MASTER

Design of a prebuilding decision support tool ; considering costs, risk on obsolenscence, and on time fulfillment of stochastic short life cycle demand

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Design of a Prebuilding Decision Support Tool; considering costs, risk on obsolescence, and on time fulfillment of stochastic short life cycle demand.

Master's thesis

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Preface

This is the report of my Master Thesis Project, the final project of my master's program Operations Management & Logistics at Eindhoven University of Technology (TU/e) in Eindhoven (NL). The project, is performed at NXP Semiconductors in Nijmegen (NL), for the Business Line Smart Antenna Solutions (BLSAS). The project focused on the production supply chain and the inventories involved, which had my interest from the beginning: I chose my master's program as a follow up after my Bachelor of Applied Sciences in Mechanical Engineering, to gain more knowledge on production processes and industrial automation.

First of all, I would like to thank my mentor at the TU/e; Dr.ir. H.P.G. van Ooijen, who helped me through my complete master's program. Moreover, he helped me with choosing a direction for my master's thesis project and then helped me finding a relevant assignment and arranged a first meeting, while I was still in Munich for my international semester. During the project, he helped me with determine directions, helped when I didn't know how to continue and always had his critical opinion ready. Thank you for your time and all feedback and help.

Secondly, I want to thank everyone at NXP Semiconductors in Nijmegen who helped me during the project. My company supervisor ir. Wouter Schutte in special, who helped me often and guided me to the right people within the organization. Moreover, he helped me with the subject and understanding the complex industry. Moreover, he helped with the process and give useful feedback when needed on the process. Thank you Wouter for your time, guidance and information and insights. Furthermore, I want to thank Janneke Smits, Wil Vaneti, Irina Blajan, Nico van Bergen, Ron Diebels, and Vincent Eveleigh, who all helped me with some part or parts during my project. Thank you all for your time and sharing your knowledge.

Finally, I want to thank all my friends who showed interest in my project, especially Lidwine and Koen, who helped me a lot when I needed some more confidence in my own strengths or just someone to talk to. Thank you so much! Moreover, I would like to thank fellow students who showed interest and helped me when I had doubts and needed some comparisons or some insights from people with experience. And then, last but not least: my parents, who always believed in me, motivated me to continue some times, and have always been there when I needed advice. Thank you all!

Youri Nabben (BEng.)
February, 2019

Abstract

Introduction

This project is carried out at NXP Semiconductors BL SAS, located in Nijmegen (NL). NXP develops and produces integrated circuits. Its headquarter is located in Eindhoven (NL). NXP operates in 33 countries worldwide. This master thesis project is initiated by the Supply Chain department.

Business Problem and solution direction

The business problem as observed at the company, is that the cost of non quality (CONQ) are above target. The CONQ consist customer claims, but the greater part is obsolescence costs. These are costs made mostly due to scrapping products; products which are produced, but no demand is existing anymore. Before products are scrapped, they are held in inventory. Three types of inventory are defined at the company: moving inventory, slow moving inventory, and non moving inventory. Inventory is labeled slow moving when the demand is low compared to the inventory value. For non moving inventory, no demand is expected in the future. Therefore, this inventory has to be scrapped which leads to high costs of non quality.

Reviewing the existing slow and non moving inventories (SNMI) from the first three quarters of 2018, some conclusions can be drawn. In general, inventory levels are too high. SNMI play a large role in this; inventory levels on moving inventory are below the targets. By studying these inventories in more detail, six causes for inventory ending up labelled as slow and non moving are found. From these six, the three causes related to highest value of SNMI are selected as possible solution direction: Large Demand drop, Prebuilding to overcome loading limits, and Prebuilding to prevent future capacity shortages.

Large demand drops can be seen as an consequence of poor demand forecasting accuracies. This is known, however, multiple projects to improve the forecast accuracy, had no large impacts. Prebuilding (both variants) means producing products for temporary inventory, to fulfill demand at a later moment (when direct fulfillment at that moment would not be possible due to production capacity constraints). The second motivation for prebuilding is preventing financial penalties. These may be obtained when production capacities (mostly at an external party) are not used up to the agreed level. A third reason for prebuilding is a production line closure and demand is expected to be present for some more time. Looking deeper into the prebuilding decision process, it is observed that no decision process is used, although the number of factors expected to be of importance is large. Therefore, expected is that a Decision Support Tool for Prebuilding decisions can help for the business problem by reducing the buildup of SNMI. Moreover, this tool could help by deciding whether at a facility the production capacity should or should not be used to prevent penalties. The this reason for prebuilding is left out of scope: this decision is completely different and therefore, the same solution would not work. Moreover, the choices made in history, have not been defined as bad.

Additional literature and analysis of situation

A simple model is found for prebuilding decisions for one product and deterministic demand. Academic work found further did provide information and some useful insights, however, a complete solution to the problem is not found. Therefore, it is chosen to take the found simple model and extend it where needed.

Before the development of the solution starts, the current situation is investigated: the semiconductor manufacturing supply chain, production planning process, and the prebuilding process. for such a decision

tool. From this study, it is found that the stochasticity of demand is not considered by normal production planning and not included in demand forecasting information. Nevertheless, information on demand characteristics and possible developments are known within the company by some people.

Conceptual design of the Prebuilding Decision Support Tool

From the study of the current situation, it is concluded that considering stochasticity of demand is important for prebuilding decisions, for taking into account the risk of ending with SNMI. The risk on SNMI aside, fulfillment of customer demand is also important. Therefore, a tradeoff between the advantage of fulfilling customer demand (increasing revenue and service levels) and the risk on SNMI has to be made. This is done by comparing the costs of having leftover inventories and the losses when products cannot be sold due to shortage. With this cost information, the Newsboy fractile is created and used to define the quantity of demand to be fulfilled (under risk). To gain insights in the risks of demand, demand scenarios are created by using known information on market developments and other useful information. Combining the scenarios and the demand; the Newsboy demand and Expected demand can be calculated.

For the future capacity shortages, the Newsboy demand is used to define the capacity shortages in the future. This can be done for one product, or for multiple products. (When the facility considered produces multiple products; all the products must be reviewed and considered.) After defining capacity shortages, overages need to be defined. This results in demand which cannot be produced (overage) and capacity available for production. Then, product already in the pipeline or inventory downstream is included. Next, the overage demand which remains; will be ‘planned’ in the available capacity just before the demand overage. After allocation all products in that way, if there is no production allocated / planned for the current period: no action is taken and with this gained information in the back of the head, the tool will be used again with new information next period.

This Newsboy demand can be used directly after defining to investigate the possibility for producing products up to the loading limit of the facility. When the Newsboy demand is sufficient, this ‘problem’ is solved. When not, the tool can help defining overage demand in the future (when demand scenarios are present for a long enough horizon). The outcomes of the tool will help defining a loading level which is acceptable for risk on SNMI, compared to the costs.

Important to note is that the tool will suggest a prebuilding quantity for a product group, not for specific products. These choice on which product to choose, depends on other factors and this can be chosen by the user of the tool.

Case study and conclusions

The tool is tested on functionality by applying it to a real life case, where a prebuilding decision was made. The case is approached from two sides. For both approached, the tool shows advantages. With the first approach, the tool suggested smaller quantities to prebuild than were actually done. This would reduce the risk on SNMI. However, when the process would not be reviewed a regularly and decisions we taken without further consideration; this could have let to SNMI of a couple of million Dollars. For the other approach, usage of the demand scenarios resulted in small quantities of unfulfilled demand, however, this shows the risk-averse working this usage of the Newsboy demand. Long term effects cannot be shown (yet), however, expectations are that when the tool will be used and suggested decision won’t be overruled constantly; long term effects will be positive.

Contents

Chapter 1. Introduction

This is the report of a project executed at NXP Semiconductors in Nijmegen. In this document, the outcomes of the project will be presented.

In section 1.1, the project hosting company (NXP Semiconductors) will be introduced. Then, a short introduction of the subject of the Project is given in section 1.2. Finally, the outline of the report is stated in section 1.3.

1.1 Introduction of the hosting company

The project is carried out at NXP Semiconductors (NXP) in Nijmegen, the Netherlands. The project is carried out at the Business Line (BL) Smart Antenna Solutions (SAS), which is part of the Business Unit (BU) Smart Connectivity and Security. SAS develops semiconductor chips, also known as integrated circuits (ic's). SAS is a relatively small BL within NXP Semiconductors N.V. (NASDAQ: NXPI). NXP originates in Phillips Semiconductors. In 2006, NXP left Philips. NXP operates in 33 countries, has more than 100 facilities and approximately 31,000 employees (NXP, 2017). Its headquarters is located in Eindhoven, the Netherlands. Its Research and Development happens in 25 countries and is done by approximately 11,000 employees. NXP has research and development activities in Asia, Europe and the Unites States of America. It has five Wafer Fabs, two in Austin, Texas (US), one in Chandler, Arizona (US), one in the country of Singapore and one in Nijmegen. NXP has in total four assembly and test facilities in Thailand, Taiwan, Malaysia and in China. The company can be seen as an Integrated Device Manufacturer (IDM).

The Project is carried out mainly in Nijmegen, where BLSAS is mainly located. The supervisor is Director Fulfillment at BLSAS. He is the coordinator for the (production) supply chain for all products of this Business Line.

1.2 Introduction to the business problem

In recent history, it is noticed that the costs of non quality of the business line exceed the target as set by the company. The target is defined as a percentage of the revenue, and given Industry-standards, set to 0.5% of the revenue.

Cost of Non Quality is a collection of different costs: Customer claims and Obsolescence. As can be seen in Figure 1, customer claims only cover a small part of the total Cost of Non Quality. Customer claims are costs which are paid to customers, due to product failures for example. Obsolescence costs are mainly costs which are made due to having too much products which cannot be sold and have to be scrapped. As can be seen, the costs of non quality fluctuate a lot, but are always above the target (one exception in Q2'17).

Obsolescence costs, as mentioned earlier, are mostly caused by having too much inventory, which cannot be sold. For a business, inventory in general is unwanted since it is financial capital which (normally) has a negative rate of return. Additionally, there is a risk of not being able to sell inventory and having to scrap the products (and capital). Additionally, resources used could have been used for other (profitable) products. On the other hand, having inventory is necessary for being able to cover uncertainties in demand when production of products cannot (completely) be aligned with orders (at the start of production). Moreover, inventories can cover for uncertainties in supply and can enable stable manufacturing throughputs (and keeping it below certain manufacturing capacities), while having unstable demand.

As can be seen in Figure 1, in 2015 the costs of non quality were about 7.5 thousand dollars, where in 2016 the costs where the highest with an average of 1.2 million dollars, in 2017 and 2018 the costs were lower (around 419 and 499 thousand dollars respectively). The year 2018 included a prediction, information on Q2 and Q3 is from the (rolling) financial forecast.

Due to the fact that the costs are above target and of magnitudes as stated above; the project is initiated. During the project, the current situation around the Costs of Non Quality will be reviewed and a solution will be designed with the goal of reducing the costs in the future.

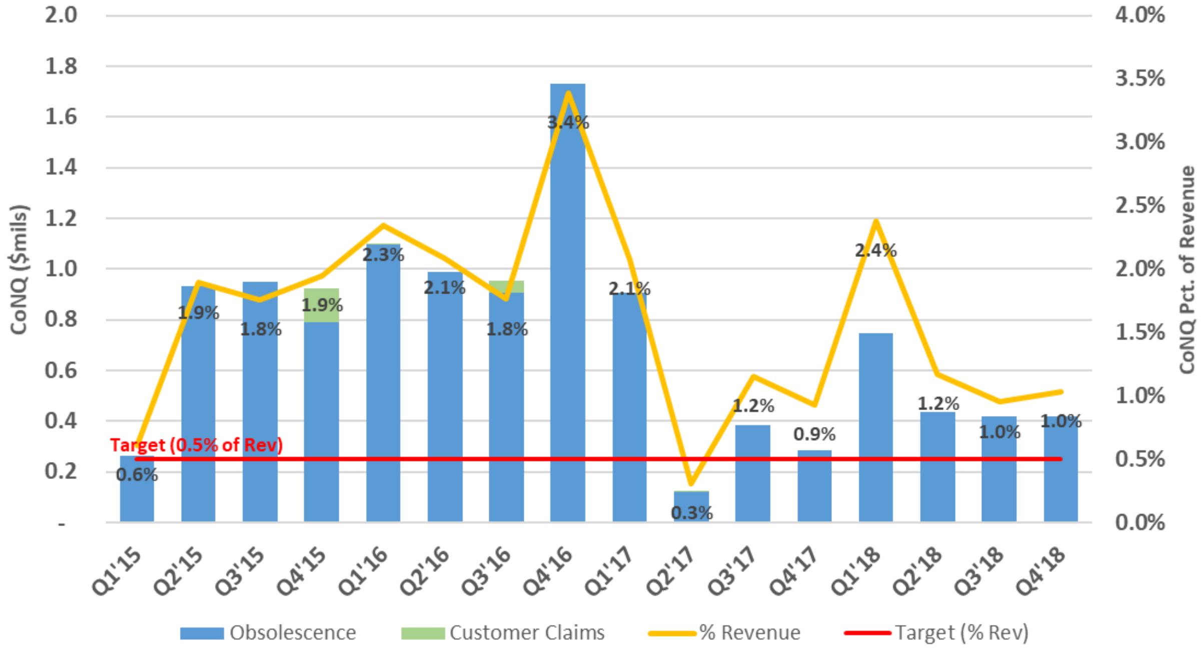

Figure 1: Cost of Non Quality at the Business Line per quarter. Up to Q2'18 it consists of real information, later the information is from estimations. Source: company internal presentation.

1.3 Outline of the report

In the following chapters of this report, the project described in more detail. In Chapter 2, the Business Problem is explained in more detail, as will be the found project direction, assignment and scope of the project. Also, the literature is described. Then, in Chapter 3, the current situation regarding the solution direction is described. Thereafter, in Chapter 4, the designed solution is described. First, conceptual, then the detailed design is shown and explained. In Chapter 5 the solution is compared to a real life case and results are reviewed. In the final chapter, Chapter 6, conclusions are drawn and some recommendations are done for usage and eventual future research. Appendices are located at the end of the report and will provide some more detailed or extensive studies: these will be referred to from the report.

Chapter 2. Business Problem and the project

This chapter describes the relation between the business problem and the project. In section 2.1, the business problem is shortly recapped and the study to determine the solution direction are presented is shortly summarized together with the conclusions (2.1.1 and 2.1.2). From this study, the solution direction is chosen in section 2.1.3. Then, in section 2.2 the literature is discussed. Finally, in section 2.3 the Master Thesis Project will be discussed: the assignment, scope, and research questions are shown.

2.1 Current situation behind high cost of non quality

The Master's Thesis project is initiated by the Business Planning (Supply Chain) department of an Integrated Device Manufacturer (IDM[1]). Within the company, it is noticed that the costs of non quality is high and above the target, which is also the case for the Business Line, as shown in the introduction (section 1.2). As can be observed, the costs of non quality consists of two main parts: customer claims and obsolescence costs and customer claims, where the latter does not contribute significantly. Therefore, the cause for the high costs of non quality, are expected to be in or found through studying the inventory, especially within the inventory labels slow moving inventory (SMI) and non moving inventory (NMI). Together with moving inventory (MI), are these the three labels with which the inventory is categorized. Non moving inventory will (eventually) be scrapped, which results in the high costs of obsolescence.

Since the semiconductor supply chain is known to be complex and large, some interviews with the Business line's supply chain stakeholders are held to form a view on the characteristics of the supply chain, combined with the demand (forecast) handling and production planning. Summarized findings from those interviews, combined with collected information on the current situation at the company, are shown in Appendix . A short summary on the findings and some conclusions drawn from this investigation are shown in section 2.1.1. Moreover, the study on existing inventories is summarized in Appendix XX2. A summary and the drawn conclusions are shown in 2.1.2. The solution direction, chosen considering the study on the current situation, is discussed in section 2.1.3

2.1.1 Production supply chain characteristics and processes

As stated in the previous section, the semiconductor production process is a complicated process with long production lead times. Different production steps must be carried out (which can differ per products): not all products have the same production process. Also, the first part in the semiconductor production process, the wafer fabrication, can differ per product (different mask layers). The total production lead times can add up to 26 weeks for product designed by and produced for the Business Line. The customer order lead time is shorter (and differs per customer), which creates the need for a Customer Order Decoupling Point (CODP), which can differ per customer. Downstream of the CODP in the production process, no production will be carried out on forecast (unless decided otherwise): this is the make-to-order principle. Upstream from the CODP, production does start on the demand forecast (make-to-stock principle). This forecast is generated by the Demand Manager and is based on information from people close at the customers and/or close in the own organization (marketing for example). Although much effort is put into demand forecasting, forecast accuracies are not high. In the past, effort is put into in

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[1] IDM: Integrated Device Manufacturer. A company which designs, manufactures and sells integrated circuits (a.k.a. ic's, chips or, semi-conductors).

improving demand forecast accuracies, however, forecast accuracies are still quite low. This is also because gained information on demand is often inaccurate: the produced products are parts for consumer products, the bullwhip effect also occurs within the demand. Additionally, customers can change their production quantities to react on changing consumer product demand, which can result in a sudden drop (or increase) in demand for the BL. To account for those uncertainties in demand, in combination with uncertainties in supply, some safety stock is kept. The inventory targets are expressed in weeks of demand (one 'week' of inventory equals the average demand of product for one week). How many weeks of inventory are kept at which locations (dependent on the product stage), is mostly predefined. This is understandable since the inventory level dependent on demand, results in inventories which are reasonable looking at the demand. Slowness of the system (average demand over a long time does combine well with non-stationary demand) and not adjusting inventory targets accordingly to the product life cycle phase could be reasons for having too much inventory in the complete supply chain. Moreover, it is uncommon to express and define safety stock levels in average demand, normally these levels would be based on variance in demand or demand forecast uncertainty to cover a certain amount of uncertainty.

Given the complicated manufacturing supply chain and a large variety of products, production planning is challenging. This is done by production planners, who are constantly trying to match demand and supply. This means; making sure that there is enough product available when there is demand. This is done with the help of a production planning engine, which used different inputs as information and calculates optimal production plans (called proposal), given inputs and constraints (for example production capacities) and rules (for example priorities). These plans are created weekly, and have to be reviewed thoroughly, since not all (important) factors are considered by the engine. A deviating choice could be better at that moment.

