>
<td>1324</td>
<td>1315</td>
<td>1308</td>
<td>1312</td>
<td>1315</td>
<td>1308</td>
<td>1324</td>
<td>1315</td>
<td>1308</td>
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<td>1315</td>
<td>1308</td>
<td>1312</td>
<td>1315</td>
</tr>
<tr>
<td>FRC</td>
<td>1253</td>
<td>1243</td>
<td>1201</td>
<td>1242</td>
<td>1215</td>
<td>1130</td>
<td>1240</td>
<td>1260</td>
<td>1260</td>
<td>1260</td>
<td>1260</td>
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<td>1260</td>
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<td>1260</td>
<td>1260</td>
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<td>1260</td>
<td>1260</td>
</tr>
<tr>
<td>RMP</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 12: actual versus historic forecast of required capacity
If PT had invested in the FMP, the company would not have had enough machines to produce all products. The utilisation of the production unit would have been too high towards the end of the horizon. In some cases this utilisation would have even approached 100%. This deviation in the realised required capacity and the forecasted required capacity demonstrates the importance of having a reliable forecasting method and also the incorporation of different scenarios in long term planning.

### 7.1.2 Demand scenario

To compute the scenarios, the demand of Customer X was analysed. This chapter discusses the computations of the fluctuations for this demand. Currently roughly 30% of the capacity of production unit SMD is allocated for the production of FERT and HALBs for Customer X. This percentage is at this high level as the FERT consists of more than twenty-five hundred sub-assemblies. To compute the ratios of the demand scenario, the forecast was evaluated against the realised demand as discussed in section 5.2.1. The choice was made to only include forecasts with fourteen or more measurements. The computed ratios are depicted in Table 13. From month 17 and onwards, less than fourteen data points were available. Thus, only a forecast up to month sixteen was taken into account. For the remaining eight months, the parameters of the probability distribution were extrapolated from data of the first sixteen months.
Table 13: Forecast Ratios of Customer X

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Ratio | 1.00 | 1.00 | 0.88 | 1.17 | 0.88 | 1.17 | 1.00 | 1.00 | 1.17 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

The data from the forecasts of months one, three, six, and twelve is plotted in Figure 33. Based on a distribution fit, it seems that the data can be approximated with a normal distribution. The distribution was fitted based on the statistical program EasyfitXL. This program fits several distributions and checks whether a distribution is accepted. The program provides a null-hypothesis \( H_0 \) and an alternative hypothesis \( H_1 \). Where \( H_0 \) is set as ‘the data follows a normal distribution’ and \( H_1 \) is set as ‘the data set does not follow a normal distribution’. The Goodness of fit test was conducted based on the Kolmogorov-Smirnov test. The program accepted an hypothesis whenever the \( p \)-value was greater than \( \alpha \). Thus, \( p > \alpha \). In all cases up to the dataset of month sixteen, \( H_0 \) was accepted based on an \( \alpha = 0.05 \).
Based on the ratios, the parameters of the normal distribution were computed for the first sixteen months (Table 14). After the computation of the $\mu$ and $\sigma$ for the first sixteen months, the parameters of months seventeen through twenty-four were extrapolated from the first 16 months.

<table>
<thead>
<tr>
<th>month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>0,061</td>
<td>0,109</td>
<td>0,131</td>
<td>0,193</td>
<td>0,183</td>
<td>0,315</td>
<td>0,473</td>
<td>0,547</td>
<td>0,559</td>
<td>0,494</td>
<td>0,491</td>
<td>0,508</td>
<td>0,526</td>
<td>0,587</td>
<td>0,698</td>
<td>0,861</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0,984</td>
<td>0,970</td>
<td>0,971</td>
<td>1,005</td>
<td>1,103</td>
<td>1,247</td>
<td>1,379</td>
<td>1,431</td>
<td>1,382</td>
<td>1,396</td>
<td>1,441</td>
<td>1,482</td>
<td>1,587</td>
<td>1,567</td>
<td>1,699</td>
<td></td>
</tr>
</tbody>
</table>

Table 14: $\mu$ and $\sigma$ for the first sixteen months

The data for $\mu$ and $\sigma$ was plotted over time for the first sixteen months. Over this data a linear trend line was fitted (Figure 34). Based on the added trend lines, it was possible to compute the formula for the $\mu$ (Eq. 41) and $\sigma$ (Eq. 42). These trend line for the $\mu$ has a $R^2$ 0,93, which implies that 93% of the $\mu$ can be predicted based on Eq. 41. This trend line for the $\sigma$ has a $R^2$ 0,8, which implies that 80% of the $\sigma$ can be predicted based on Eq. 42.