On top of not considering all important factor, in the production planning engine's way of working is the fact that this considers demand as being deterministic, where planning uses forecasted demand most of the time. Since demand (forecast) can change, this can result in inefficient production proposals. When the production plan is not followed, it is often the case that strategic choices are made, or prebuilding is chosen. Prebuilding means building up inventory, based on different motivations. These are high-risk decisions since the demand for the product is not yet there, and the forecasting horizon is longer than normal (which results in even lower forecast accuracies). Although these negative factors, prebuilding decisions have to be made quite often and large sums of money can be involved. Surprisingly, a solid decision making process is absent.

2.1.2 Currently existing inventories in production supply chain

After investigating the current situation with a wide view on the existence of inventories and invent buildup in the semiconductor supply chain, existing and historic inventories are explored and reviewed.

Considering the historic inventory numbers of the Business Line, it is clear that these numbers are too high. When Days of Inventory Outstanding is used as measurement and the numbers compared to industry standards (which are 85-95 DIO), one can conclude that the actual levels at the BL are too high: more than 140 DIO (averaged from January 2017 until June 2018). Reviewing inventories with(in) the Entitlement Model[2], the existing inventory is also too high. There is one exception; mid 2018 (this is the

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[2] a company internal measurement for inventory management considered healthy using the SC settings as input.

last part of the reviewed horizon). This information shows that not only the inventory levels compared to industry standards are too high, but also compared to the company-internal targets for overall inventory. This leads to the conclusion that inventory targets or situation settings are not (completely) the cause for the high inventory problem: when the settings were the problem, the value Entitlement values would have been the same as the current values. Therefore, the composition of inventories is reviewed more thoroughly.

The existing inventory is divided into three categories: moving, slow moving, and non moving. Inventory is labeled as slow moving inventory when there is more product in inventory than the average demand for 26 weeks. When there is no demand the next 22 weeks, inventory is marked as non moving inventory. Looking at the numbers, slow moving and non moving inventory represents about 50% of the total inventory. Where slow moving inventory is unwanted since it is locked up capital without other use (and being at risk of ending up as non moving), non moving inventory is even more unwanted since this will be scrapped eventually and by being scrapped, NMI contributes to the cost of non quality. Important to note is that total inventory value is not double the wanted value. Therefore, or the moving inventory is not at a healthy level, or, a large group of products for which there is demand (and inventories should be labeled as moving), inventory levels are too high and therefore the inventories are labeled as slow moving inventory.

The slow moving and non moving inventory (SNMI), is reviewed on a regular (quarterly) basis. During this review, the products with a slow or non moving value higher than 100 thousand Dollars are reviewed. This is done based on the Pareto-principle: roughly 80% of the SNMI-value is represented by 20% of the products. Looking at the these products which have a SNMI-value higher than $100,000, there are six causes which are found for the products in the SNMI (of which multiple can be the cause for one product):

1. Cancelled orders
2. Large Demand Drop
3. Personal Mistakes
4. Prebuilt (Loading Commitment)
5. Prebuilt (No Loading Commitment)
6. Ramp-up

Important to note is that a specific product in inventory can have multiple causes simultaneously. Only considering the occurrences, not at the values of the SNMI; Large Demand Drop (no. 2) is the most occurring cause (83% of the cases). Then, prebuilding is the second most occurring cause (27% and 22%). The other causes are relatively rare (2%, 7%, and 15%). Since causes appear often with more than one, the relation between causes is investigated. It is observed that a large demand drop is always combined with other causes, except for the 'Personal Mistake'. This is logical, since the other reasons would not be a problem if there was no demand drop.

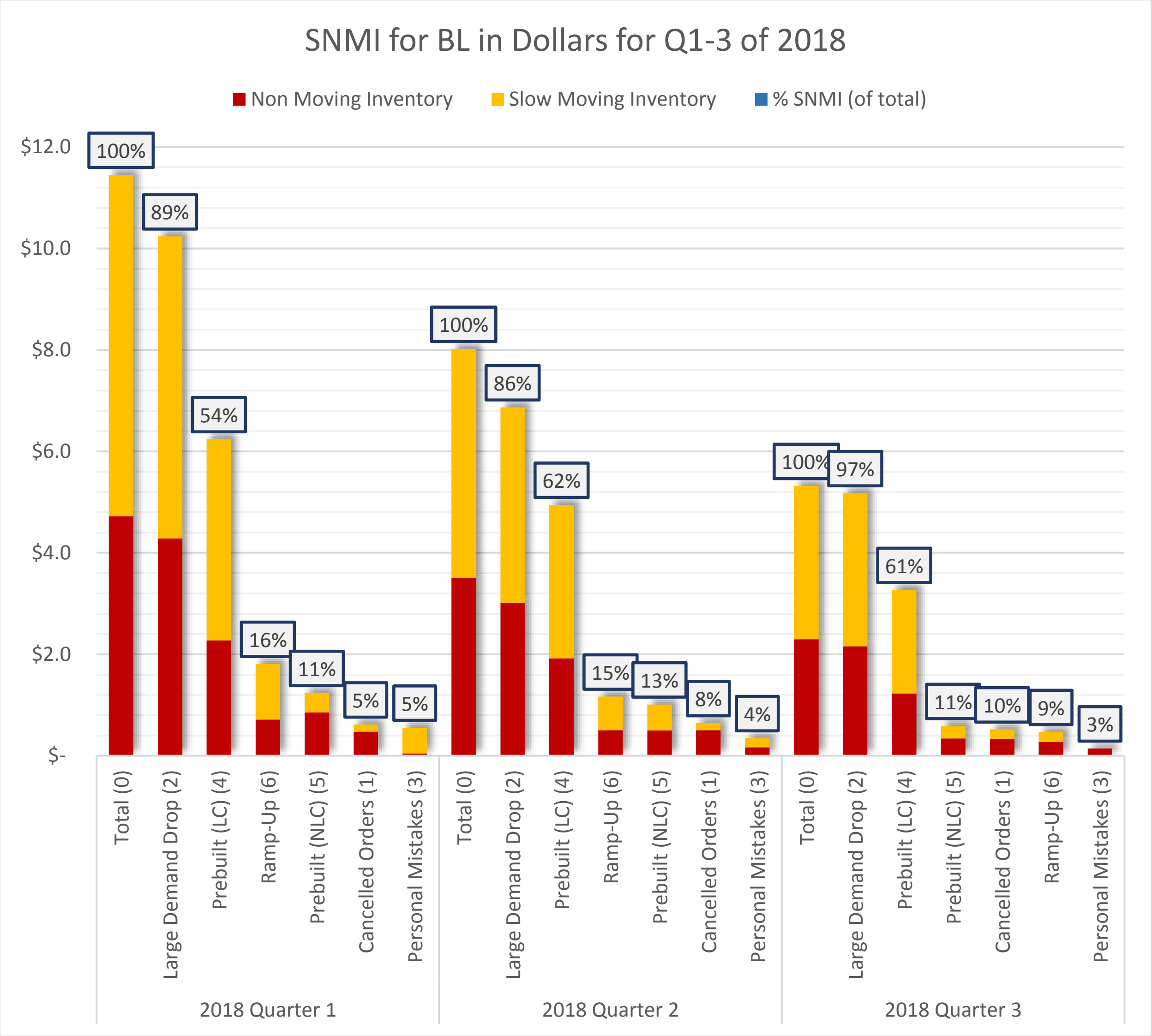

Figure 2: Slow moving and non moving inventory value per end product larger than $100,000, linked to the different causes. On the horizontal axis, quarter one to three of 2018 are shown. In red, the non moving value is shown. In yellow, the slow moving value is shown. Moreover, per cause, the percentage the cause represents of the total value per quarter is shown, depicted above the bars. Per quarter, the total value (number 0) is shown. Then, the value represented per cause is shown, sorted from largest (left) to smallest (right) sum of slow moving and non moving inventory. The numbers with the causes refer to the list of causes with explanation earlier in this section. The values (and percentages) of different causes do not add up to the total value since inventory can be caused by multiple causes and the inventory is considered multiple times. Moreover, it can be notices the total value of slow moving and non moving inventory decreases over the year 2018; it almost halves.

Figure 2 shows the value of SNMI connected to the different causes, for the first to the third quarter of 2018. There, it can be observed that Large Demand Drop represents the largest part of the SNMI-value. This is logical since no production is carried out when there is no (forecasted) demand. After that, prebuilt products due to Loading Commitments represent the largest value of SNMI. Then ramp-up and the second variant of pre-building (clearly lower than the first variant) show the largest causes (in the first two quarters of 2018, the third quarter Cancelled Orders is the fourth cause). Considering prebuilt products as one cause for SNMI, this is clearly the second cause after the Large Demand Drop.

Additional to the causes for SNMI as listed above, it must be stated that there is a third reason (besides 4 and 5) for prebuilding products: closure of a production facility or line. This reason has caused SNMI, however, this is not shown in the list as stated above or in Figure 2 since the inventory caused by this cause, is not considered in the regular review. This is because the inputs for this prebuilding decisions are completely different than the other two variants. Moreover, the inventories created by prebuilding for this reason, are still declining and the decisions made in this direction are considered fine.

Finally, the ratio between slow moving inventory and non moving inventory must be reviewed. Logically, the two inventory parts cannot be viewed separately, since (normally), non moving inventory (NMI) was slow moving inventory before it was labeled non moving. Besides that, slow moving inventory is unwanted but not a large problem, where non moving inventory is a problem since this has to be scrapped because it cannot be sold anymore. Considering the ratios between SMI and NMI in 2018 (based on inventory values, since both the labels SMI and NMI could be linked to a product), for the total SNMI ('Total (0)' in Figure 2), slow moving inventory represents 56-58% of the value. Cancelled orders result often in non moving inventory. Personal Mistakes is a good example of products starting as SMI, ending as NMI. Inventory due to ramp-up ends up with a bit more non moving inventory over time, but the change isn't large. For Prebuilt inventory due to a loading commitment, the ratio is quite constant over the three quarters, and more SMI than NMI is present. For Prebuilt inventory not due to a loading commitment, in quarter one the percentage was 30% SMI, in quarter two 51 and 42% respectively. From this, it can be concluded that it is more likely that products not built to overcome loading commitments, end up as non moving inventory. Moreover, prebuilt products to overcome loading commitments, do end up less as NMI.

2.1.3 Defining the solution direction for the business problem

In the previous section, three causes for slow moving and non moving inventory are marked:

- Large Demand Drop
- Prebuilt products to overcome loading commitments
- Prebuilt products to overcome future capacity shortages

These could be regrouped in to 'main causes': Large Demand Drop and Prebuilding. The third motivation for Prebuilding (to fulfill demand after a facility or line closure), was not listed as one of the six causes in section 2.1.2, since the motivation for these decisions is completely deviant from the others. However, the SNMI as observed is not judged as problematic.

As has been observed in previous sections, demand drops cause most of the current SNMI. This can be related to demand forecast accuracy. This forecast inaccuracy has been observed multiple times before, improvement projects have been executed, however, no large improvements have been made. Although the demand forecast accuracy is poor, investigating how this demand forecast is created, combined with the information on the industry (semiconductor): short product life cycles, business to business (high volume), long production lead times (combined with shorter customers order lead times), and unreliable information provided by customers (they will react on consumer demand when the production of the semiconductor is already ongoing), result in a situation where unreliable demand is a given and not probable to gain large progress since most of the critical factors are not within the company's control.

Moreover, for the second cause as mentioned (prebuilding), decisions must be made under high risks (information is unreliable: demand forecast with horizon longer than the production lead time is worse) and with possible large impact. One would expect a thorough decision model, where in practice no clear decisions are made. Decisions on prebuilding (in all three cases) are often based on gut-feeling of some people, mostly the Business Planner, provided with information from the Demand Planner and some other roles within the organization. However, decisions are still based on gut-feeling and are therefore not defendable, well underpinned decisions. Additionally, it is not clear whether important information on demand and products is considered or (accidentally) left out in the decision.

Finally, the other causes have clearly less impact on slow moving and non moving inventory. Still, these causes are worth looking into: since only inventory valued above 100 thousand dollars is reviewed, the value is still high.

From the conclusions in sections 2.1.1 and 2.1.2, the solution direction for the business problem within this master thesis project, is chosen to be in the direction of improving and/or supporting prebuilding decisions. This to reduce the buildup of SNMI in the future. Completely preventing slow moving and especially non moving inventory is not realistic, since this is also a risk of doing business and doing business in a way that these inventories would not occur, would result in major service level drops and may result in lost sales. However, lowering the buildup slow moving and non moving inventories should be possible by creating a decision support model / tool for prebuilding decisions. This model and/or tool should be easy to use for users and moreover, should not replace existing units / software (like the production planning engine or demand handling systems). A complicated model would not simplify the work of the people who will use it and by that, end up not being used. Moreover, the tool should incorporate different insights which are not considered in the current situation.

To handle existing slow moving and non moving inventory, parallel to this master project, a project is run on handling slow moving and non moving inventory. This project focusses on handling slow moving and non moving inventory in a way that scrapping is the last option, after effort is put in trying to sell the inventory or use it in other ways. Moreover, a regular root cause analysis is carried out to reduce the occurrence of slow moving and non moving inventory in the future. Although this will be a major help in continuously improving the demand fulfillment and inventory handling process, will not make the work done in this project redundant since this analysis and solution will help by reducing the slow moving and non moving inventory in the future.

2.2 Literature review on semiconductor supply chains

As stated in previous sections, the semiconductor supply chain is complex. Therefore, a literature review on the supply chain and demand forecasting and handling is carried out. First, a more general review is carried out by Nabben (2018), as preparation for this project. The outcomes of this review are shortly described in section 2.2.1. Then, after investigating the current situation at the Business Line and reviewing the currently existing inventories, related to the business problem; an additional literature review is carried out to find input for the chosen solution direction.

2.2.1 General literature review on semiconductor production supply chains

Based on the original project assignment, as preparation, a literature review is conducted by Nabben (2018) to gain academic knowledge on demand management and, forecasting and inventory modeling &

optimization, in the semiconductor industry. Moreover, the product life cycle is included, especially in demand management. This literature review is carried out before the project has started and is initiated on the available information at that moment. Therefore, handling capacity shortages (bottlenecks) or excesses, is not considered in the preparatory literature review, but considered later in additional literature review.

On demand management in the semiconductor industry, plenty of information is found on semiconductor demand forecasting. Additionally, information is found on Product Life Cycles (PLC's) and how to combine these demand forecasting and PLC's. This is found in Growth Models.

For inventory modeling, information on semiconductor production supply chains is found. This is general information on the outline of the supply chain and the (general) semiconductor production process, which provides good insides. Moreover, it is notices that the semiconductor supply chain can be viewed as a multi echelon supply chain. For multi echelon supply chains, a lot of information is found, especially in the direction of inventories. Many models are found which can be used to model and optimize inventory levels. However, no complete solutions are found to the problem, no model is directly applicable to the problem. Therefore, when the problem solution can be found within the inventory level direction; combining different models would help.

As can be seen in the previous paragraphs, in the literature, much useful information on demand management (combined with product life cycles) and inventory (level) modeling, is found. However, a research gap is recognized in the direction of including strategic factors for optimizing. For the problem environment, to make well founded strategic decisions, additional factors like profit margins are important. Nevertheless, no models are found which include these factors in models. Therefore, when important, this should be included in the model used for the solution.

2.2.2 Literature review on prebuilding

Since the solution direction was not clear at the start of the project, the Literature Review by Nabben (2018) was oriented more at inventory levels in the semiconductor production supply chain. Knowing the solution direction of the project, a literature review must be done to find out whether some relevant academic work has been done on prebuilding or related topics. The solution direction and the boundaries of this solution are considered during the study.

Since the solution direction is chosen on prebuilding, academic literature on 'prebuilding' is searched for. This did not result in much results. However, the book The Profitable Supply Chain (Ganesan, 2015) does name prebuilding, in this case for seasonal demand. In the example given, the demand exceeds the production capacity (even the additional capacity) and therefore a supply shortage would occur. To prevent this, inventory has to be built up beforehand. This is a well-known problem, which is also addressed in the most standard and simple (mathematical) production-inventory models. Ganesan (2015) states that when multiple product use the resource, some additional considerations have to be done like ensuring availability of RAW materials and storage, and minimizing leftovers. The latter is only the case when demand is uncertain, which is the case for the current product. A simple method for prebuilding decisions (when to prebuild what amount) with some basic Excel-based rules, one-product problems given discrete demand, is provided. The writer explains that this solution could be extended to multiple products. However, for large numbers of products and when more factors need to be considered, he states that a heuristic methods or linear programming becomes necessary; many advanced planning systems have such capabilities, and so does the production scheduling engine for the company. Prebuilding will therefore also be proposed in the production proposal. However, these proposals do consider forecasted demand as deterministic and therefore, decisions still must be made considering demand uncertainty. Literature on (production) capacity levelling is found; however, the found material did not contribute to the problem as desired. There, the focus is on using 'empty' capacity, where the focus for this project is one demand and capacity is a constraint.

To overcome the problem as observed (no demand uncertainty is considered within the production planning engine[3]) with stochastic demand, another planning engine should be used (or other planning models). In the literature, solutions are found in this direction, for example by Escudero, Kamesam, King, & Wets (1993). There, two models are presented for production planning, considering stochastic demand (using scenario modelling). Although this seems to be a good approach, the author also recognizes the problem of expanding the model by including scenarios. This is not considered problematic since the result from the real-life instances are encouraging. However, looking into these cases, the tested cases seem relatively small (100 products, 25 scenarios, 12 periods, 1 resource). Although the computational times are good (maximal 153 seconds, with computational hardware of 1993) for these cases, the practical problem at the company is way larger (more product variants, complex supply chains, multiple resources, more periods, etc.) and a solution like this doesn't seem workable. This is confirmed with the knowledge that currently the planning engine (a world-wide well-known planning engine), without considering any demand stochasticity, can only be run once a week because the run is done during the weekend (because of run-time). This confirms the need for a simple solution which can be used as an extension of the current situation.

In addition to this academic work, some information is found on (multi-echelon) supply chains, given uncertain demand. These articles focus on ordering decisions for retailers, sourcing decisions when multiple sourcing decisions are possible (for short-lifecycle products). These solutions are not relevant enough for this solution direction and therefore not applicable.

An extensive three-part literature review on Semiconductor supply chains is conducted by (Mönch, Uzsoy, & Fowler, 2017a, 2017b; Uzsoy, Fowler, & Mönch, 2018). In this literature reviews, literature is searched for about semiconductor supply chains, in all relevant directions. Usable concepts when not directly meant for the Semiconductor supply chain, are also mentioned. In the third part of the LR, the focus is on master planning, production planning and demand fulfillment. Master planning is in this case the most interesting part, since this planning outcomes provide information for production planning, ATP (Available to Promise) and demand fulfillment. Within the master planning, decisions have to be made on how the supply chain must react on different topics, for example how to react on seasonal demand peaks and the how capacity shortages have to be allocated. These decisions must be made on a relatively high level, therefore often aggregation is used. The information generated by the Master planning module, is then

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[3] Two variants of demand are considered within the planning engine: normal demand, and 'flex' demand. Normal demand is prioritized over flex demand. Unfortunately, in practice, this can cause other prioritizing problems (for example: production for safety stocks based on real demand could be prioritized over supply for possible demand). This results in having to flag everything as normal demand for the system, which can result in inaccurate reflection of reality.

used for the detailed production planning. Mönch et al. (2017b) recognize the need for Inventory Management and Production planning to be strongly linked. However, in practice, this is often not the case, especially since production planning models take mostly a deterministic perspective, where inventory management uses variabilities as most important information input. Moreover, production planning is often based on demand forecasts that are subject to random errors, which is exactly the problem for the current project. Finally, Mönch et al. (2017b) conclude their LR with the conclusion that over the years, there was and still is a lot of academic attention for the semiconductor supply chain. Although, it is recognized that in the 1990s more work was known to be done for planning systems and such. It could be that not many research is published in this direction, because of the commercial side of this market (some large companies provide planning systems), and publishing research outcomes would provide competitors with advantages.

Going back to the chosen solution direction, it can be concluded that material is found, but not much useful information in the direction of simple additional help for production decisions. Combining the information gained on the current supply chain situation (outline and processes) at the company, together with standard knowledge on production and supply chain decisions, and the information and insights from the (found) literature; it seems be possible to design a tool decision support tool. Some important basic information kept in mind, is information gained in lecture notes of Atan (2017) and some other gained information and experience. The Newsboy-rule (or Newsvendor problem, model, fractile, or fraction) is proven to be effective and useful for decisions based on costs and uncertainties. Moreover, trying to spent as less as possible on production and most important; on production of products which have to be scrapped, will result in a certain decision direction.

2.3 Master thesis project

In the previous sections, some points of interest regarding the Business Problem are recognized. Moreover, in the study on the causes for the currently existing slow moving and non moving inventory, a direction for the solution as will be designed during the Master Thesis Project is chosen. How this choice will be given an interpretation to, will be explained in section 2.3.1. In section 2.3.2, the scope of the project is provided. Finally, the defined research questions for the project are stated in section 2.3.3.

2.3.1 Master thesis project assignment

In section 2.1.3, the solution direction for the business problem is chosen: improve prebuilding decision making. Therefore, in this project, a prebuilding decision support tool (PDST) will be designed.

The prebuilding decision support tool for will incorporate some factors which are of importance when prebuilding products. Please note that the tool will support in decision making, the decision will still have to be made by people on the given information and other factors which are not included in the tool. Moreover, not all prebuilding decisions will be within scope of the project, as will be explained in the next section.

2.3.2 Master thesis project scope

As stated earlier in this chapter, a prebuilding decision can be made different motivations. Three categories stand out:

- Future capacity shortage at a production facility or line
- Avoid consequences of (under)loading a production facility or line
- Production stop (at supplier)

Within the project, the focus will be on short term operational decisions, where short term stands for a maximal horizon of one year, approximately. Further in the future, forecasted demand does not make sense anymore; too many other factors need to be considered in the decision making. Additionally, decisions made on production capacity increases (in case of large capacity shortages further in the future) won't be included in the project since these decisions are too capital intensive and wider (market) research has to be carried out. Moreover, the supported decisions are decisions taken now, given the current information and considering the future. Finally, the tool will support decisions for one product or product group, on an aggregate level, because at a facility multiple products could be produced. Decisions on the specific products within the product group have to be made by the user of the tool; since other factors may be of importance.

When in the (near) future, production capacity shortages are recognized for one or multiple products, to ensure supply to fulfill demand, prebuilding products can be done to overcome the shortage in supply. This decision must be possible to make within a time period of one or two days (acting on new information almost instantly is important to prevent unfulfilled demand). Moreover, the decision needs to be possible to make by using the tool; which implies that the tool must be easy to use and the calculations done are not very difficult (to understand) for people at different departments in the company. Besides that, it is possible that multiple of these decisions have to be made within a couple of days, which also implies that simplicity is must.

(Under)loading a production facility can have different consequences in the future. One of the consequences can be having to pay a penalty for the unused capacity. This penalty can be included in the calculation carried out by the decision tool, and therefore will be within the scope of the project. This penalty is mostly the case when production occurs at a supplier, not at company internal production facilities. For internal facilities, a penalty for not loading the facility to its agreed level, will most likely not result in direct (financial) penalties. When this under-loading occurs regularly, it is possible that the business line will lose production capacity to other production lines with will endanger supply of product (and by that revenue, among other things) in the future. Since this decision is not easily expressible in numbers, these decisions are left out of scope. More research on the risks and/or benefits of such a choice would be necessary.

Finally, the third (main) motivation for prebuilding would be a production capacity line or facility closure. In this case, when the production of that product cannot be continued at another facility or another product can replace the product precisely, and losing sales is not an option; products to fulfill the demand in the complete future must be prebuild (when production capacity allows it). Since determining this demand and studying the risks and benefits of this problem are completely different from the other decisions, these decisions will not be included in the scope of the decision tool design. When the production stop is considered a temporary thing; the decision support tool could be used (by setting the production capacity to zero, for a given period of time).

2.3.3 Research questions to answer during the project

This report describes the process as is followed during the master thesis project and the designed solution for the business problem. The process of ending up with the solution, is followed by answering a couple of research questions, as stated below. These questions helped providing the structure of the project and this report.

1. What is the Business Problem and what could be a solution for the problem?

In the Introduction and this chapter, these question is answered. First, the business problem is explained and the investigation to find the solution direction is summarized. Then, the solution direction and the scope is stated in more detail.

2. What are current processes and methods used within the company in relation to the solution?

In Chapter 3, this question will be answered. A detailed description of the current situation at the company is provided. This information will be of importance for the solution design.

3. How should the solution be shaped and what will be the outline of the solution?

Chapter 4 describes the conceptual design of the solution. This chapter will show how the solution will be designed and the conceptual design of the solution.

4. What calculations does the tool and how should it be used and interpreted?

Later in Chapter 4, the calculations as done by the decision support tool are described. At the end of the chapter, some tips and insights are provided on usage of the tool.

5. What is the effect of using the tool in practice?

Finally, Chapter 5 will provide a case study, where in a real life case, the tool is used. Then, the decision as proposed by the tool is compared to the decision as has been made without using the tool. Then, the differences are explored and explained.

Finally, in the Chapter 6, the research questions are answered shortly and the some recommendations are done for future projects and/or research.

Chapter 3. Detailed analysis

In the previous chapter, the business problem is explained in detail, followed with the investigation on the solution direction: a prebuilding decision support tool. In this chapter, the semiconductor manufacturing supply chain is discussed in 3.1. In 3.2, production planning is explained. Then in 3.3, the current prebuilding process is explained.

3.1 Semiconductor manufacturing process

The semiconductor manufacturing supply chain is complicated and long, as is the production process itself. The manufacturing supply chain can be divided into two main parts: the front-end and the back-end. In section 3.1.1, the front-end production process is explained. Then, the front-end production supply chain is shown and described shortly. Then, in 3.1.3, the back-end production process is explained and a simplified supply chain is shown and described. Next, in section 3.1.5 inventories and service levels are shortly described, Finally, in 3.1.6 the Customer Order Decoupling Point is described.

3.1.1 Front-end production process

In the front-end; the dies[4] are created on silicon slices (the silicon is raw material, which is sawn into slices). Dies are created layer per layer. The time needed per layer on a wafer is roughly the same for all dies: the number of layers out of which the die exists defines the production time. At the BL, dies can contain up to ±45 mask layers. The number of dies on one silicon slice, depends on the size of the die. The number of dies on one slice can vary between 1,000 and 500,000. Although the product is build layer per layer, the process is continuous and has only one decoupling point: the so-called metal bank (between front-end and back-end diffusion, both in the front-end of the production supply chain). For some products, after the metal bank different products can be created from one semi-finished die (often called mother-die), for other products the die is unique from start to finish. A silicon slice with finished dies, is called a wafer.

3.1.2 Front-end production supply chain

As explained in the previous section, the front-end production process is the production of wafers with dies; using silicon slices as raw material. This production process is also known as Diffusion. Table 1 shows this supply chain: the process starts, the first part of the diffusions process is done (1.1). Then, an inventory or buffer is placed: SLPD (Slice Partially Diffused), previously described as the 'metal bank'. This production step takes approximately 105 days, dependent on the product, this can differ 7 days (less or more). After the SLPD, the back-end of the diffusion process (1.2) will take place, which results in the SLDI-inventory (Slice Diffused). Here, the production time is 5 weeks or 35 days.

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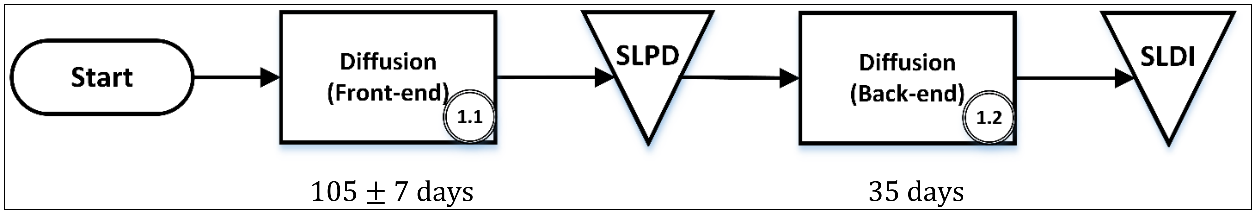
[4] Die: heart of the chip, the electrical circuits, mostly multiple layers on a piece of metal. Multiple dies are created on one metal slice, later the wafer (slice with dies on it) is cut up into singular dies.

Table 1: Front-end supply chain, lead times of the process steps stated below the process.



3.1.3 Back-end production process

In the back-end of the production supply chain, the wafers are transformed into chips (or semiconductors or integrated circuits). The first step is probing (a.k.a. wafertest): testing every single die on deviations from the requirements. Dies who deviate from the requirements are marked and will not be used later in the process. The fraction of dies which does comply with the requirements, is called the yield. A possible step before or after probing is bumping; there metal bumps will be placed on the die which will function as contact points. After probing (or bumping), the dies cut loose and put into a package (small plastic box), also known as Assembly. This package provides the contact points to connect the die with the outer world (some dies have these contact points already: so-called bumps). After the assembly of the die and package; a final test on requirements is carried out and chips are put into packing and will be shipped to the customer (via a warehouse or directly).

3.1.4 Back-end production supply chain

As explained in the previous section, the back-end of the production supply chain contains more different processes. There are three different variants for the production supply chain (the fourth is only front-end and not relevant for inventory handling). All three variants are shown below and explained shortly. Note that the starting inventory for all three variants is the same inventory as the last inventory of the front-end production supply chain.

Table 2: Back-end production supply chain for product group 1, lead times of the process steps are stated below. The first buffer (SLDI) is the last buffer of the front-end supply chain from Table 1.

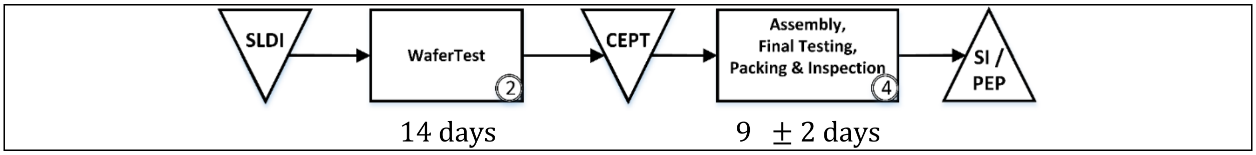
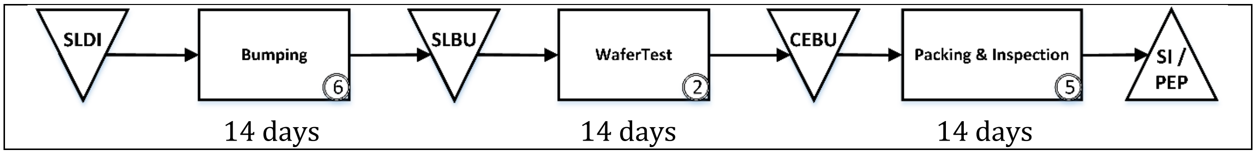


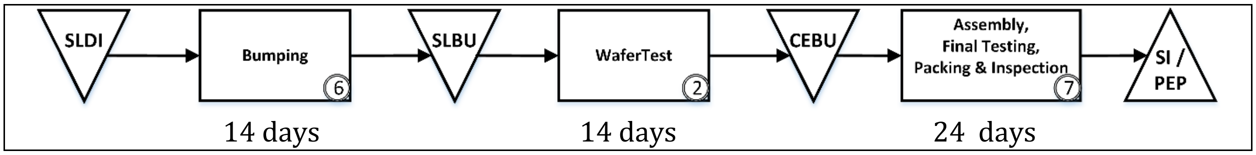
Table 2 shows the production supply chain variant where no bumping occurs. In this case, assembly, final testing and packing (4) are combined into one process step and carried out at one factory. The testing of the wafer (2) takes place before assembly, and uses approximately two weeks, where process-step 4 takes 9 plus minus 2 days. The inventory places between the steps is the CEPT (Circuit Element PreTested). The final inventory is the SI/PEP (Sales Item / Packed End Product). The total (mean) production lead time for this variant is 163 days.

Table 3: Back-end production supply chain for product group 2, lead times of the process steps are stated below. The steps Bumping and WaferTest could be carried out in a different order. Semi-finished products in between would be called CEPT. The first buffer (SLDI) is the last buffer of the front-end supply chain from Table 1.



In Table 3 the first of the two production variants which include bumping (6) is shown, this takes two weeks extra production time, additional to the Wafertest (2). Morover, Packing & Inspection (5) takes two weeks; this is longer than the non-bumped variant. Important to note is the fact that no assembly takes place: the pure die is used as end-product. The inventories in between are the SLBU (Slice Bumped) and CEBU (Circuit Element Bumped), the last one is the SI/PEP. The total (mean) production lead time for this variant is 182 days.

Table 4: Back-end production supply chain for product group 3, lead times of the process steps are stated below. The steps Bumping and WaferTest could be carried out in a different order. Semi-finished products in between would be called CEPT. The first buffer (SLDI) is the last buffer of the front-end supply chain from Table 1..



The final supply chain variant is shown in Table 4. Here, Bumping (6) and WaferTest (2) occurs, just like in Table 3. The main difference is that Assembly, Final Testing, Packing & Inspection (7) is included, which takes 24 days. This variant is the so-called Flip-chip: the die is placed in a Package, for which is has to be flipped. The inventories do not differ from the previous supply chains. The total (mean) production lead time for this variant is 192 days.

3.1.5 Inventories and service levels

Between the production steps in the production supply chain, buffers of material can be kept. This are temporary collections of (semi-finished) products; only there for production purposes (e.g. waiting for shipment to the next step). This is logical since different production steps are not performed at the same locations: different production steps are located all over the world.

Not all buffers are seen as inventories. An inventory is a controlled stock point, a buffer with a controlled number of products located. Inventories are created so that reaction unexpected shortages in supply of product or unexpected deviations in demand can be covered or reacted on, in a shorter time than the complete manufacturing supply chain. Therefore, they are mostly referred to as Safety Stocks. Multiple locations between production steps can be used as inventory location, however, normally only three location are used as inventory locations.

- SLPD
- CEPT
- PEP

At these locations, a standard inventory level is set as target where the level is determined a function which uses the future average demand as input, together with quantity of periods to be covered with inventory. High demand will lead to high inventories and lower demand will lead to low inventories, when the other settings are kept the same. Normally, one would expect service levels, in combination with variability in demand to be the main input for defining levels, but this is not the case.

Within the company, two measures for service level are defined:

- RLIP (Requested Line Item Performance), this is the fraction of the requested demand (actual demand, customer orders) which is fulfilled. The objective is to have an overall RLIP >85%.
- CLIP (Committed Line Item Performance), this is the fraction of committed demand (accepted demand, accepted customer orders) which is fulfilled. The objective is to have an overall CLIP >95%.

3.1.6 Customer Order Decoupling Point

The customer order decoupling point (CODP) is the point in the supply chain, up till where products are manufactured based on forecast and not directly to orders: make-to-stock. After the CODP, production is only continued when customer orders are present (make-to-order). Exceptions are made (prebuilding in most of the cases), but the rule is that no production without customer orders occurs after the CODP.

Currently, production lead times are roughly 23, 26, or 28 weeks. Customers do not accept order lead times this long because of two reasons: most of them are not sure what they need such a period ahead, and competitors can offer shorter lead times. Therefore, the customer order lead time for most products, is set to 13 weeks. This is in line with the market. Please note this is the standard time; some customers are allowed to place orders later, some products are only made to order. For these exceptions, the CODP-location will change: for products and/or customers with a shorter customer order lead time, the CODP will be located further downstream in the SC. For make-to-order; no CODP will exist (production will only occur on order).

For the current lead times as stated earlier in section 3.1, combined with the standard order lead time of 13 weeks, the CODP should always be placed at the SLPD. So, wafer starts (production until the metal-bank), needs to be done on forecast. From there on, products are only produced when orders are present. Exceptions can be made when needed (for example for prebuilding), but these exceptions have to be considered first.

3.2 Production Planning

Production planning is an important and complicated task, carried out by a special department within the company: Product Planning and Fulfillment. Their job is to align supply with demand. Since the production supply chain is large and complicated and production lead times are long, supply is not deterministic. Minor disruptions in production, can lead to large effects in supply of end product. Moreover, demand is also stochastic up to a certain time before delivery: customers face a customer order lead time (COLT) shorter than the production lead time.

3.2.1 Planning task and used information

As inputs for what should be produced, demand forecast, and customer orders are used. Moreover, customer programs, flex demand and safety stocks are used. Customer programs (also VMI, Vendor Managed Inventory) are inventory locations at (important) customers; the COLT is equal to zero. Flex demand is demand which is ‘created’ on information from marketing (or other sources) that there will be demand, although this is not observed in the forecast (yet). In that case, preparations can be done to ensure supply if the demand appears and prevent lost sales, when possible. Normal Demand has priority over Flex Demand. The used of Flex Demand can be seen as introducing stochasticity into the demand, however, in practice this is seldom used in that way because of multiple reasons.