$\mu(t) = 0,051t + 0,8551$ \hspace{1cm} Eq. 41

$\sigma(t) = 0,0455t + 0,0345$ \hspace{1cm} Eq. 42

By inserting the values of months seventeen through twenty-four as $t$ in the formulas $\sigma(t)$ and $\mu(t)$, it was possible to compute the remaining $\sigma$ and $\mu$ (Table 15).

<table>
<thead>
<tr>
<th>month</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>0,808</td>
<td>0,854</td>
<td>0,899</td>
<td>0,945</td>
<td>0,99</td>
<td>1,036</td>
<td>1,081</td>
<td>1,127</td>
</tr>
<tr>
<td>$\mu$</td>
<td>1,722</td>
<td>1,773</td>
<td>1,824</td>
<td>1,875</td>
<td>1,926</td>
<td>1,977</td>
<td>2,028</td>
<td>2,079</td>
</tr>
</tbody>
</table>

Table 15: Computed $\sigma$ and $\mu$ for Month 17 until 24

The demand ratio probability distributions were plotted over time (Figure 22). This is to give more insight into the deviation of the demand over time. As can be seen, the deviation towards the end is much bigger than that at the beginning.

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Based on the distribution and the confidence interval, the scenarios for Customer X were determined. These scenarios are based on an 80% interval; the outer ranges of this interval represent the most pessimistic and optimistic scenarios, and the mean represents the most likely scenario. The output of these scenarios is provided in Table 16.

As previously mentioned, this study uses the demand fluctuations of Customer X. However, the required capacity of other customers for production unit SMD must also be taken into account to compute total aggregate capacity requirements. Because the fluctuations of other customers are not taken into account in this study, the total aggregate capacity requirements of the other customers will be taken as fixed requirement without fluctuations. This data is extracted from the ERP-system of PT. This method is illustrated in Figure 36.
Based on the demand of Customer X, the demand for the scenarios is computed and converted to required capacity as discussed in section 5.2.2 and 5.2.3. The outcome of the required capacity for machine and labour for the 80% confidence interval is depicted in Table 17 (and Figure 37) and Table 18.

**Table 17: Required Machine Capacity SMD in hours**

<table>
<thead>
<tr>
<th>Month</th>
<th>Pessimistic</th>
<th>Most Likely</th>
<th>Optimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4842</td>
<td>4746</td>
<td>4956</td>
</tr>
<tr>
<td></td>
<td>4957</td>
<td>4815</td>
<td>5373</td>
</tr>
<tr>
<td></td>
<td>5244</td>
<td>4947</td>
<td>5613</td>
</tr>
</tbody>
</table>

**Table 18: Required Labour Capacity SMD in hours**

Based on the aggregate required capacity, workforce and machine plans were computed by means of the objective function. The outcome of the machine and workforce plan and the corresponding cost for the production unit for the twenty-four months for each scenario is depicted Table 19.
To evaluate the impact of an actual scenario against an invested scenario, the invested and actual scenarios were compared. This scenario evaluation focused on the machine plan. This is due to the fact that it is much easier to hire or fire people than to purchase or sell a machine. The evaluation was based on the average utilisation levels of the machines. Thus, the available capacity of one scenario was compared to the required capacity of another scenario. Table 20 shows the average utilisation over the 24 months. Table 21 shows the number of periods where the utilisation surpassed the 85% threshold.

As previously mentioned, the surpassing of the utilisation of 67% indicates using the last shift. This shift implies that overtime is used to absorb the extra capacity which was required to produce all products. The number of times that overtime was used under the different scenarios is provided in Table 22. The worst case scenario would be for PT to not fulfil demand. This could happen if PT invested in the machine plan of the pessimistic scenario, but the optimistic scenario actually happens. In this case the average utilisation is 80%; there are six periods where the utilisation surpasses 85% and overtime occurs in 18 of the 24 periods.