It is self-explanatory that products for inventories must also be produced. What the inventory targets are (in number of products) depends on the chosen method of setting inventory targets. These levels are often based on demand information and are calculated on the demand information from the previous weeks.

3.2.2 Demand (forecast) input for production planning

As stated before, production is planned on demand: products with demand are produced. The demand as observed by production planning is mostly forecasted demand, however, from the customer order lead time onwards, the demand is based on customer orders.

The demand as observed by production planning is the demand in products, per customer, per time period. The forecasts are created based on information from customers and marketing. This is the demand for finished end-product, so the products which are sold to the customer. Demand for semi-finished products will be created by production planning; using production lead times, inventory levels and customer demand. These processed demands are used for production starts (production orders for factories). Of course, downstream from the CODP, only demand covered with customer orders may be produced. The standard customer order lead time is 13 weeks, where customers can cancel orders till 8 weeks before the due date.

Because of business characteristics and short product life cycles, only a small fraction of the demand forecast will be based on statistical forecasting. For the other part, only information from customers and market signals are used as inputs. Since customers often do not know the amount of product they need half a year ahead (when the BL must start production for on time demand fulfillment), demand forecast accuracies are low. The six-month ahead forecast for the BL (over all products) has a Mean Average Percentage Error of 85% (!), reviewing forecast accuracies from February until July 2018. This Error is calculated per product group and then averaged. In this period, under-forecasting (forecasted demand is lower than the customer orders) happened more than over-forecasting. Considering forecast accuracies from previous years, this was not the case: over-forecasting happened more often (and resulted in large inventories, often eventually slow and/or non moving). Moreover, no clear connection between forecast accuracies (or under- or over-forecasting) and specific customers are found.

From this forecast accuracy number, one can see that the demand forecast is highly inaccurate. In the history of the company, multiple projects have been conducted trying to improve the forecast, without major successes. Therefore, the low demand forecast accuracy is seen as a given. Important to note is that the demand as provided (a number of products, per customer and per period) is considered and measured on correctness. People within the company (e.g. the demand manager) have often more knowledge on and insights in demand development and market changes. This information could be used for special decisions.

The detailed information on demand management can be found in App. C.

3.2.3 Creating the production plan

Once a week, in the weekend, a production planning engine calculates the optimal production plan (based on forecasted demand). This is done twice: once without production constraints and once with production constraints. Later, the differences are compared and this provides useful information for the production planners. For example; this makes production capacity shortages visible.

The first run, without production constraints, is purely based on demand. Given the demand; how much products should be produced and where, including inventories. When executing this plan would be possible, no supply shortages would be observed. Unfortunately, this is seldom the case.

The second run, where constraints are considered, provides information on what products need to be produced where and when to fulfill demand. When production capacities are not sufficient somewhere in the future, the planning engine will try to plan the production of these product somewhere earlier on the horizon to ensure no supply gaps. However; despite the fact that production planning engine considers an enormous amount of useful information, the demand considered is the standard demand and the flex demand. Therefore, uncertainties in demand are not considered and without noticing this fact, producing products which will not be sold eventually is possible.

After the weekend, the production plans from both runs are compared by the production planners. By doing this; shortages in capacities can be observed and actions can be taken when needed (this will be decided later). Moreover, when the production plan suggest producing production earlier in the future (prebuilding), it can be considered whether this is needed or not. Moreover, flaws in the plan should be searched for, together with wrong proposals (caused by incorrect system settings for example).

When the evaluation is done, the definitive production plan is ready and production orders are sent out to production facilities (back-end, semi-finished products). The production plan for the front-end of the production supply chain, in particular wafer starts, are sent to the Business Planner(s). They will review the plan and ok this plan or not. Suggestions for changes are discussed and the (possibly updated) production plan for wafer starts is also converted into production orders.

3.2.4 Sales and Operation Planning Meeting

During the weekly meeting, the S&OP-meeting (Sales and Operation Planning), the differences between the two runs are discussed for the current quarter and for the coming quarters. When the demand exceeds the production capacity and unfilled demand is unwanted, actions must be taken. These can be of different kinds; yield improvements can be investigated, but these are often not possible within a short period of time. Capacity increases are often not possible since the lead times for capacity increase are longer and structural shortage in capacity is needed for getting approval for capacity increase. Finally, two options remain: not fulfilling demand (by that: not delivering products) in time, or prebuilding. Prebuilding will be discussed in more detail in section 3.3.

3.3 Prebuilding in the semiconductor supply chain

Prebuilding is defined as (early start) producing product to fulfill end product demand or safety stock levels, before needed considering only the production lead times. In more simple words: prebuilding is creating additional, temporary inventory.

Prebuilding can be done in the front-end and the back-end of the production supply chain, with multiple motivations. As mentioned in section 2.3.2, three (main) motivations for the prebuilding products exist, of which two motivations will be (partially) considered in the prebuilding decision tool. In section 3.3.1, all three motivations and possible consequences of the decision are explained. Section 3.3.2 explains how prebuilding decisions are currently made.

3.3.1 Prebuilding motivations and consequences

Prebuilding is not started automatically, prebuilding is (mostly) a decision which needs to be made. Three main motivations to initiate pre-building can be defined:

- Future capacity shortage at a production facility or line
- Avoid consequences of (under)loading a production facility or line
- Production stop (at supplier)

In the first case, when the prebuilding is not done, there is a high risk of not fulfilling demand. For example; the capacity needed to fulfill the (forecasted) demand three quarters from now, is not available then, but at this moment capacity is sufficient. In that case, it can be decided to start production for this product now to ensure supply in the future. However, it is possible the forecast is incorrect and the supply is still too short (forecast too low) or supply is too high (forecast too high). The prebuilding decisions as proposed by the production planning engine, do not consider information on forecast inaccuracies. As stated before, others solutions to ensure supply in the future or to enable production postponing, are often not possible, too expensive, or too risky.

For the second case, prebuilding is not done to fulfill future demand, but to use currently available production capacity. In case capacity needed at a certain (part of) a production process is lower than the forecasted and (contractual) reserved capacity, this capacity is unused (where it could be used for other production). When this capacity is at company-internal production facilities, production for other business lines could have been scheduled there, where capacities for those products is already gained somewhere else (possibly at third party). Therefore, capacity will be unused, which is undesirable. Moreover, from a strategic point of view, the capacities will not be (completely) reserved for the BL in the future (with the risk of ending up with capacity shortages). In the case the capacity is not reserved at company-internal facilities (but at a third party, a supplier), contracts for those capacities exists. In that case, when less capacity is used than agreed upon, financial penalties will have to be paid by the BL to those third-party companies. This is undesired since these costs are pure loss. On the contrary, is incorrect decisions are made and unsellable products are produced, this also leads to costs (production & scrapping).

In the third case, a production line or facility will be shut down and no production of product is possible in the future, from that moment in time. In that case, if there is still demand for that product, the choice can be made to prebuild as much as the demand prediction is for the complete product life cycle length for the product, possibly with some extra. In that case, the inventory will be large and is highly likely to become obsolete. However, when pre-building is not executed, selling the product is not possible and customers will complain. This pre-building can also occur ‘naturally’; if customers know a product is EOL (End of Life), then may buy more product to create inventory for themselves. The less extreme version of this third prebuilding case, is when there is a temporary capacity shortage of a changeover in production line or location. In that case, the time with less or no capacity needs to be bridged and the motivation for prebuilding could be viewed as a capacity shortage: a temporary capacity of zero.

When pre-building is done to prevent supply shortages in the future, the product which needs to be build is clear. When pre-building is done to prevent getting loading penalties, it needs to be chosen which products are produced upfront. These decisions are mostly made on gut-feeling by Business Planning, based on information of other people in the BL. In this case, products which are at that time produced in large quantities and where demand is present for a long horizon, will most of the time be chosen. An addition check by Demand Management is carried out. However, since the forecast horizon is longer than the actual production lead times, forecast accuracies are often low (the possibility on demand drops or change of product are high).

Pre-building can be chosen for all manufacturing stages. When loading of a factory or line is needed, loading that specific factory or line is important. Depending on inventories before and after that location, new wafers must be or must not be produced.

3.3.2 Current prebuilding decisions

Currently, the decisions made on prebuilding are quite simple. Decisions are made by the Business Planner. Triggers for having to make a decision are provided by production planners: they recognize a gap in supply in the future (using the production proposals) or large amounts of product is planned before production should be started considering production lead times. Additionally, they could also notice a production facility is or will be not loaded as agreed upon. When a production facility or line will be closed, this is decision which is taken with a longer horizon and information will arrive via other sources and will be used in other ways.

In the first case, after being triggered by production planners, the Business Planner collects information on the situation. Relevant inventory levels are reviewed (upstream in the supply chain). Additionally, the demand (high level), the production capacity and the production capacity shortfall when no action is taken, is considered. Finally, information is gained from the Demand Manager on the demand forecasts, on the expectations of changes in demand or demand forecasts. Then, having collected all this information, a decision is made, based on gut-feeling (possibly checked with supply chain colleagues). These prebuilding decisions have caused a slow and non moving inventory present of 1.28 million Dollars in the first quarter of 2018, which decreased to 0.57 million Dollars in the third quarter.

For the second case, the decision is made a bit differently; when a facility is about to be loaded less than the committed loading, the product portfolio which can be produced at that facility is reviewed and the future demand for these products is explored. Then, the Demand Manager is consulted on expectations on changes in demand or demand forecast. Based on this information, a product portfolio is compiled to load the facilities to the agreed level, to prevent obtaining a penalty for under loading, since this is a direct cost, with no contribution to demand fulfillment. These prebuilding decisions resulted in a slow and non moving inventory level of 6.26 million Dollars in the first quarter of 2018, and 3.17 million Dollars in third quarter.

Chapter 4. Design of Prebuilding Decision Support Tool

In Chapter 2, the business problem (high costs of non quality) is mentioned and an investigation on real causes and possible solution directions is provided. It is found that the one main of the causes for high inventories labelled as slow moving and non moving is prebuilding, besides 'large demand drops'. Improving the latter is not recognized as a realistic goal, since the large forecast incorrectness is seen as a business characteristic and previously conducted improvement projects did not provide the desired improvements. Moreover, after studying the current prebuilding motivations and decision, the absence of a well-defined process for taking decisions stood out.

For that reason, prebuilding decision making is chosen to be the cause for which during this project, an improvement will be searched for. Since there is no real decision making process is in place and decisions are mostly made based on gut-feeling combined with some high-level information, it is expected an improvement can be made by providing a Prebuilding Decision Support Tool. Chapter 3 provided information on the current situation (processes and parameters), relevant for prebuilding decisions.

This chapter will provide the Conceptual Design of the Prebuilding Decisions Tool in 4.1. The scope and motivation will be stated shortly. Then, the decisions to make in the prebuilding decision process are stated. In section 4.2, the variables as used by the tool are shown. Thereafter, in sections 4.3 and 4.4 the calculations as done by the tool are explained. Finally, in section 4.5 some information on the interpretation of the outcomes is provided.

4.1 Conceptual design of PDST

In this section, the conceptual design of the PDST is explained. First, the motivation for the tool and the scope is recapped shortly, and extended with the general decisions to make. Then, the decisions to be made for prebuilding for future capacity shortages are explained in 4.1.2. Decisions for prebuilding to overcome loading commitments are explained in following section: 4.1.3. Section 4.1.4 explains the extra calculations done by the tool to provide additional insights.

4.1.1 Motivation for the PDST

Prebuilding can be done on multiple motivations: expected future production capacity shortage, underloading of a production facility, or a production stop at a supplier. This third motivation is out of scope for this project and therefore not included in the solution. Moreover, the scope is set to short term operational decisions. For decisions on capacity shortages for the long term for example, other options like production capacity increase should be considered, moreover, no decisions can be made given the demand information as available.

In the prebuilding process, some general questions have to be answered, independent on the motivation for prebuilding:

- *Is prebuilding needed or not to fulfill (expected) customer demand?*
- *When prebuilding is needed,*
    - *what products can be prebuilt?*
    - *when is prebuilding possible?*
- *How much of the product group should be prebuilt and when should this occur?*

- *How should products be scheduled within the prebuilding product group?*

The solution as designed and described below (for two motivations), helps the user of the tool with making a well-founded decision for prebuilding, considering different factors. Important to note is that the last question (*"How should products be scheduled within the prebuilding product group?"*), will not be answered by the tool: these decisions are left open for the user. Nevertheless, some suggestions are done for these decision and how the outcomes of the tool can be interpreted with this is mind, for both motivations for prebuilding.

4.1.2 Future production shortage

In case of the first motivation, future capacity shortage is expected. This can be noticed by the production planning department (after reviewing the unconstrained and constrained production schedule proposal). An example of a production plan where a capacity shortage is visible, is shown in Figure 3. When somebody within the company has information on demand increase which could lead to capacity shortages; the same decisions steps could be taken, although the shortage is not (yet) visible in the production plan.

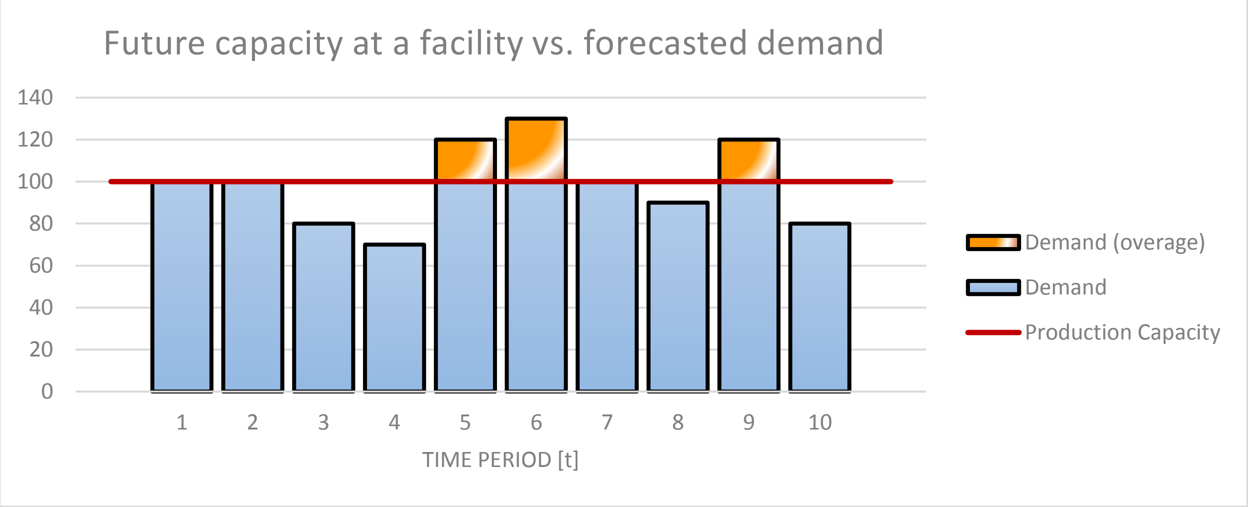


Figure 3: Illustrative example of a production plan of a facility, with production capacity limit. In periods 5, 6 and 9, the demand exceeds the capacity limit which results in overage demand (orange). In periods 3, 4, 8 and 10, the production capacity is higher than the demand: production capacity overage. The demand (normal and overage) is the total observed demand at the facility and can consist out of multiple products. The production capacity is flat in this example, this doesn't have to be the case.

As can be seen, the forecasted demand at the facility per period is given. The maximal production capacity (red line) is not sufficient to produce all demand in the actual period. When no action is taken, the product cannot be produced and unfulfilled demand will occur. To prevent unfilled demand, products can be prebuild. Currently, often the complete overage is prebuild, with a high risk on obsolete inventory (the original business problem) because of forecast inaccuracy. Moreover, prebuilding all forecasted demand does not guarantee complete demand fulfillment.

Therefore, a decision on whether to prebuild products now (and how much) must be made. The decision is made only for the current period, since in the following periods new information can be obtained which results in a more qualitative decision. For prebuilding, one questions needs to be asked:

1) *Do I need to prebuild this period now?*

To answer question 1), additional information must be collected by answering the sub-questions:

a). *Is production capacity available in the current period?*
b). *What is the risk in demand?*
c). *What fraction of demand must be considered for prebuilding?*
d). *What quantities of demand can be prebuild in what period?*

First, question a) must be answered. When in the current period no production capacity is available, the review of the demand and capacities could be useful for insights in preparations needed (for semi-finished products). When semi-finished goods needed are amply available, this review is not needed: question one can be answered with no. When still a risk for future capacity shortage is still existing the next period; question 1) must be answered again then.

Question b) needs some work to be answered. The demand information as provided by demand management (and used by the production planners and engine), does not provide information on probabilities in demand. The demand as shown is the demand for a product group and can be split into product and customer specific demand. However; this does not provide information on risk. Historical forecast accuracies could be used, however, they are only available on two forecasting horizons and per product group; not necessarily on de group as reviewed here. Moreover, the needed information is available by people within the organization, for example the demand manager. These people can make a proper estimation for possible demand scenarios per product. With these scenarios; the risk on the demand can be quantified.

The decision to make for question c) is also important. In the history, this question is often not answered or not considered thorough enough. Choices could be made on different factors:

- Probabilities in demand: e.g. only products where the risk on disappearing demand is negligible or below a certain level.
- On customers: only demand for important customers will be prebuild, e.g. demand from ‘first tier customers’[5].
- On demand period: only demand observed within a specific horizon is selected.
- On product costs: only products with production costs below or profit margin above a certain number.
- On ration between costs: the ratio between losses for not selling and the profits for not producing product.

The final option (a ratio) is chosen because the profit margin (in percentage) can differ a lot between products and creating revenue (and profits) is one of the main motivations for prebuilding. For this ratio the Newsboy fractile is used: the fraction between underage and overage costs. This results in selecting low quantities of the product with a minimal profit margin, and much product with high profits. Important to note is that decision tool will only suggest a decision: a different decision based on one of the options as stated above can always be done.

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[5] First tier customers are the most important customers for the company. Customers are grouped into different ‘tiers’, based on customer’s demand and other factors

Then, to answer question d), the answers to question b) and c) are used to create the Newsboy demand (using the Newsboy Fractile). With this demand the production capacity shortage (considering risk in demand) are defined. Then, the overage demand is tried to be planned in capacity shortages. This is done by trying to fulfill shortages as far in the future as possible: since demand is always a forecast, the shorter the horizon, the lower the risk on obsolescence. Just like question c), other decisions can be made: for example to plan demand with no risk as early as possible to increase potential production capacity. However, since prevention of SNMI is also a main motivation for these decisions, this is not suggested by the tool. The final answer to question d) is the prebuilding suggestion for the complete horizon (for all products together) as reviewed by the tool.