### Table 19: Workforce and Machine Plan

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | Total cost (EUR) |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----------------|
| Pessimistic | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 20.1 M11 |
| Most Likely | 26 | 24 | 26 | 33 | 34 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 30.9 M11 |
| Optimistic | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 35.2 M11 |

Table 20: Scenario comparison utilisation

<table>
<thead>
<tr>
<th>Invested scenario</th>
<th>Pessimistic</th>
<th>Most Likely</th>
<th>Optimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual scenario</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pessimistic</td>
<td>66%</td>
<td>64%</td>
<td>58%</td>
</tr>
<tr>
<td>Most Likely</td>
<td>72%</td>
<td>70%</td>
<td>64%</td>
</tr>
<tr>
<td>Optimistic</td>
<td>80%</td>
<td>78%</td>
<td>70%</td>
</tr>
</tbody>
</table>

Table 21: Times utilization surpass 85% threshold
Invested scenario

<table>
<thead>
<tr>
<th>Actual scenario</th>
<th>Pessimistic</th>
<th>Most Likely</th>
<th>Optimistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pessimistic</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Most Likely</td>
<td>10</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Optimistic</td>
<td>18</td>
<td>17</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 22: Times Overtime is used

Based on this information, it is possible for management to determine the boundaries for the forecasts and to evaluate which scenario it should invest. Each scenario has its advantages and disadvantages. For example, investigating in the optimistic scenario would assure minimal overtime and surpassing the 85% threshold if any other scenario occurs. However, this scenario has the highest overall cost. In contrast, investigating in the pessimistic scenario has the lowest overall costs; however, investing in this scenario involves too high of an utilisation and excess use of overtime if other scenarios occur. Based on these figures, it would be wise for PT to currently invest and focus on the most likely scenario. The costs of this scenario is €1.7 Million higher than the pessimistic scenario and €5.2 Million times lower than the optimistic scenario. If invested in this scenario, indeed the 85% threshold is surpassed 4 times if the optimistic scenario occurred. This is a risk for PT. However, as discussed in section 3, the S&OP-process is a repetitive process of capacity evaluation. This means that it is not necessary to make the full scope of decision for the full horizon of 24 months. Decisions should be made based on procurement lead time. For PT, this indicates that the procurement decision of production unit SMD should be made 6 months prior to the placement of the machine. The latest time when such a decision should be made is referred to as the decision horizon. In month 10, for example, a machine should be procured according to the optimistic scenario, although this decision does not correspond with the outcomes of the other scenarios. Due to the decision horizon, the purchase decision should be postponed at least to the next monthly S&OP-meeting. Thus, in the next S&OP-meeting, when new forecast scenarios are generated and evaluated, PT can again take a closer look at whether the procurement of the machine is a necessity.

On the other hand, assuming that the procurement lead time is nine months, the decision should be made whether the machine should be procured. Due to the nature of the workforce (quick hire and fire decisions), only costs regarding machines were taken into account for the evaluation. Thus, a cost based evaluation regarding the procurement of the machine in the tenth month was conducted. This evaluation entails the summation of the cost of all three scenarios if one machine would or would not have been procured. The costs consists of idle time of the machine and fees for a deficit of available capacity. The idle costs equal the fixed cost per hour (€200,-) and the fee costs is denoted as a fee per hour (€1.500,-). The cost of the fee was based on information from the finance department. For example, the required capacity for the pessimistic, most likely and optimistic scenario for the tenth month equals 2204, 2464 and 2695 hours respectively. The available capacity in the tenth month with five machines equals 2550. Thus, the costs for idle time equals \((2550 - 2204 + 2550 - 2464) \times €200\) \(€86.400\) and the fee cost equals \((2695 - 2550) \times €1500\) \(217.500\). Therefore, the total costs equal \(€303.900\). However, the finance department mentioned that these cost could differ. For this reason a sensitivity analysis was conducted for these costs.
and the fee was adjusted from €1.000 to €2.000 with increments of €50. Based on Figure 38, it can be concluded that it is not wise to procure the sixth SMD machine. This latter decision, however, is open for discussion at the next S&OP-meeting when new data is available.

Figure 38: Sensitivity Analysis 5 Machines vs. 6 Machines of month 10 for production unit SMD
8. Conclusion and recommendations

The final chapter includes the overall conclusions of this research project (section 8.1), feedback on the research questions (section 8.1.1), implications and recommendations (section 8.3), and limitations and further research (section 7.3).