From this final answer to question d), question 1) can be answered: when production for this period is suggested: prebuilding should be done, considering demand stochasticity, costs and profits of product and postponement in mind.

What products from the product group need to be build, must be chosen by the user of the tool. In case the product group consists of only one product, there is no choice. Otherwise, a decision must be made by the user, and can be based on different options. This could be one of the options as stated earlier as possible answers to sub-question c).

4.1.3 Loading commitment

The other motivation for prebuilding as considered in this project is loading a facility up to a certain level, to prevent having to pay a financial penalty. This penalty is observed when at a (external) facility will not be loaded to the agreed level. The alternative to a financial penalty is more long term (mostly for company internal facilities); less production capacity will be reserved in the future for the BL when the currently reserved capacity will not be reviewed. This motivation for prebuilding is not included in the project, since this is a more strategic decision.

When a facility is not loaded up to the agreed level, the following and sub-questions must be answered:

1) *Is producing up to the capacity limit wise?*
    a). *What are probability characteristics of the demand?*
    b). *What fraction of demand can be produced with acceptable risk?*
    c). *Does this fraction of demand fill the capacity shortage?*
    d). If not: *Is future demand overage present and can this be prebuild?*
2) *What quantity of products should be produced?*

These questions are like the questions for the other motivation (capacity shortage), but have a little different motivations.

Question 1) can be answered by answering the sub-questions. For sub-question a), demand scenarios as in the previous section are created to include stochasticity. Then, for sub-question b), the Newsboy fractile is calculated per product, including the penalty costs per product as costs when not producing the product. With these scenarios and Newsboy fractiles, Newsboy Demand is calculated. When this Newsboy Demand is higher or equal to the loading limit, the production capacity can be used up to the limit, answering question c) with a yes. The cases where the Newsboy demand of the current period is higher than the loading limit, will be rare since the demand of the current period is mostly certain and the

Expected demand will be equal to the Newsboy demand. When the Expected demand is higher than or equal to the loading limit, no prebuilding has to be considered.

When the Newsboy Demand is below the capacity limit, the Newsboy demand for the future periods needs to be reviewed. When the Newsboy demand is higher in some periods than the loading limit, the prebuilding planning can be done as with for the capacity shortage motivation. Also here, capacity overage must be filled in from the latest possible period to the first, to reduce risk on SNMI. When overage capacity is present in the future and all overage capacity is filled: the overage capacity in the current period can be used to fill this Newsboy demand (also when this not fills the total capacity overage). This answers question d).

When the answer to question d) is that there is not enough demand to fill the capacity up to the limit, question 2) can be answered with: the Newsboy demand as calculated for the current period. This demand quantity is defined to be acceptable regarding risk on production, considering underage and overage costs. Producing up to the loading limit to prevent a financial penalty, would be considered as risk production and is not advised.

Finally, when the questions 1) and 2) are answered, information is known on the total quantity of products which needs to be prebuild. If the reviewed demand is only from one product (just one product in the product group), the determined quantity is for that specific product. When multiple products are reviewed, a selection on which products to use for prebuilding must be made. This must be chosen by the used, however, the possible choices are dependent on the outcome:

I. *The total quantity of products to be prebuild in this period is lower than or equal to the loading limit*: Prebuild all the Newsboy demand of that period. For the demand brought forward from other periods, a choice needs to be made. Some possible options would be:
    i. Product(s) with highest probability of demand (e.g. the lowest scenario)
    ii. Product(s) with lowest production costs
    iii. Product(s) with highest Newsboy fractile
    iv. Product(s) with demand the earliest in the future
II. *The total quantity of products to prebuild in this period is higher than or equal to the loading limit, however the demand for the period is lower*: Prebuild al the demand of the current period. For the demand brought forward from other periods, the same choice as under bullet I can be made.
III. *The total demand for products from the current period is higher or equal to the loading limit*: production of the current period demand must occur. In the rare case of Newsboy demand higher than the Expected demand; the same choices can be made as under I (for the uncertain demand).

4.1.4 Insights generated by tool

When the prebuilding suggestion based on the Expected demand and Newsboy demand are calculated, evaluation of the effects of these decisions can be reviewed.

First, an additional decision on prebuilding will be introduced: the own decision. The user of the tool can suggest a prebuilding quantity for every period. That quantity is checked with the capacity overage (based on the Expected demand), which results in a feasible quantity.

Then, for the ‘own decision’, the Expected demand and for the Newsboy demand, the prebuilding suggestion is shown, together with the production plan (the total of producing product to fulfill normal demand and prebuilding demand).

Moreover, projected inventory over time (Inventory buildup) for Expected demand and Newsboy demand are shown, together with the unfilled demand. These numbers are only interesting when the overall production capacity is not sufficient to produce all product; otherwise there will be no unfilled demand and the ending inventory level will always be zero (decision based on perfect information). Therefore, other review scenarios are created.

Next, the utilization of the facility is defined for the Expected demand, Newsboy demand, and Own decision. This shows whether the facility is always loaded to the maximum capacity, or just a peak is demand is observed.

For the first evaluation scenario, the Expected demand is compared to the quantity of product prebuild, using the Newsboy demand for prebuilding decision. In that case, expected (most realistic) demand is compared to the decisions made on the Newsboy demand. This scenario approached reality, however, when in period for example in period 3, it is recognized that the quantity of product prebuilt is too high, this will be considered differently (this overage of prebuild product will be stated as starting inventory). This second moment decision is not included in the evaluation scenario; so the inventory and unfilled demand as shown is based on a prebuilding suggestion as suggested in period 1.

The second evaluation scenario shown; provides insight on not taking any action and by that, not prebuilding anything. The starting inventory is considered: when a production capacity shortage is noticed, the inventory is used to fill the shortage. When the inventory is depleted, no additional product is created.

The last scenario shown, is the scenario where the ‘own decision’ is evaluated. The prebuilding quantities as entered by the user are tested against the Expected demand and inventory. This shows the possible result of a decision, deviating from the suggested quantities.

For all three scenarios, the RLIP (Requested Line Item Performance) is calculated. The CLIP cannot be calculated, rescheduling orders with customers would create a different situation and the tool would have to be run again.

4.2 Definition of variables as used by tool

The calculations as performed within in the tool, use different variables. In this section, the variables are explained which are used later.

4.2.1 Product cost information

- y Identification number of product which can be produces at the production facility.
- $|Y|$ Identification number of last product.
- Y Set of identifacion numers of product ($\{1 \leq y \leq |Y|\} \in Y$).

Then, the costs information of product y is defined:

- c_o^y Overage costs: the costs made when the product is produced, but not sold anymore.

- c_u^y Underage costs: the costs made when the product is not produced, but could have been sold.
- sp^y Selling price of the product.
- pm^y Profit margin of the product.
- pc^y Production costs of the product.
- sc^y Scrapping costs of a product.
- pec^y Penalty costs for the product: the penalty when product is not produced and the product is not produced. Often this is expressed as fraction of the production costs.
- NF^y Newsboy Fracticle: this fractile can be calculated using the overage and underage costs.

4.2.2 Time period variables.

Second, the timeline must be defined. The tool will consider a specified number of periods (the length of these periods is not of importance for the definition / calculations)

- t Time period
- T Set of all time periods
- $|T|$ Latest time period.

4.2.3 Demand scenario

As stated earlier, demand scenarios will be created to consider uncertainty in demand in the calculations. For these scenarios and demand, some variables are defined:

- ds Demand scenario (identification number) per product.
- $|DS^y|$ Last demand scenario and by that also the number of scenarios for product y.
- DS^y Set of all demand scenarios for product y. ($\{1 \leq ds \leq |DS^y|\} \in DS^y$)
- $\mathbb{P}_{ds,y}$ Probability on demand scenario ds, for product y.
- s$\mathbb{P}_{ds,y}$ Summed Probability on demand scenario ds, for product y..
- $D_t^{ds,y}$ Demand in scenario ds for product y in period t.
- $AS_{t,y}$ Available supply for product y in period t.
- PDS Processed Demand scenario: Expected demand ($\mathbb{E}[D_t]$ or E) or Newsboy demand (NFD_t or NF).
- $D_{t,y}^{PDS}$ Demand for scenario PDS, for product y and time t.
- D_t^{PDS} Total demand for scenario PDS for all products in time t.
- pt Downstream production time from the facility.

4.2.4 Production capacity

Then, for every time period, there will be a defined production capacity per time period. This capacity can be interpreted in a number of different ways: for example as number of products which can be produced in one period or as possible production starts in that period. By using the latter; the output of the products will be a certain time later, so not at the end of the period. This is not important for the calculated, although, it is important for interpreting the outcomes.

- PrC_t Production capacity at the location at time t.
- $APrC_t$ Adjusted Production capacity at the location at time t. This will be used to incorporate Available supply of product.

Then, combining the demand (Expected demand and the Newsboy demand), the following numbers can be calculated.

- SH_t^{PDS} Production capacity shortage at time t, considering demand from PDS.
- OV_t^{PDS} Production capacity overage at time t, considering demand from PDS.

4.2.5 Prebuilding variables

Then, the prebuilding calculations can start. The following variables will appear:

- QU_t^{PDS} Prebuilding Quantity Unconstraint: the quantity which should be prebuild at time t, but nu constraints are not considered.
- QI_t^{PDS} Prebuilding Quantity needed at time t, taking into account the inventory level already existing downstream of the production location.
- QIC_t^{PDS}Prebuilding Quantity needed at time t, taking into account the inventory and the production capacities.
- QO_t Prebuilding Quantity chosen by a person, for comparison.
- QOC_t Prebuilding Quantity chosen by a person, for comparison, but constraints considered.

After all these calculation have been done, some outputs are generated to gain insights in the effects of the decisions and possibilities.

- PP_t^{PDS} Production Plan at time t: the prebuilding quantities and production for normal demand fulfillment.
- PP_t^{O} Production Plan 'own decision' at time t: the prebuilding quantities as decided by the person and production for normal demand fulfillment.
- CU_t^{PDS} Capacity Utilization at time t, for scenario PDS: the fraction of production capacity used in period t. This is used for creating additional insights.
- tCU^{PDS}Total Capacity Utilization for scenario PDS.
- I_t^{PDS} Inventory built up by prebuilding at time t, calculating with PDS as demand and prebuilding decision input.
- UD_t^{PDS} Unfulfilled demand at time t, calculating with PDS as demand and prebuilding decision input.
- I_t^{O} Inventory built up at time t by prebuilding, calculating with Expected demand as demand and prebuilding decision by person as input.
- UD_t^{O} Unfulfilled demand at time t, calculating withas demand and prebuilding decision input.

4.2.6 Evaluation scenarios and variables

For further comparisons of choices on effects, some other comparisons are made considering the following situations:

- SQ (Situation Q): Prebuilding according to the Newsboy demand, but using Expected demand as demand.
- SN (Situation N): Expected demand as demand, but no prebuilding.
- SO (Situation O): Prebuilding according to the Own decision, using Expected demand as demand.

For all these situations, the following new variables are introduced:

- S Set of Scenarios as described above; $\{SQ, SN, SO\} \in S$.
- IL_t^S Inventory level at time t, using Newsboy demand as prebuilding input and Expected demand as demand.
- UD_t^S Unfulfilled demand at time t, using Newsboy demand as prebuilding input and Expected demand as demand.
- $RLIP_t^S$ Requested Line Item Performance: one of the service levels as used by the company: the fraction of demand which will be fulfilled at the moment as requested.

4.3 Design of tool: Demand preparation

As seen in 4.1, to suggest a prebuilding decision, the tool first processes the demand of multiple products and scenarios into Newsboy demand and Expected demand. Then, the prebuilding calculations for the suggestions are done with the demands as input. Here, the demand preparation calculations are explained. When multiple products are reviewed, the calculations are done for multiple products and eventually, the demands are summed to find the demand for input in the second part of the tool. Demand for one product, from different customers could also be reviewed a separate products, when characteristics differ: e.g. profit margin.

4.3.1 Demand scenarios

The demand scenarios is the most important information for the tool: on these scenarios all decisions are based. Scenarios are created per product (and if needed: per customer). The following steps are based on one product, these calculations can be repeated per product.

The number of scenarios is not important, however, it is important to include as many information as possible. Therefore, a low scenario, a high scenario and a mid-scenario are recommended. More scenarios would be possible. The demand (in the scenarios) per time period can be stated by people with knowledge on the situation and demand (forecast). The same goes for the probabilities of the demand scenarios. Of course, it is important the following equation holds:

$$\sum_{x=1}^{|DS^y|} \mathbb{P}_x = 1 \tag{1}$$

Then, the demand has to be generated. The demand per period will have to be defined, based on information from people and possible from the demand forecast. Each demand scenario needs to be filled with the corresponding demand and stated as variable ($D_t^{ds,y}$), for the further calculations. Important is that if the downstream production lead time is significant and the demand should be considered one or more periods earlier, the time period should be replaced with $(t - pt)$.

For later calculations, it will be important that the lowest scenario has truly the smallest value for every time period. When multiple scenarios are created but the first scenario is not constantly the smallest value, the demand should be processed further into scenarios from low to high. It can be done by creating more scenarios to incorporate differences in probabilities, but also by specifying probabilities per scenario and per time period. This would not change a lot; $\mathbb{P}_{ds,y}$ would be updated to $\mathbb{P}_{(ds,y),t}$ and equation (1) would need to hold for every time period: $\sum_{x \in DS^y} \mathbb{P}_{x,t} = 1$.

The creation of demand scenarios as explained, demand of only one product is considered. For these When a prebuilding decision for multiple products (a product group) needs to be made, such scenarios will be created for all different products which have to be considered simultaneously.

4.3.2 Newsboy fractile calculation

To calculate the Newsboy fractile, the overage and underage costs need to be calculated. The overage costs are the production costs, combined with the costs of a product having to be scrapped:

$$c_o^y = pc^y + sc^y \tag{2}$$

The underage costs, are the costs for not having the product when it could have been sold. These as calculated as follows:

$$c_u^y = pm^y + pec^y \tag{3}$$

$$pm^y = sp^y - pc^y \tag{4}$$

The pec^y will only be present when the prebuilding decision addresses a decision for prebuilding to overcome loading commitments. When these are not present, these can be set to 0. The profit margin could be calculated as stated in equation (4).

Then, the Newsboy fractile can be calculated as follows:

$$NF^y = \frac{c_u^y}{c_u^y + c_o^y} \tag{5}$$

Then, the NF^y will be used later to calculate the demand per period.

4.3.3 Demand processing

As explained above, different scenarios for demand are created for products. Additionally, the Newsboy fractile is calculated. Then, from these scenarios, combined with the probabilities, the Expected demand and the Newsboy demand can be calculated, for all products $y \in Y$. For all products, these demands can be calculated. Finally, they will be summed.

The Expected demand (Processed Demand Scenario $\mathbb{E}[D_t]$ or E) for product y in time period t, can be calculated as follows (for every $t \in T$):

$$D_{(t,y)}^E = \mathbb{E}\left[D_{(t,y)}\right] = \sum_{x=1}^{|DS^y|} (\mathbb{P}_x \cdot D_t^x) \tag{6}$$

The Newsboy demand is calculated in slightly different way. Because the demand scenarios are ordered from low to high, the first scenario is always the lower bound of the demand. Then, the summed probabilities are important to define first as follows:

$$\mathrm{s}\mathbb{P}_{(ds,y)} = \sum_{x=1}^{ds} \mathbb{P}_x \tag{7}$$

The demand for the Newsboy demand will cover the demand with the probability lower and equal to the Newsboy Fractile as calculated earlier. Therefore, the scenarios could to be converted into a demand distribution. When the fractile is not equal to a one of the sums of the probabilities per scenario as calculated with formula (7), the demand will be interpolated. Therefore, the highest scenario with the cumulative probability lower than the Newsboy Fractile, needs to be determined. This scenario is called H^y and defined as follows:

$$H^y = \underset{ds}{\operatorname{argmax}} DS^y | \mathrm{s}\mathbb{P}_{(ds,y)} < NF\} \tag{8}$$

Having defined H^y, the Newsboy demand can be calculated in the following way for every t:

$$D_{(t,y)}^{NF} = NFD_{(t,y)} = \begin{cases} D_t^{ds,y} & \textbf{if } NF^y \leq \mathbb{P}_{1,y} \\ D_t^{H^y} + \left(D_t^{H^y+1} - D_t^{H^y}\right) \cdot \dfrac{NF^y - s\mathbb{P}_{H^y}}{\mathbb{P}_{H^y}} & \textbf{else} \end{cases} \tag{9}$$

After calculating this for all time periods, the processed demands (for all products) are ready for the final check: feasibility of supply.

4.3.4 Production capacities and available supply

For all time periods, the production capacity needs to be determined. This will be the base for the prebuilding decision calculations. When dealing with one product ($Y = \{1\}$), this is quite simple. When dealing with multiple products and the capacity consumption per produced product is not equal for all different products; the demand needs to be adjusted so that the capacity consumption is comparable.

Moreover, when dealing with one product, the available supply of raw material can be combined into the adjusted production capacity:

$$APrC_t = \min(PrC_t, AS_t) \tag{10}$$

This will only be of importance when product cannot be available in the first time periods. Letting the Tool suggest prebuilding in that time period, would not be needed since it is unfeasible. However, for later periods, when the available supply is larger than the production capacity, it does not have to be defined anymore: the production capacity is the limiting factor. When the adjusted production capacity is applicable in the calculation (one product and supply smaller than production capacities); PrC_t can be substituted with $APrC_t$ in the rest of this chapter.

When considering multiple products; the available supply per product should be evaluated and compared to the Newsboy demand and Expected demand. When supply is not sufficient to fulfill demand, it needs to be considered whether demand will be moved to a later period. When not possible, allocation decisions need to be made. Moreover, when supply is sufficient to fulfill demand, however, after the suggestion for prebuilding is done by the tool and it comes out to insufficient, it needs to be reviewed later. This will result in other demands and therefore, the tool can be used again with the new demands or allocation needs to be done.

4.3.5 Total demand

When different products are considered for the decision (multiple products with demand can be produced at the facility; $|Y| > 1$), the total demand for the prebuilding decision is needed. These are calculated with the following formulae:

$$D_t^{PDS} = \sum_{y \in Y} D_t^{PDS^y} \tag{11}$$

This combined / summed demand over all products, per time period, is used in part 2 of the Tool.