8.1 Conclusion

Currently, insight into the S&OP-process and manner of forecasting process is lacking. Therefore, PT does not know if their forecast policy is efficient and reliable and what can be done to make it more so. Insight in the process regarding S&OP and the incorporation of its uncertainty should make it possible for PT to improve their S&OP-policy; a structured S&OP-process with different scenarios where demand can be fulfilled and PT can anticipate capacity changes. Therefore, the following research aim was defined:

To develop a reliable sales and operations planning process from which a reliable forecast is developed using accurate estimations for the available and required capacity.

8.1.1 Feedback Research Question

What are the relevant aspects for S&OP?

Sales and operations planning is the long-term management of capacity. Decisions on when and how much available capacity levels should increase or even decrease are at the heart of S&OP. Thus, it determines the long-term deployment of manufacturing resources; it keeps capacity in consideration and is based on sales and demand forecast. Its process normally entails monthly planning periods over a period of nine to eighteen months. S&OP encompasses long-term production planning and predicts sales based on forecasted demands. Though literature provides different steps to the S&OP-process, according to Ivert & Jonsson (2010) and Karrenbauer (2015), it generally entails cross functional meetings where the sales forecast and differences compared to the old forecast are discussed. Key points of these meetings are the planning horizon, planning frequency and planning objects. Apart from balancing demand and supply, S&OP also balances risks. The balancing of risk plays a more important role when the production environment is characterised by high uncertainties due to demand fluctuations, inadequate forecasts and inconsistencies between product-level and aggregate production plans. This is often the case in high-tech firms. Scenario analysis can provide a better understanding of these risks scenarios by managing demand uncertainty. However, a disadvantage is that scenario analysis is mostly limited to several scenarios and does not provide a great understanding of the required capacity distribution. It is a rather simplistic view; it merely presents the worst-case scenario, the expected scenario and the best-case scenario.

Based on these scenarios, capacity should be managed. The management of capacity, especially within the manufacturing environment, entails three or four stages, including short-term capacity control and execution, intermediate capacity management, and long-term capacity planning. Here, a distinction is made between two strategy perspectives; the manufacturing strategy and the S&OP-strategy. The manufacturing strategy perspective seeks to adjust the available capacity based on the required capacity by means of lag,
lead or a combination strategy. In contrast, the S&OP perspective aims to adjust the required capacity over different time periods based on the available strategy by means of a chase, a level or a mix strategy.

Lag and level strategies tend to be suitable for standardised, high volume products as well as line production and continuous processes. Lead and chase strategies tend to be suitable for highly customised, low volume products as well as project manufacturing and job shops. The latter is the case for high-tech firms. Thus, a combination of lead and chase strategies seems to be the most appropriate strategy for high-tech firms.

What are the capacity and decision models that affect S&OP in a high tech firm with a high demand uncertainty?

Based on obtained information of the literature study and PT, the chase and lead strategy were defined as the best strategy to optimise the machine and workforce plan against minimal costs. First, to enclose demand fluctuation, different demand scenarios were established: pessimistic, most likely, and optimistic. This was conducted by means of the Demand-Scenarios-Model. Subsequently, the output of these scenarios was used as input for the Required-Capacity-Estimations-Model. The computation of capacity requirements was based on monthly infinite MRP (planning without capacity restrictions). This indicates that demand is planned without taking existing available resources into account. Common usage of aggregate demand is justified. However, aggregate demand in an environment, which includes long lead times and high BOM-levels, can disemboque in an inaccurate representation of the demand over time. The same case holds for PT. Next, the required capacity of the Required-Capacity-Estimations-Model is used as input for the IP-Model. The IP-Model is an integer programming model; the model evaluates the required capacity against the available capacity. The evaluation roughly entails checking the required and available capacity against predefined constraints. Following that, the output of these scenarios was evaluated against one another to provide more insight into the risks and problems which could arise when investing in the wrong scenario. These scenarios also provide insight into the maximum deviation of the forecast over time.

How should purchasing decisions be evaluated?