4.4 Design of tool: Prebuilding calculations in additional insights

In the previous section, the demand preparation calculations are explained. When the Newsboy demand and Expected demand are determined, these are used as inputs for the calculations as explained in this section, to determine the prebuilding suggestion. The calculations and calculation steps are based on the algorithm as presented by Ganesan (2015). However, the algorithm is expanded to include inventory or decisions taken earlier into the suggestion.

4.4.1 Production capacity shortage and overage

Prebuilding product(s) is only needed when somewhere in the future as considered, the production capacity is not sufficient to produce enough material to fulfill demand. To determine where and how much the production shortage is, for every time period, the production shortage is determined using the following formula, for both Expected demand and Newsboy demand (in formula addressed with PDS):

$$SH_t^{PDS} = (D_t^{PDS} - PrC_t)^+ \tag{12}$$

The opposite of production capacity overage is the production capacity shortage. This is calculated for every time period with the following formula, also for Expected demand and Newsboy demand:

$$OV_t^{PDS} = (PrC_t - D_t^{PDS})^+ \tag{13}$$

This overages and shortages are inputs for the prebuilding calculations.

4.4.2 Prebuilding calculations

As stated earlier, the prebuilding calculations will be done in three steps. First, the needed prebuilding quantities are determined, not considering any constraints. Then, the available inventory is considered. Finally, the production constraints are considered.

The first calculation, is defining the quantity of products which needs to be prebuild. This is done for both demand scenarios. The prebuilding quantities can be determined starting at the last period of the total horizon. The logic behind it is that in the last period, no prebuilding is needed (demand nor capacity in period $t+1$). Therefore: $QU_{|T|}^{PDS} = 0$. Then, from there, from the last period to the first, the need for prebuilding can be determined with the following formula (for $t \in T \backslash |T|$):

$$QU_t^{PDS} = \sum_{x=t+1}^{|T|} SH_x^{PDS} - \sum_{x=t+1}^{|T|} QU_x^{PDS} \tag{14}$$

Please note that currently, the formula could be rewritten to $QU_t^{PDS} = SH_{(t+1)}^{PDS}$. However, this formula creates the possibility in the tool to create extensions of the model in an easy way. For example: including a (minimal) batch size or a threshold.

Then, having determined all these values, the available inventory after the location can be considered. The prebuilding quantities calculated can be done starting from the first period, to the last. Important is that the inventory considered must be available for usage for prebuilding completely. When inventory must be kept for a reason, this quantity should not be included. Next, the prebuilding quantities can be calculated for all periods:

$$QI_t^{PDS} = \left(\sum_{x=1}^{t} QU_x^{PDS} - \sum_{x=0}^{t-1} QI_x^{PDS} \right)^+ \tag{15}$$

Where QI_0^{PDS} is the quantity of product available after the location at the current moment, which is the same as I_0^{PDS}.

After calculating the prebuilding quantities considering inventory, the constraints can be included: the production capacity at time t. Because when no production capacity is available; no production can take place. Also for this calculation, calculations starts with the latest period and then works to the first period.

$$QIC_t^{PDS} = \min\left(OV_t^{PDS}, \left(\sum_{x=t}^{|T|} QI_x^{PDS} - \sum_{x=t+1}^{|T|} QIC_x^{PDS} \right) \right) \tag{16}$$

Having calculated the prebuilding quantities as needed to fulfill as much demand as possible, the 'own decision' prebuilding quantity will be included in the model. This is an own set quantity by the person using the tool and reviewing the numbers. This chosen prebuilding quantity has no constraints and is called QO_t. Because not more capacity than available can be used, the following formula is used to ensure feasibility of the 'own decision' to define the Constrained prebuilding quantity chosen:

$$QOC_t = \min(QO_t, OV_t^E) \tag{17}$$

For determining the overage capacity in this case, the Expected demand is considered (not the Newsboy demand).

4.4.3 Production plan, inventory buildup and unfulfilled demand

When the quantities needed for prebuilding are determined, the Production quantities per time period ("Production Plan") can be calculated. This production plan is determined for both the Processes Demand Scenarios and for the 'own decision' calculated.

$$PP_t^{PDS} = D_t^{PDS} + QIC_t^{PDS} \tag{18}$$

$$PP_t^{O} = D_t^{E} + QOC_t \tag{19}$$

Then, the inventory built up over time can be calculated for the PDS and for the 'own decision', for all t:

$$I_t^{PDS} = \left(I_{t-1}^{PDS} - D_t^{PDS} + PP_t^{PDS}\right)^+ \tag{20}$$

$$I_t^O = \left(I_{t-1}^O - D_t^O + PP_t^O\right)^+ \tag{21}$$

Then, additionally to the inventory, the unfulfilled demand can be calculated for all t:

$$UD_t^{PDS} = \left(I_{t-1}^{PDS} - D_t^{PDS} + PP_t^{PDS}\right)^- \tag{22}$$

$$UD_t^O = \left(I_{t-1}^O - D_t^O + PP_t^O\right)^- \tag{23}$$

Please note that the unfulfilled demand at $t = 0$ equals zero.

4.4.4 Utilizations and review scenarios

As stated earlier, the tool uses some combinations of scenarios and decisions to provide additional insights. These additional 'evaluation scenarios' are stated in section 4.2.6.

Before the scenarios are calculated, for additional insights, the utilization of the facility is calculated for every production plan (Expected demand, Newsboy demand, and the Own decision), for every $t \in T$:

$$CU_t^{PDS} = \frac{PP_t^{PDS}}{PrC_t} \tag{24}$$

Additionally, the total utilization per scenario can be calculated for $t \in T$:

$$tCU^{PDS} = \frac{\sum_{t \in T} PP_t^{PDS}}{\sum_{t \in T} PrC_t} \tag{25}$$

The first scenario used (Situation Q); reviewing Expected demand and the prebuilding decisions based on the Newsboy Demand Fractile, is reviewed using the following formulas:

$$IL_t^{SQ} = (I_{t-1}^{NF} - D_t^E + PP_t^{NF})^+ \tag{26}$$

$$UD_t^{SQ} = (I_{t-1}^{NF} - D_t^E + PP_t^{NF})^- \tag{27}$$

$$RLIP_t^{SQ} = 1 - \left(\frac{UD_t^{SQ}}{D_t^E}\right) \tag{28}$$

$$RLIP^{SQ} = 1 - \left(\frac{\sum_{t \in T} UD_t^{SQ}}{\sum_{t \in T} D_t^E}\right) \tag{29}$$

Then, the second evaluation scenario used Expected demand and no prebuilding. This result in no inventory buildup (available inventories will in this case be used to reduce production quantities for normal demand) and unmet demand will only occur when the production capacity is not sufficient to fulfill demand. Therefore:

$$IL_t^{SN} = IL_{t-1}^{SN} - (PrC_t - D_t^E)^- \tag{30}$$

$$UD_t^{SN} = (IL_{t-1}^{SN} + PP_t^E - QIC_t^E - D_t^E)^- \tag{31}$$

$$RLIP_t^{SN} = 1 - \left(\frac{UD_t^{SN}}{D_t^E}\right) \tag{32}$$

$$RLIP^{SN} = 1 - \left(\frac{\sum_{t \in T} UD_t^{SN}}{\sum_{t \in T} D_t^E}\right) \tag{33}$$

Finally, in the last evaluation scenario, the ‘own decision’ on prebuilding quantities will be evaluated against Expected demand. Then, the following formulas are used:

$$IL_t^{SO} = \left(IL_{t-1}^{O} - D_t^E + PP_t^O\right)^+ \tag{34}$$

$$UD_t^{SO} = \left(IL_{t-1}^{O} - D_t^E + PP_t^O\right)^- \tag{35}$$

$$RLIP_t^{SQ} = 1 - \left(\frac{UD_t^{SO}}{D_t^E}\right) \tag{36}$$

$$RLIP^{SQ} = 1 - \left(\frac{\sum_{t \in T} UD_t^{SO}}{\sum_{t \in T} D_t^E}\right) \tag{37}$$

4.5 Interpretation of outcomes

In the previous section, all formulas used in the Prebuilding Decision Support Tool are stated and explained where needed. Moreover, the Tool can be used for two different cases: production capacity shortages and capacity under-loading. The following sections will explain those differences.

4.5.1 Production capacity shortages

As can be seen, the Tool will provide a lot of numbers. This section will shortly explain what outcomes gain certain insights.

- Shortage: these numbers show (given the processed demands), the quantity of product which should be produced but cannot.
- Overage: these numbers make visible where production capacity is available and the size.
- Prebuild possible: these numbers show where prebuilding is needed, given the processed demands and considering inventory information and production capacity constraints.
- Suggested prebuilding quantity: this is the suggestion for prebuilding in the current period given the Newsboy demand or Expected demand, production capacities, available product in the first period, and with the Newsboy demand, the costs of the product.
- Production Plan: these numbers show the number of products produced at the production facility, in three different situations.

- Utilization: these numbers provide the insight in the utilization of the facility: whether the capacity shortage is a one-time problem or whether the capacity shortage is present for a longer time. Therefore; the utilization with prebuilding quantities included and excluded is shown.
- Total Utilization: this number gives an insight in the overall utilization of the reviewed facility.
- Inventory buildup and Unfulfilled demand: these numbers show the created inventory and the unmet demand when using the demands (expected and Newsboy) for the decision and eventually as real demand. This provides insight in the feasibility of production.
- Evaluation scenario Newsboy Prebuild and Expected demand: this gives an insight in the expected progress over time. The Expected demand is calculated on the demand scenarios and therefore, should be probable. The Newsboy demand (upon which the prebuilding decision is based, provided costs and margin) provided other numbers, and therefore, the effect will be visible (lost sales when it is unattractive to prebuild) or large inventories when Newsboy fractile is high.
- Evaluation scenario No Prebuilding: These numbers show the effects of taking no action on prebuilding, on how many unmet demand is created and what the service level for this product will be.
- Evaluation scenario Own Decision: These numbers will show the effects of the prebuilding plan as provided by the user of the tool. It is possible to try different possibilities and observe the effects.

Moreover, it is important to review the information as put into the Tool. For example; when multiple products are viewed as one, the prebuilding quantity decision should be reviewed with that information in mind. The suggested prebuilding quantity is than for multiple products; attention should be paid to interpreting those numbers to choose which products to produce in what quantities. Some suggestions on possible information to consider for this decision is presented in the conceptual design (section 4.1)

Chapter 5. Case study with Prebuilding Decision Support Tool

In Chapter 4, the Prebuilding Decision Support Tool is explained; the used formulas and how the numbers are calculated is shown. In this chapter, the tool is used at a real situation, where a prebuilding decision was made. First, information is collected as was available at the time of the decision. Then, the Tool is used to create a suggestion for a prebuilding decision. Then, this is compared to the decision made at that moment (without the tool) and what the effects would have been for the decision suggested by the tool and the actual decision made.

5.1 Introduction to the case study

The case is about an assembly production facility, so the back-end of the production supply chain. The production line is used for multiple products (15 different) with demand. The time periods considered are months, following the company's production calendar: a quarter is built out of three months, where the first two weeks consists out of four weeks and the last out of three. Therefore, the production capacity (provided per week) will fluctuate per month, although it is constant per week.

The decision which needs to be made is whether a product of this set of products, needs to be prebuild or not. On the first sight, there is no shortage in production capacities, comparing them to the demand quantities (without stochasticity). This is demand information of customer orders, combined with forecast, where no stochasticity is included. Demand increase is expected within the group of products, which is not (yet) observed in the shown demand information.

There are multiple ways to approach this problem. The first, easiest way (very comparable to the situation as observed at the time of the decision), is by approaching the product group as one product. However, by doing this, some important factors are neglected, which have contributed to the decision (on gut-feeling). Therefore, the demand data available in combination with other information at that time, is used to create a situation as would have been created back then, using the guidelines as described in this report. Then, the Prebuilding Decision Support Tool is used for making decisions and comparing them to the actually taken decision.

5.2 Provided information and calculations with tool

As stated in the previous section, the problem will be approached from two directions: considering the demand for the product group as one product, and, using the demand for one product as input for the model, adjusting the production capacities. This information is collected and evaluated in the following sections. However, the first section shows the information which will be equal for both approaches.

5.2.1 General information

There are a couple of factors which will be equal for both the approaches. First, costs of the product determined, which are the same for the products within the product group and therefore not defined per product. The production costs of one product are \$ 0.02. The selling price is \$ 0.07. This will be used in the first part of the tool calculations, where a Newsboy fractile of 71.46% will be the outcome.

Moreover, the production process considered is part of the last production step in the process: assembly, final test, and packing. This complete production process step normally takes around 24 days. Since this is less than the defined time periods used with this application, the demand for the final product can be carried through.

Finally, the inventories in front of the production facility and downstream of the facility are the CEBU and PEP, respectively. At the moment of the prebuilding decision, the supply of 'raw material' will be reviewed later. Moreover, there is no inventory after the facility which could be used for prebuilding, however, 10 million pieces are prebuilt before the decision moment: this can be seen as inventory available.

5.2.2 Handling product group as product (Approach one)

The first approach using the combined demand for the product group as input for the Tool. For this product group, the demand is stated in Table 5, per time period and for all three demand scenarios (ds): low (1), mid (2), and high (3). The number of time periods chosen for this situation is 8. This has no further effects, but is reviewed as a realistic number of periods to consider prebuilding decisions for this product group. The corresponding probabilities per scenario ($\mathbb{P}_{ds}$) are as follows:

$$\mathbb{P}_1 = 20\%, \mathbb{P}_2 = 50\%, \mathbb{P}_3 = 30\%$$

Table 5: Demand quantities per time period per scenario. The demand is the combined demand for the complete product group produced at the location.

ds \ t	1	2	3	4	5	6	7	8
1	60	52	68	75	56	40	50	40
2	60	56	72	90	72	72	90	72
3	60	60	72	110	88	88	110	88

It might stand out that the demand for $t = 1$ is the same for all scenarios. This is because the demand for the next period is known: it is backed by customer orders.

As stated before; the number of weeks per period (months) can differ. The production capacity at the location is defined per week, and equals 17.5 million pieces per week. The production capacity available can then be calculated and is shown in Table 6.

Table 6: Production capacities per time period for total product group

t	1	2	3	4	5	6	7	8
# weeks	5	4	4	5	4	4	5	4
PrC_t	87.5	70	70	87.5	70	70	87.5	70

Given this information, the tool can be used. First, part one for the generation of Expected demand and Newsboy demand, then part two for the prebuilding decisions and insights in effects.

5.2.3 Product specific demand and situation (Approach two)

As can be observed in the previous section, the Expected demand for the complete product group within the prebuilding review horizon, is higher than the production capacity for some periods. This means that prebuilding should be done, when the number of sales lost will would be minimized. Moreover, since the Newboy fractile is used to determine the fraction of demand to cover to have a good fulfillment of the demand considering the costs and profits of the product; prebuilding seems a wise decision.

When considering the demand for all products within the product group and the supply of raw material available for prebuilding; it is noticed that just one product can be prebuild. For this product, wafers are available for production. For other products, the available supply is hardly enough to cover the Expected demand and prebuilding for this product would result in supply shortages earlier in the horizon. Of course, this is unwanted.

Moreover, it is noticed that the available production capacity in periods $t = 3 \dots 7$ will be consumed for the products for which prebuilding is not possible. Therefore, the demand scenarios are created for the product for which prebuilding is possible. Moreover, the production capacity available for this product is reviewed. Both demands for the specific product and the production capacities available for the product, are stated in Table 7. The probabilities for the demand scenarios are equal to those stated for the first approach:

$$\mathbb{P}_1 = 20\%, \mathbb{P}_2 = 50\%, \mathbb{P}_3 = 30\%$$

Table 7: Demand for one product: the product whit enough raw matieral supply. The Production capacities are adjusted to the available capacity considering the other products and their capacity usage.

t / ds	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	7.82	0.63	0.16	1.18	5.17	1.23	1.23	0.32
2	7.82	0.70	0.26	1.47	6.90	2.05	2.05	0.63
3	7.82	0.77	0.29	5.88	10.35	3.07	2.56	0.79
PrC_t	20	0	0	1	3	1	2	2

This information as explained above, are put into part one and two of the tool.

5.2.4 Actual demand data (Approach one and two)

Finally, the information on demand and overage capacity will be compared to the information as available in the current situation; at the moment of decision and later. These numbers are directly put into the second part of the tool: the real data is put into the tool instead of the Expected demand. By doing that, the tool will compare real demand and the Newsboy demand created from the demand scenarios. Moreover, for the second approach, the actual available capacity is put into the tool instead of the expected capacity levels. Table 8 and Table 9 show the actual demand for both approaches; the old (D_t^o, demand (forecast) when the decision is made) and the new (D_t^n, demand (forecast) at a later moment). Moreover, in Table 9, the actual production capacities are shown (old and new).

Table 8: Actual demand information for the first approach, data from the time the decision is made and the information later. The production capacity is not provided since there is no difference in the actual capacity and the capacity as used.

t	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
D_t^o	62.875	62.987	50.920	59.544	65.384	57.840	55.686	51.036
D_t^n	55.700	56.820	49.347	61.122	78.011	55.497	53.620	50.796

Table 9: Actual demand information for the second approach, data from the time the decision is made and the information from later. Moreover, the available production capacity (given both demands per product) is provided.

t	1	2	3	4	5	6	7	8
D_t^o	7.820	0.700	0.260	0.735	3.449	2.048	2.048	0.630
D_t^n	7.825	0.575	0.160	5.310	7.112	2.280	2.080	0.650
PrC_t^o	32.445	7.713	19.340	28.691	8.065	14.208	33.862	19.594
PrC_t^n	39.625	13.755	20.813	31.688	0.000	16.783	35.960	19.854

5.2.5 Evaluation of suggestions and insights of tool compared

Given the information as described in the previous sections, the tool can be used to suggest a prebuilding quantity decision. This can be for both approaches (product group and specific product). Four different demands are used: Expected demand and Newsboy demand (both from demand scenarios) and the actual demand forecast, retrieved at different moments (at the moment of the actual prebuilding decision and the latest available information). Using the tool and the demands, the following comparisons are made for both approaches:

- Prebuilding quantities:
    - The suggested prebuilding quantity based on the Expected demand
    - The suggested prebuilding quantity based on the Newsboy demand
    - The actually taken decision for prebuilding.
    - The suggested prebuilding quantity based on the old demand
    - The suggested prebuilding quantity based on the new demand
- Effects of prebuilding decision …
    - By comparing the Expected and Newsboy demand decision
    - By comparing the Expected demand and actual decision
    - By comparing the Old demand decision and the Newsboy fractile decision
    - By comparing the new demand decision and the Newsboy fractile decision
    - By comparing the old demand decision and the new demand decision

The calculations are all done with the tool, for both approaches. For the second approach, different available production capacities are reviewed since for this approach, the production capacity is predicted and the actual demand information provides insights in the actual capacities.

5.2.6 Prebuilding decisions suggested for approach one

Using the information as stated before, the Expected demand and Newsboy demand are determined. Moreover, using the different situations as stated in section 5.2.5, the prebuilding quantities as determined are determined by the tool. The results are stated in Table 10.

Table 10: The Expected and Newsboy demand are calculated by the tool. Moreover, the prebuilding quantities using given different demand information are given.

t	1	2	3	4	5	6	7	8
$E[D_t]$	60.0	56.4	71.2	93.0	73.6	70.4	88.0	70.4
NFD_t	60.0	56.19	72.0	90.952	72.762	72.762	90.952	72.762
QIC_t^{ED}	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{NF}	0.0	7.19	0.0	0.0	0.0	0.0	0.0	0.0
QOC_t	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{AO}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{AN}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{ON}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

5.2.7 Prebuilding decision suggestion for approach two

This second approach is different from the first in the way that not the demand for the product group and total capacity for the facility is used, but the demand for the product which is considered for prebuilding. Then, the available capacity for the product is determined: the capacity (expected) to be used for producing other products, is not available for the product to prebuild. Therefore, the capacities are included in the tables with suggestions. Table 11 shows the prebuilding suggestions for the current situation (with 10 million products available to fulfill capacity shortages), when the available production capacity as expected with the demand scenarios is considered. Table 12 shows the same calculations, however the available production capacity is determined from the actual demand data (old and new), given the total capacity and the (forecasted) demand for other products within the product group.

Table 11: The Expected and Newsboy demand are calculated by the tool, for the second approach. The capacities as used are shown. Moreover, the suggested prebuilding quantities by processing different demands are shown.

t	1	2	3	4	5	6	7	8
$E[D_t]$	7.825	0.575	0.16	5.31	7.112	2.28	2.08	0.65
NFD_t	7.82	0.703	0.261	1.68	7.064	2.099	2.074	0.638
PrC_t	20.0	0.0	0.0	1.0	3.0	1.0	2.0	2.0
QIC_t^{ED}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{NF}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QOC_t	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{AO}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{AN}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{ON}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 12: The Expected and Newsboy demand are calculated by the tool, for the second approach. The capacities as used are shown. Moreover, the suggested prebuilding quantities by processing different demands are shown.

t	1	2	3	4	5	6	7	8
$E[D_t]$	7.825	0.575	0.16	5.31	7.112	2.28	2.08	0.65
NFD_t	7.82	0.703	0.261	1.68	7.064	2.099	2.074	0.638

PrC_t^O	32.445	7.713	19.34	28.691	8.065	14.208	33.862	19.594
PrC_t^N	39.625	13.755	20.813	31.688	0.0	16.783	35.96	19.854
QIC_t^{ED}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{NF}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QOC_t	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{AO}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{AN}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
QIC_t^{ON}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

5.3 Review of outcomes

Given the suggestions for the prebuilding decisions as calculated with the tool and shown in the previous section, some further interpretations will be done, as stated in 5.2.5. As can be observed, the tool provides a lot of suggestions not to prebuild any product (given the current situation). In this section, this is reviewed (why these suggestions are done), what effects are and would be when product would be prebuilt (to demand scenarios). Also effects on (ending) inventory are reviewed. Important to note is that in this review, the prebuilding plan as suggested by the tool for the complete horizon is considered. In real life, when the tool would be used, only the suggestion for period 1 would be adapted; the next period, the information would be updated and the outcomes could be completely different. However, reviewing the complete horizon does give some useful insights in the behavior of the tool.

The suggestion as done by the tool will be on the product group as reviewed. However, supply of raw material was only available for one product out of the complete product group which results in that being the only product possible to prebuild. Therefore, selection of product to prebuild is not needed.

5.3.1 Approach one

As stated in section 5.1, the first approach to the case, is by defining the demand by demand scenario for the product group instead of defining demand scenarios for all products in the group and summing them afterwards. First, the demand scenarios and the resulting suggestion for prebuilding is reviewed. Next, the actual demand in included and the suggestions by the tool are reviewed. The outputs of the tool (only for this approach) are shown in App. A.

5.3.1.1 Demand scenarios

Considering the first approach to the case study, the Tool suggest 7.19 million pieces prebuilding in period 2, considering the costs of the product via the Newsboy demand. When using the Expected demand, the Tool suggests prebuilding 1.6 million pieces in period 2. In both cases, the inventory of 10 million pieces after the production step is included in the calculation. When this wouldn't be considered or present, the suggestion for prebuilding (Expected demand considered) would be 11.6 million products in period 2, where for the Newsboy demand the suggestion would be to prebuild 3.6 million pieces in period 1 and 13.8 million in period 2. The production capacity available would be sufficient in all cases.

When the inventory of 10 million pieces is present in period 0, the actual decision taken at that time, starting 10 million pieces in period 1, would be sufficient to fulfill all demand over the horizon (put into the tool as 'own decision'). When the inventory in period 0 would not be available; it would not be sufficient (results in a shortage of 1.6 million pieces over the complete horizon). When the inventory in period 0 is present and the prebuilding decision of 10 million pieces is made; this would result in an ending inventory of 9.5 million pieces.

Moreover, the first 'evaluation scenario' (combining prebuilding to Newsboy demand and Expected demand as demand), results completely fulfilled demand and closing inventory of 5.6 million pieces. Not prebuilding anything (though using the existing inventory) results in a shortage of 1.6 million pieces (RLIP of 99.7%).

5.3.1.2 Actual demand

This first approach is evaluated by using the known demand information at the moment of decision making and the demand information known later (when uncertainty is less). In both cases this 'real demand' is put into the tool as Expected demand.

Considering the information from the decision moment, it is first noticed that considering this information as demand; no capacity shortages exist. Therefore, no prebuilding is suggested for the real data. When the prebuilding quantities as defined by the original scenarios are still kept (without any change); this would result in an ending inventory of 122 million pieces. Naturally, this will not be done in practice, but it shows the importance of constantly updating and evaluating prebuilding decisions. When the Newsboy demand is only used for the prebuilding quantities, the final inventory would have been 17 million pieces. Moreover, when the 'old information' would be used only for the prebuilding planning for the whole horizon; this would have let to unmet demand (no prebuilding done because no capacity shortage observed). This highlights the need for updating and evaluation of the prebuilding decisions.

Using more recent demand data, the situation is slightly worse. Period 5 shows a shortage in capacity, however, overall, there is a large capacity overage. When the production plan as calculated with the Newsboy demand scenario is kept; the ending inventory would be 127 million pieces. In practice, this cannot occur when the prebuilding decision and constantly updated and evaluated. This is also seen when for the production plan the actual values are considered; the final inventory is then 9.4 million pieces (when products are prebuild in period 2; for which the decision is not made in that moment). Moreover, it can be seen that no prebuilding would be needed (over the complete tool-horizon) when 10 million pieces have been built before; the no-prebuilding scenario 2 million pieces in inventory at the end of the horizon.

When the prebuilding decision as suggested would have been actually made and the total demand would have been prebuild for the one available product, it depends on the advertence of the involved people whether it would have been a problem. When nobody pays attention, it could have let to an inventory with an approximated value of 2.5 million Dollar. However, when attention is paid to the process; it could have let to an inventory of approximately 0.2 million Dollar. Even better: when real attention is paid to the process, the inventory could have been used earlier, instead of producing new product (over a longer horizon, demand is higher than the ending inventory).

Another important observation is that the prebuilding decisions as suggested by the tool (for this approach) are lower than the actually made decisions. Moreover, when the 10 million pieces weren't already built, the decision would have been made later as suggested by the tool (which should result in more accurate demand scenarios available for decision making).

5.3.2 Approach two

The second approach prepares the demand in a different way; since supply is only available for one product, only that product is considered for prebuilding. Because the future production capacity would have been used by the other products in the product group; the available capacity is put into the tool for calculations. For this review, not only the expected available capacity is used, also the actual available capacity is used.

5.3.2.1 Demand scenarios

The second approach of the case, in contrast to the first approach, the demand for the product selected for prebuilding is used, instead of the demand for the complete product group. Then, the expected production capacity available for the product is determined; which results in production capacity shortages for both processed demand scenarios. The overall production capacity available is comparable.

Looking to the suggested prebuilding decision: the tool suggests for both processed demand scenarios not to prebuild any product. The available inventory in period 0 is sufficient to cover the shortage in demand. When this inventory would not be present, the prebuilding to the Newsboy demand and observing Expected demand, 1.6 million pieces of demand wouldn't be fulfilled, however, the ending inventory would be positive. The RLIP would be 93%. Considering the production capacities from the actual data; this does not differ the results: production capacity shortages is not the reason for prebuilding, but the small difference between expected and newsboy demand. This is due to the fact that the Newsboy demand does incorporate a high demand less strong than the Expected demand.

Moreover, when the 10 million pieces inventory would not be available; a prebuilding suggestion for period 4 for period 5 would be done. Both the capacities from the actual data are sufficient in period 4.

5.3.2.2 Actual demand

The second approach used the demand for the product itself, combined with the information of production capacity left for producing the one product. This would result in prebuilding suggestions only applicable for the specific product.

First, considering the actual demand and capacity data at the decision moment, it is noticed that the tool does not suggest prebuilding; the 10 million pieces available in period 0, are sufficient for fulfilling the shortages observed. However, when the production plan as calculated is used for the complete horizon; the final inventory (without prebuilding within the tools horizon) will be 14.65 million pieces (approximately 300 thousand Dollar). This is higher than the inventory expected when using the tool with the demand scenarios; this is due to the fact that a shortage in production capacity was expected for a large part of the horizon, where this shortage is not visible in the data. When the production capacities would be as expected, the final inventory would have been 8 million pieces. With the new actual capacities, the inventory would be 7.5 million pieces.

Using the more recent data on demand, combined with the old production capacities, no shortages exist and the demand . Here, the Newsboy demand is very close to the real demand, and therefore, no large overages are created. The final inventory level equals 6.3 million pieces. Comparing the new actual demand with the newest actual capacities; the ending inventory equals zero, but 700 thousand pieces of demand is not met. When the capacities would be as expected, the unmet demand would be 500 thousand pieces.

Comparing the old to the new demand (new demand as actual demand and the old demand as demand where the decisions are based on), considering the expected capacity, a shortage of 800 thousand pieces would occur. Considering production capacities as from the old demand, the no shortage will occur; the ending inventory would be 1.7 million pieces. Using the newer capacities, a shortage of 1.8 million pieces will occur.

The same conclusion on the decisions suggested by the tool as drawn earlier, can be drawn here. The tool suggest a lower prebuilding quantity than the actual decision made. This could work great, however, when the capacity shortage does occur (as can be seen in the most recent data) this can lead to shortages in supply. Further, it can be seen that the demand on which the prebuilding is decided is also important. The demand scenarios are constructed in such a way that the expected and Newsboy demand are very close and sometimes the Expected demand is higher than the Newsboy demand and this results in unmet demand (at this moment). This is not a real problem: in this situation, the risk was too high for prebuilding based on the demand scenarios as used as input.

Chapter 6. Conclusions and recommendations

In this chapter, the conclusion of the project are stated. These conclusions answer the research questions as stated in section 2.3.3. Later, some recommendations based on the findings or results during the project are done.

6.1 Conclusions on project

At the company, the costs of non quality are observed to be above target. These costs consists for the greater part of costs made when throwing away products which are build, but no demand is existing (anymore). These products end up in inventory and will eventually be scrapped when future demand is not likely anymore or products are too old. To investigate what the real main causes for this observed inventory overages and from there costs are, and find a solution or improvement, the master thesis project is initiated at the company.

In the first phase of the project, a couple of causes are found which are responsible for the current inventories with insufficient demand compared to the inventory levels: Slow moving and non moving inventory (SNMI). Six causes are defined and further investigation shows that unexpected drops in demand caused almost 90% of the SNMI. Prebuilding (building inventory on top of the safety stocks) caused 60% of the SNMI present in 2018. In the area of demand forecasting accuracies; improvement projects are conducted with limited results. Further investigation on the Prebuilding decision process, shows lack of a clear and usable prebuilding decision process. Therefore, the solution direction is chosen to be improving the prebuilding decisions.

To improve the prebuilding decisions, the current decision process needs to be investigated, together with the current process around. Moreover, the factors needed to be included in such decisions are defined. Moreover, the scope of the solution is defined: prebuilding can be done with different motivations; future production capacity shortages and underloading penalties are included.

For such decisions on prebuilding, information on (stochastic) demand, future production capacities, supply chain information and information on costs of product are considered. During the project, a Prebuilding Decision Support Tool is designed, which combines this information and based on this information, suggest a quantity of product to produce (prebuild).

Studying an actual case where a prebuilding decision is taken without using the tool and the suggestions by the tool when applied at that situation, shows that demand will fairly certain be fulfilled and inventory leftovers are acceptable when attention is paid to the process and the previously taken decisions. Moreover, in the case study, is it observed that the Newsboy demand turns out to be useful for reducing risk of overproduction: when the demand in the high scenario is much larger than the mid scenario, the Newsboy demand will not follow as easy as the Expected demand. This because of the approach of the scenarios. Moreover, the decisions as suggested result in less leftover inventory than the decision taken in real life. Long horizon improvements on reducing SNMI cannot be shown, however, the short term results create the expectation that this will be the case.

6.2 Recommendations on usage and further research

In the previous section, the research questions for the complete project are answered. While executing the project, some points of interest appeared. Moreover, there are some points where further research could be possible.

6.2.1 Recommendations on usage of tool

As stated earlier in the report, the tool provides suggestion on prebuilding quantities. These suggestion can only be as good as the information used to come up with the suggestion. Therefore, it is important to use correct information (at least, as certain and correct as possible). When information is unknown or known to be uncertain, this should be considered when interpreting the suggestion.

Moreover, it should always kept in mind that the tool uses uncertain demand information as input. Although this considers stochasticity, this does not mean that the information used is correct. Therefore, it is of enormous importance that the information is updated as often as possible and updates in suggested prebuilding decisions will be processed as fast as possible. The tool will attempt to postpone decisions to ensure more reliable information, but the can also result in an underestimation of demand. To overcome shortages in supply (not only to prevent overages in inventory), updating and evaluating information is needed. Therefore, only the suggested decision for the first period can be used.

6.2.2 Further research suggestions

During the project, some points of interest for further research appeared:

- Production supply chain inventories
  At the company, inventory levels are mostly defined in future (expected) demand. However this seems to be a good solution to ensure no inventories are kept for products where no demand exist, however, this results probably in inventory targets which unnecessary high: inventory (safety stocks) should cover uncertainty or fluctuations in demand. This could be investigated in more detail, what the benefit of defining them differently would be. It seems that defining these levels differently this could mean improvement of service levels, reducing overall inventory sizes and reducing risk on SNMI, and finally, by having to produce less products, improving the available production capacity.
- Processing demand scenarios into demand scenario as input
  During the current prebuilding decision (information preparation) process, demand needs to be combined into different scenarios, where the first scenario is clearly the lowest demand scenario and the last scenario is the high scenario. It could be further looked into a way to create such a scenario out of other, more practical scenarios. Moreover, using different scenarios per product and combining them into the such low-high scenarios or a distribution, this would ease the usage of the tool while having real possible practical cases in vision.
- Evaluating demand for multiple products
  In the Prebuilding Decision Process, when multiple products need to be considered, a ranking is made on which demand to fulfill first, combined with cost information. Evaluating how this combination of products into information input for the tool could be done in a better (supported)

and easier way, could improve the decision outcomes of the tool. Moreover, when a suggestion is done by the tool for a product group, what would be an optimal strategy to schedule the different products could be a useful subject for further research.

- Extension of model to include more information
  For the Tool as designed during this project, the desire was to have a simple decision process and tool so that suggestions made are easy to create and interpret. The downside of this approach is that the factors included are limited. To include more factors (for example: available supply semi-finished products over time or different costs of products) or to included multiple products and customers, possibly with other characteristics, the model cannot be a simple model with some formulas as presented in this report. Also, different production capacity scenarios could be included. Using Linear Programming would support more complex and extensive decisions. However, the usability should be assured. Otherwise, the solution will not be used in practice.