The machine plan, workforce plan, required capacity and the total cost of the different forecast scenarios serves as a foundation for the evaluations of different scenarios by management. These forecast scenarios provide insight if and when decision should be made. However, only decisions which fall within the decision horizon should be made. Other decisions should be revaluated in a monthly S&OP-meeting. In this meeting newly generated forecast scenarios are evaluated against the scenarios of the previous month. By analysing and evaluating these differences, management could cope with the procurement decisions. The points which are critical for such an evaluation differ per company. However, it can be safely stated that costs are the focus of evaluation. However, these cost-related evaluations do not account for factors such as customer relations and loss of face. This latter issue could occur if products were not delivered timely due to a deficit of available capacity. It can be concluded that the development of scenarios provides great insight into possible outcomes and thus is a valuable asset for management.
8.2 Discussion

In this section three aspects are discussed: the recommendations for PT, the implications of this study on scientific research and its limitations.

8.2.1 Recommendations for PT

This research project provided insights and a tool which are useful for the decision making regarding the S&OP-process. The Operations, Supply Chain and Sales department can use these insights and tool for estimating the course PT pursues.

Regarding the IP-Models, all parameters can be altered, which provides an extensive set of possibilities and also makes the model generically applicable. Therefore, the model is able to support decision making concerning the procurement of machines and the size of the workforce by evaluating the required capacity on the basis of various possible scenarios and the total investment cost. The Demand-Scenarios-Model also provides valuable insight in the demand deviation over time of a customer. This information can accurately adjust profit forecasts.

The first and most important recommendation for PT is to hold structured monthly S&OP-meetings with a clear agenda and which are led by the head of the Operations, Sales and Planning departments. This meeting should evaluate the forecast and the gaps between the new and previous forecast for a specific production unit. The focus regarding the capacity strategies should be on a lead and chase strategy.

The second recommendation entails the usage of the models for the S&OP-meetings. The developed scenarios are valuable input into how the company is growing and also gives a reliable confidence interval based on a pessimistic and optimistic scenario. However, management should take a closer look at the chosen confidence interval and try to fine tune it by using alternative confidence intervals. Using these methods, the probability of a detrimental situation in the future due to bad judgment can be prevented.

The third recommendation, for future improvement of the model, concerns data management. PT should save all customer forecasts. By saving this data, the forecast and forecast scenarios will also be more reliable due to the fact that there will be more data points to determine a distribution of a forecast.

The fourth recommendation is that the models should be used to evaluate the scenarios of all the customers of PT and also for other key production units. This is important in order to ensure that PT can continue to produce demand. This evaluation should also be used to gain more insight into the behaviour of the customer and the reliability of a customer’s forecast. Based on this output, PT may even produce on forecast and adjust the size of their production batches.
8.2.2 Implication Scientific Research

Various papers have been dedicated to the field of capacity forecasting strategies and procedures. However, these papers mainly focused on planning strategies and capacity planning with low product groups under low demand uncertainty instead of a high product variety and high demand uncertainty. Based on the literature review of Anzar (2016) it was concluded that the best strategy regarding planning for a high tech firm is a combination of lead and chase strategy. Be that as it may, the procedure of forecasting the required capacity was still inconclusive. Therefore the phenomenon of scenario analysis in combined with the use of distributions have not been studied often. Scenarios are often mimicked from economic conjuncture. Sodhi and Tang (2011) did a study on scenario analysis with distributions. However, they focused on simulating the distribution over time. Other research regarding forecasting by scenario analysis was inconclusive.

This research contributes on several manners to the literature. This research provides a framework to the capacity evaluation based on scenario analysis. As mentioned this is rather new in literature. The introduction of a confidence interval to determine the optimistic and pessimistic scenario is also new for the determination of the different scenarios over time. This research also emphasize the influence of a customer on the demand uncertainty. Scenario analysis that exist are mainly based on product groups. However the influence of the customer is neglected.

Therefore, this research has contributed data to the literature on S&OP forecasting and scenario analysis under high demand uncertainty.

8.3 Limitations & Future Research

Despite the contributions, this study also encountered several limitations. The greatest limitation was that the model was solely conducted for one customer. Due to the scope of the research, there was not sufficient time to process all customer demand through the models. An additional limitation, which also contributed to the limited analyses of the customer studied, relates to the fact that the data management of PT is not fully in place regarding the storage of historical forecasts.

A second limitation in this research regards the incorporation of projects and new customers. The current model provides several forecast scenarios. However, these scenarios are based on existing customers and products. The model does not account for new projects or the entrance of new customers. These aspects could increase the required capacity.

Improve the reliability of the forecast scenarios is suggested for future research. This can be accomplished by applying various kinds of distributions per time period for each customer. An additional possibility for future research is to expand the set of decision variables with the lot size. Increasing lot sizes have a direct impact on the required capacity. Thus, a trade-off can be made when increasing the lot sizes or increasing the amount of machines and/or shifts. Additionally it would also be interesting to take the option of outsourcing into account, especially for periodic peaks.
As mentioned, this research contributes to the relatively small number of studies that have been conducted on scenario forecasting based on customer reliability in an environment with high demand uncertainty. Hopefully, this will motivate scholars to further investigate the forecasting optimisation possibilities.
Bibliography


Appendix B: Fishbone cause and effect diagram
## Appendix C: Lot size rules

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Appendix D: Example Customer Y

Appendix Figure D-I: Example forecast of Customer Y

Appendix Figure D-II: Example Demand Ratios of Customer Y

Appendix Figure D-III: 80% & 90% Confidence Interval of the demand distribution
### Appendix E: Total MRP scheme of product A, B, C and D

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Appendix G: List of MRP scheme parameters

\( NR_n(t) \): The Net Requirement of material \( n \) on time \( t \) 

\( D_n(t) \): Demand of material \( n \) on time \( t \) 

\( OH_n(t) \): On hand stock of material \( n \) on time \( t \) 

\( SR_n(t) \): The scheduled receipt of material \( n \) on time \( t \) 

\( LS_n; \): The lotsize rule of material \( n \) expressed in weeks 

\( S_n(t) \): Stock of material \( n \) on time \( t \) 

\( POD_n(t) \): Planned order due \( n \) time \( t \) 

\( SCR_n \): Scrap percentage of material \( n \) 

\( POQ_n(t) \): The production order quantity of product \( n \) on time \( t \) 

\( POR_n(t) \): The production order release of product \( n \) on time \( t \) 

\( L_n \): Leadtime of material \( n \) 

\( FLS_n \): Float at the start of production of product \( n \) 

\( FLE_n \): Float at the end of a production order of product \( n \) 

\( QT_{j,n} \): Queue time of a material \( n \) on a production unit \( j \) 

\( ST_{j,1,n} \): Setup time of a machine of production unit \( j \) of product \( n \) 

\( ST_{j,2,n} \): Setup time of labor of production unit \( pu \) of product \( pn \) 

\( PT_{j,1,n} \): Process time of a machine of production unit \( pu \) of product \( pn \) 

\( PT_{j,2,n} \): Process time of labor of production unit \( j \) of product \( n \) 

\( QBOM_{pn+i,pm} \): Bom multiplier factor; times product \( n+i \) is required to produce one product \( n \) 

\( SPLITQ_{j,n} \): Split quantity for product \( n \) on production unit \( j \) 

\( BQ_{j,n} \): Base quantity for product \( n \) on production unit \( j \)
Appendix H: Parameters and (decision) variables

Decision variables

- \( W_j(t) \): The Workforce of a production unit \( j \) on time \( t \)
- \( Mach_j(t) \): The Machine plan of a production unit \( j \) on time \( t \)
- \( SH_{j,z}(t) \): Total hours worked in shift \( z \) of production unit \( j \) on time \( t \)

Parameters

- \( ReqCap_{j,1}(t) \): Required Machine Capacity of production unit \( j \) in period \( t \) in hours
- \( ReqCap_{j,2}(t) \): Required Labor Capacity of production unit \( j \) of period \( t \) in hours
- \( SD_{j,z} \): Length of shift \( z \) of production unit \( j \)
- \( FT \): Full time job in hours a month
- \( MD_j \): Available hours of a Machine per day of production unit \( j \)
- \( OD_j(t) \): Operational days of production unit \( j \) per period \( t \)
- \( Util_{j,1} \): Maximum set utilization of machine capacity of production unit \( j \)
- \( Util_{j,2} \): Maximum set utilization of labor capacity of production unit \( j \)
- \( C_{j,F} \): Cost of Firing an employee on production unit \( j \)
- \( C_{j,H} \): Cost of Hiring an employee on production unit \( j \)
- \( C_{j,P} \): Cost of purchasing one machine for production unit \( j \)
- \( C_{j,S} \): Cost of selling a machine for a production unit \( j \)
- \( C_{j,m} \): Cost per hour of labor for shift \( z \) of production unit \( j \)
- \( C_{j,m} \): Cost per hour of holding a machine of production unit \( j \)
- \( C_{j,1} \): Cost per hour of using a machine in shift \( z \) of production unit \( j \)
- \( ZCAP_{j,1}(t) \): Maximum hours that can be worked on shift \( z \) of production unit \( j \) on time \( t \)

Variables

- \( AvCap_{j,1}(t) \): Available Machine Capacity of production unit \( j \) of period \( t \) in hours
- \( AvCap_{j,2}(t) \): Available Machine Capacity of production unit \( j \) of period \( t \) in hours
- \( H_j(t) \): Employees hired for production unit \( j \) on time \( t \)
- \( F_j(t) \): Employees fired for production unit \( j \) on time \( t \)
- \( P_j(t) \): Machines purchased for production unit \( j \) on time \( t \)
- \( S_j(t) \): Machines sold for production unit \( j \) on time \( t \)
Appendix I: IP-Model

Decision Variables

\[ W_F(t) = \text{The Workforce of a production unit } j \text{ on time } t \]
\[ Mach_j(t) = \text{The Machine plan of a production unit } j \text{ on time } t \]
\[ SH_{j,z}(t) = \text{Total hours worked in shift } z \text{ of production unit } j \text{ on time } t \]

Parameters and Variables

\[ AvCap_{j,1}(t) = Mach_j(t) \times OD_j(t) \times MD_j \]
\[ AvCap_{j,2}(t) = W_F(t) \times FT \]
\[ RLMC_j(t) = \frac{ReqCap_{j,2}(t)}{ReqCap_{j,1}(t)} \]
\[ ZCap_{j,z}^{pu}(t) = SD_j \times Mach_j(t) \times OD(t) \times RLMC_j(t) \]
\[ H_j(t) = W_F(t) - W_F(t - 1) \]
\[ F_j(t) = W_F(t - 1) - W_F(t) \]
\[ P_j(t) = MACH_j(t) - MACH_j(t - 1) \]
\[ S_j(t) = MACH_j(t - 1) - MACH_j(t) \]
\[ TotCost_j = \sum_{z=0}^{Z} \left( C_{j,m}^{pu} \times AvCap_{j,1}(t) + C_{j,P} P_j(t) - C_{j,s} S_j(t) + C_{j,h} H_j(t) + C_{j,F} F_j(t) + \sum_{z=1}^{Z} \left( \frac{SH_{j,z}(t)}{RLMC_j} C_{j,z,1} + SH_{j,z}(t) C_{j,z,1} \right) \right) \]

Constraints

\[ \forall t : \frac{ReqCap_{j,1}(t)}{AvCap_{j,1}(t)} \leq Util_1 \]
\[ \forall t : \frac{ReqCap_{j,1}(t)}{AvCap_{j,2}(t)} \leq Util_2 \]
\[ \forall t : W_F(t) - W_F(t - 1) - H_j(t) + F_j(t) = 0 \]
\[ \forall t : Mach_j(t) - Mach_j(t - 1) - P_j(t) + S_j(t) = 0 \]
\[ \forall z, t : SH_{j,z}(t) \leq ZCap_{j,z}(t) \]
\[ SH_{j,1}(t) \geq SH_{j,2}(t) \geq SH_{j,3}(t) \]

\[ z = 1, z = 2, \forall t : \]
\[ ZCAP_{j,z}(t) - SH_{j,z}(t) \leq M(y - 1) \]
\[ SH_{j,z}(t) \leq My \]
\[ y = 0 \text{ or } 1 \]

**Sign Constraints**

\[ \forall t: H_j(t) \geq 0 \]
\[ \forall t: F_j(t) \geq 0 \]
\[ \forall t: P_j(t) \geq 0 \]
\[ \forall t: S_j(t) \geq 0 \]
\[ \forall t: Mach_j(t) \geq 0 \]
\[ \forall t: WF_j(t) \geq 0 \]
\[ \forall t: SH_{j,z}(t) \geq 0 \]
\[ \forall t: AvCap_{j,1}(t) \geq 0 \]
\[ \forall t, z: ZCap_{j,z}(t) \geq 0 \]
## Appendix J: Validation BOM-Model

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### BOM

- **Product A**
  - 5 x **Product B**
    - 4 x **Product C**
      - 3 x **Product D**
      - 4 x **Product E**

### BOM Level

- **Level 0**
- **Level 1**
- **Level 2**
- **Level 3**
- **Level 4**