Chapter 7. Bibliography

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App. A. Output of Prebuilding Decision Support Tool (approach one)

A.1. Demand preparation

Time Period	0	1	2	3	4	5	6	7	8
Total Expected Demand		60.0	56.4	71.2	93.0	73.6	70.4	88.0	70.4
Total Newsboy fractile Demand		60.0	56.19	72.0	90.952	72.762	72.762	90.952	72.762

Product A												
Production costs	$ 0.02											
Scrapping costs	$ -											
Selling Price	$ 0.07											
Product Margin	$ -											
Penalty costs												
Overage inventory costs	**$ 0.02**											
Underage inventory costs	**$ 0.05**							*Time Period*				
Demand Scenario	**Probability**	**CumP**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	*H*
Scenario 1	20%	20.0%		60	52	68	75	56	40	50	40	0
Scenario 2	50%	70.0%		60	56	72	90	72	72	90	72	1
Scenario 3	30%	100.0%		60	60	72	110	88	88	110	88	0
Scenario 4		100.0%										0
Scenario 5		100.0%										0
Scenario 6		100.0%										0
Scenario 7		100.0%										0
Scenario 8		100.0%										0
Scenario 9		100.0%										0
Scenario 10		100.0%										0
Scenario 11		100.0%										0
Scenario 12		100.0%										0
Expected Demand				60.0	56.4	71.2	93.0	73.6	70.4	88.0	70.4	
Newsboy fractile Demand	71.43%			60.0	56.19	72.0	90.952	72.762	72.762	90.952	72.762	

A.2. Expected demand & Newsboy Demand

			Time period								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Production capacity available			87.5	70.0	70.0	87.5	70.0	70.0	87.5	70.0	
Expected Demand		0	60.0	56.4	71.2	93.0	73.6	70.4	88.0	70.4	
Newsboy fractile Demand		0	60.0	56.19	72.0	90.952	72.762	72.762	90.952	72.762	
Inventory available for Prebuilding	10										
Own Prebuilding decision			10.0								
Shortage	Expected Demand		0.0	0.0	1.2	5.5	3.6	0.4	0.5	0.4	
	Newsboy f. Demand		0.0	0.0	2.0	3.452	2.762	2.762	3.452	2.762	
Overage	Expected Demand		27.5	13.6	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		27.5	13.81	0.0	0.0	0.0	0.0	0.0	0.0	
Overall Capacity overage (Capacity - Expected Demand + Inventory)			39.50								
(Capacity - Newsboy f. Demand + Inventory)			34.12								
Prebuild needed (without constraint)	Expected Demand		0.0	1.2	5.5	3.6	0.4	0.5	0.4	0.0	
	Newsboy f. Demand		0.0	2.0	3.452	2.762	2.762	3.452	2.762	0.0	
Prebuild needed (considering inventory)	Expected Demand	10	0.0	0.0	0.0	0.3	0.4	0.5	0.4	0.0	
	Newsboy f. Demand	10	0.0	0.0	0.0	0.0	0.976	3.452	2.762	0.0	
Prebuild possible (with constraint)	Expected Demand		0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	7.19	0.0	0.0	0.0	0.0	0.0	0.0	
	Own decision		10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Production Plan	Expected Demand		60.0	58.0	70.0	87.5	70.0	70.0	87.5	70.0	
	Newsboy f. Demand		60.0	63.381	70.0	87.5	70.0	70.0	87.5	70.0	
	Own decision		70.0	56.4	70.0	87.5	70.0	70.0	87.5	70.0	
											Total
Utilization	Expected Demand (NP)		69%	81%	100%	100%	100%	100%	100%	100%	93%
	Expected Demand		69%	83%	100%	100%	100%	100%	100%	100%	94%
	Newsboy f. Demand (NP)		69%	80%	100%	100%	100%	100%	100%	100%	93%
	Newsboy f. Demand		69%	91%	100%	100%	100%	100%	100%	100%	94%
	Own decision		80%	81%	100%	100%	100%	100%	100%	100%	95%
Inventory Buildup	Expected Demand	10	10.0	11.6	10.4	4.9	1.3	0.9	0.4	0.0	
	Newsboy f. Demand	10	10.0	17.19	15.19	11.738	8.976	6.214	2.762	0.0	
Unfulfilled Demand	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Inventory level & unfulfilled demand	Inventory level		10.0	16.981	15.781	10.281	6.681	6.281	5.781	5.381	
using expected demand and newsboy	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
fractile for prebuilding	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%
Inventory level & unfulfilled demand	Inventory level		10.0	10.0	8.8	3.3	0.0	0.0	0.0	0.0	
using expected demand and no	Unfulfilled demand		0.0	0.0	0.0	0.0	0.3	0.4	0.5	0.4	**RLIP Total**
prebuilding	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*99%*	*99%*	*99%*	99.73%
Inventory level & unfulfilled demand	Inventory level		20.0	20.0	18.8	13.3	9.7	9.3	8.8	8.4	
using expected demand and own	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
prebuilding decision	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%

A.3. Actual demand at decision moment

			Time period								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Production capacity available			87.5	70.0	70.0	87.5	70.0	70.0	87.5	70.0	
Actual demand at decision moment	(Expected Demand)	0	62.875	62.987	50.92	59.544	65.384	57.84	55.686	51.036	
Newsboy fractile Demand	(Newsboy f.Demand)	0	60.0	56.19	72.0	90.952	72.762	72.762	90.952	72.762	
Inventory available for Prebuilding	10										
Own Prebuilding decision			10.0								
Shortage	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	2.0	3.452	2.762	2.762	3.452	2.762	
Overage	Expected Demand		24.625	7.013	19.08	27.956	4.616	12.16	31.814	18.964	
	Newsboy f. Demand		27.5	13.81	0.0	0.0	0.0	0.0	0.0	0.0	
Overall Capacity overage (Capacity - Expected Demand + Inventory)			156.23								
(Capacity - Newsboy f. Demand + Inventory)			34.12								
Prebuild needed (without constraint)	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	2.0	3.452	2.762	2.762	3.452	2.762	0.0	
Prebuild needed (considering inventory)	Expected Demand	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand	10	0.0	0.0	0.0	0.0	0.976	3.452	2.762	0.0	
Prebuild possible (with constraint)	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	7.19	0.0	0.0	0.0	0.0	0.0	0.0	
	Own decision		10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Production Plan	Expected Demand		62.875	62.987	50.92	59.544	65.384	57.84	55.686	51.036	
	Newsboy f. Demand		60.0	63.381	70.0	87.5	70.0	70.0	87.5	70.0	
	Own decision		72.875	62.987	50.92	59.544	65.384	57.84	55.686	51.036	
											Total
Utilization	Expected Demand (NP)		72%	90%	73%	68%	93%	83%	64%	73%	76%
	Expected Demand		72%	90%	73%	68%	93%	83%	64%	73%	76%
	Newsboy f. Demand (NP)		69%	80%	100%	100%	100%	100%	100%	100%	93%
	Newsboy f. Demand		69%	91%	100%	100%	100%	100%	100%	100%	94%
	Own decision		83%	90%	73%	68%	93%	83%	64%	73%	78%
Inventory Buildup	Expected Demand	10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
	Newsboy f. Demand	10	10.0	17.19	15.19	11.738	8.976	6.214	2.762	0.0	
Unfulfilled Demand	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Inventory level & unfulfilled demand using expected demand and newsboy fractile for prebuilding	Inventory level		7.125	7.519	26.599	54.556	59.172	71.332	103.146	122.11	
	Unfulfilled demand		2.875	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
	RLIP (per period)		*95%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	99.38%
Inventory level & unfulfilled demand using expected demand and no prebuilding	Inventory level		10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%
Inventory level & unfulfilled demand using expected demand and own prebuilding decision	Inventory level		20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	
	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%

A.4. Actual demand at review moment

			Time period								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Production capacity available			20.0	0.0	0.0	1.0	3.0	1.0	2.0	2.0	
Expected Demand		0	7.825	0.575	0.16	5.31	7.112	2.28	2.08	0.65	
Newsboy fractile Demand		0	7.82	0.703	0.261	1.68	7.064	2.099	2.074	0.638	
Inventory available for Prebuilding	10										
Own Prebuilding decision			10.0								
Shortage	Expected Demand		0.0	0.575	0.16	4.31	4.112	1.28	0.08	0.0	
	Newsboy f. Demand		0.0	0.703	0.261	0.68	4.064	1.099	0.074	0.0	
Overage	Expected Demand		12.175	0.0	0.0	0.0	0.0	0.0	0.0	1.35	
	Newsboy f. Demand		12.18	0.0	0.0	0.0	0.0	0.0	0.0	1.362	
Overall Capacity overage (Capacity - Expected Demand + Inventory)		13.01									
(Capacity - Newsboy f. Demand + Inventory)		16.66									
Prebuild needed (without constraint)	Expected Demand		0.575	0.16	4.31	4.112	1.28	0.08	0.0	0.0	
	Newsboy f. Demand		0.703	0.261	0.68	4.064	1.099	0.074	0.0	0.0	
Prebuild needed (considering inventory)	Expected Demand	10	0.0	0.0	0.0	0.0	0.437	0.08	0.0	0.0	
	Newsboy f. Demand	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Prebuild possible (with constraint)	Expected Demand		0.517	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Own decision		10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Production Plan	Expected Demand		8.342	0.0	0.0	1.0	3.0	1.0	2.0	0.65	
	Newsboy f. Demand		7.82	0.0	0.0	1.0	3.0	1.0	2.0	0.638	
	Own decision		17.825	0.0	0.0	1.0	3.0	1.0	2.0	0.65	
											Total
Utilization	Expected Demand (NP)		39%	100%	100%	100%	100%	100%	100%	33%	53%
	Expected Demand		42%	100%	100%	100%	100%	100%	100%	33%	55%
	Newsboy f. Demand (NP)		39%	100%	100%	100%	100%	100%	100%	32%	53%
	Newsboy f. Demand		39%	100%	100%	100%	100%	100%	100%	32%	53%
	Own decision		89%	100%	100%	100%	100%	100%	100%	33%	88%
Inventory Buildup	Expected Demand	10	10.517	9.942	9.782	5.472	1.36	0.08	0.0	0.0	
	Newsboy f. Demand	10	10.0	9.297	9.035	8.355	4.291	3.192	3.118	3.118	
Unfulfilled Demand	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Inventory level & unfulfilled demand	Inventory level		9.995	9.42	9.26	4.95	0.838	0.0	0.0	0.0	
using expected demand and newsboy	Unfulfilled demand		0.005	0.0	0.0	0.0	0.0	0.442	0.08	0.012	**RLIP Total**
fractile for prebuilding	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*81%*	*96%*	*98%*	97.92%
Inventory level & unfulfilled demand	Inventory level		10.0	9.425	9.265	4.955	0.843	0.0	0.0	0.0	
using expected demand and no	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.437	0.08	0.0	**RLIP Total**
prebuilding	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*81%*	*96%*	*100%*	98.01%
Inventory level & unfulfilled demand	Inventory level		20.0	19.425	19.265	14.955	10.843	9.563	9.483	9.483	
using expected demand and own	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
prebuilding decision	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%

A.5. Actual demand at review moment & at decision moment

			Time period								
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Production capacity available			87.5	70.0	70.0	87.5	70.0	70.0	87.5	70.0	
Actual demand at review moment	(Expected Demand)	0	55.7	56.82	49.347	61.122	78.011	55.497	53.62	50.796	
Actual demand at decision moment	(Newsboy f.Demand)	0	62.875	62.987	50.92	59.544	65.384	57.84	55.686	51.036	
Inventory available for Prebuilding	10										
Own Prebuilding decision			10.0								
Shortage	Expected Demand		0.0	0.0	0.0	0.0	8.011	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Overage	Expected Demand		31.8	13.18	20.653	26.378	0.0	14.503	33.88	19.204	
	Newsboy f. Demand		24.625	7.013	19.08	27.956	4.616	12.16	31.814	18.964	
Overall Capacity overage (Capacity - Expected Demand + Inventory)			161.59								
(Capacity - Newsboy f. Demand + Inventory)			156.23								
Prebuild needed (without constraint)	Expected Demand		0.0	0.0	0.0	8.011	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Prebuild needed (considering inventory)	Expected Demand	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Prebuild possible (with constraint)	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Own decision		10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Production Plan	Expected Demand		55.7	56.82	49.347	61.122	70.0	55.497	53.62	50.796	
	Newsboy f. Demand		62.875	62.987	50.92	59.544	65.384	57.84	55.686	51.036	
	Own decision		65.7	56.82	49.347	61.122	70.0	55.497	53.62	50.796	
											Total
Utilization	Expected Demand (NP)		64%	81%	70%	70%	100%	79%	61%	73%	74%
	Expected Demand		64%	81%	70%	70%	100%	79%	61%	73%	74%
	Newsboy f. Demand (NP)		72%	90%	73%	68%	93%	83%	64%	73%	76%
	Newsboy f. Demand		72%	90%	73%	68%	93%	83%	64%	73%	76%
	Own decision		75%	81%	70%	70%	100%	79%	61%	73%	76%
Inventory Buildup	Expected Demand	10	10.0	10.0	10.0	10.0	1.989	1.989	1.989	1.989	
	Newsboy f. Demand	10	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
Unfulfilled Demand	Expected Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	Newsboy f. Demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Inventory level & unfulfilled demand	Inventory level		17.175	23.341	24.914	23.335	10.708	13.051	15.117	15.357	
using expected demand and newsboy	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
fractile for prebuilding	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%
Inventory level & unfulfilled demand	Inventory level		10.0	10.0	10.0	10.0	1.989	1.989	1.989	1.989	
using expected demand and no	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
prebuilding	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%
Inventory level & unfulfilled demand	Inventory level		20.0	20.0	20.0	20.0	11.989	11.989	11.989	11.989	
using expected demand and own	Unfulfilled demand		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**RLIP Total**
prebuilding decision	RLIP (per period)		*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	100.00%

App. B. Extensive study on supply chain

App. B. Current processes and parameter definition in the production supply chain

This section will go more into detail for the production or manufacturing supply chain, the related processes and the relevant parameters.

B.1. Manufacturing supply chain building blocks

The semiconductor manufacturing supply chain is complicated and long. It can be divided into two main parts: the front-end and the back-end. In the front-end; the dies[1] are created. This is done on silicon slices, and the dies are created layer per layer. The time needed per layer on a wafer is roughly the same for all dies: a complicated die with many layers will need more time to create. At the BL, dies can contain up to ±45 mask layers. The number of dies on one silicon slice, depends on the size of the die. The number of dies on one slice can vary between 1,000 and 500,000. Although the product is build layer per layer, the process is continuous and has only one decoupling point: the so-called metal bank (between front-end and back-end diffusion, both in the front-end of the production supply chain). For some products, after the metal bank different products can be created from one semi-finished die (often called mother-die), for other products the die is unique from start to finish. A silicon slice with finished dies, is called a wafer.

In the back-end of the production supply chain, the wafers are transformed into chips (or semiconductors or integrated circuits). The first step is probing (a.k.a. wafertest): testing every single die on deviations from the requirements. These dies are marked and will not be used later in the process. The fraction of dies which does comply with the requirements, is called the yield. After probing, the dies cut loose and put into a package (small plastic box), also known as Assembly. This package provides the contact points to connect the die with the outer world (some dies have these contact points already: so-called bumps). After the assembly of the die and package; a final test on requirements is carried out and chips are put into packing.

B.2. Inventory levels and locations in the manufacturing supply chain.

As described before, the manufacturing supply chain consists of some building/production blocks. Between production blocks, inventories can be kept. Possible locations for holding inventory:

- SLPD: In the wafer fabrication process (Slice Partially Diffused), so-called metal-bank.
- SLDI: Finished wafers (Slice Diffused), after wafer fabrication process.
- SLBU: Finished wafers (Slice Diffused), after Bumping process (probing not yet done).
- CEPT: Finished wafer (Circuit Element Pre Tested), after probing (testing on uncompliant dies).
- CEBU: The same as CEPT, except that these are bumped wafers (Circuit Element Bumped)
- PEP: Finished product (Packed End Product), put into certain packing.

Within the company, only one inventory type exists, which is often called safety stocks. This because inventories only exist to cover uncertainties in demand and/or supply. Inventory build-up with other intensions occurs, but are not regular (for example, pre-building because of expected capacity shortages). Furthermore, the inventory level per location (the Safety Stock) is stated as a target.

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[1] Die: heart of the chip, the electrical circuits, mostly multiple layers on a piece of metal. Multiple dies are created on one metal slice, later the wafer (slice with dice on it) is cut up into singular dies.

Whether this target is met, is dependent on the available manufacturing capacities and (existing) priorities (on product, customer, demand type, etc.).

Inventory targets can be defined in six different ways. Four of the options are shown in Table 1. The other options are *fixed* and *infinite*. These mean: a number set for a location and product for the entire planning horizon, and an unlimited number of products for a certain location, respectively. The latter is used for raw material; raw material inventories are controlled by factories (not by product planning).

Table 1: Different ways to define safety stock targets used in the company.

	Item-location *Inventory levels set for a product at a specific location*	**Seller-product** *Inventory levels dependent on the customer for the product*
Time phased Inventory Position *A projection of desired safety stock levels based on future demand.*	Dynamic Safety Stock Calculation (DSSC)	Dynamic Seller Specific Safety Stock Calculation (D4SC)
Time phased User *A time-phase safety stock defined by user.*	User defined Safety Stock calendar (UDSSC)	User Defined Seller Specific Safety Stock calendar (UD4SC)

Within the BL, the Dynamic Safety Stock Calculation is mostly used as definition for the inventory target. This means, the inventory target levels are set for a specific product at a specific location, as a function of the future demand. The level is defined in weeks, where weeks is the future demand (forecasted and/or actual), averaged over a certain period of time. So, if the inventory target is five weeks, the level is products in inventory should be roughly enough to cover five weeks of demand. The level of the target can be altered per product but is mostly the standard format. The standard levels are: *6 weeks SLPD*, *5 weeks CEPT* and *2 weeks PEP*. This means that roughly 13 weeks of demand are kept in inventory, partially in finished products, partially in semi-finished. This enables reacting on changes or disruptions in supply or demand, faster than the complete production lead time. This strategy differs from the usual way of determining safety stock (targets). Safety stocks are usually based on the variation or standard deviation in demand, combined with the desired service level(s). At the company, two measures for service level are defined:

- RLIP (Requested Line Item Performance), this is the fraction of the requested demand (actual demand, customer orders) which is fulfilled. The objective is to have a RLIP >85%.
- CLIP (Committed Line Item Performance), this is the fraction of committed demand (accepted demand, accepted customer orders) which is fulfilled. The objective is to have a CLIP >95%.

However, the RLIP and CLIP are not considered directly for defining the safety stock levels.

B.3. Production lead times

As stated in the introduction of this chapter, the production lead times at the BL are longer than industry-standard. From a production supply chain perspective; (almost) all products can be placed into three groups:

1. IC's without bumps, in a package.
2. IC's with bumps, not in a package.
3. IC's with bumps, in a package.

Of course, because of the differences in production process, the lead times differ. A schematic representation of the production process (including inventories/buffers) are shown in Table 3 to Table 6. The corresponding lead times per process step are shown below the process steps. As can be seen, the front-end is the same for the different product groups, the back-end differs. Please note the SLDI-buffer is shown in the front-end and back-end diagram; this is just as reference. Only one SLDI-buffer per supply chain is defined.

Summing the lead times per product group, provides the total production lead times, as stated in Table 2.

Table 2: Total production lead times per product group, providing the minimal, the mean and the maximal number of weeks.

Product group	Minimal [weeks]	Mean [weeks]	Maximal [weeks]
1	22	23 2/7	24 4/7
2	25	26	27
3	26 3/7	27 3/7	28 3/7

As can be seen in Table 2, the total (mean) production lead times are 163 days, 182, and 192 days for product group one, two, and three, respectively. As stated before, this is longer than the industry standard, and therefore a disadvantage in comparison to competitors. As can be seen after looking at the separate process steps, the front-end (Diffusion process), uses the largest part of the total time (19 to 21 weeks). The longer than standard lead in the front-end, can be explained by the product complexity (up to 46 layers on a wafer). This complexity is a key advantage compared to competitors' products (cost of manufacturing/material are often lower). However, this has as downside the long production lead times. This results in having less flexibility in the production supply chain.

Table 3: Front-end supply chain, lead times of the process steps stated below the process.

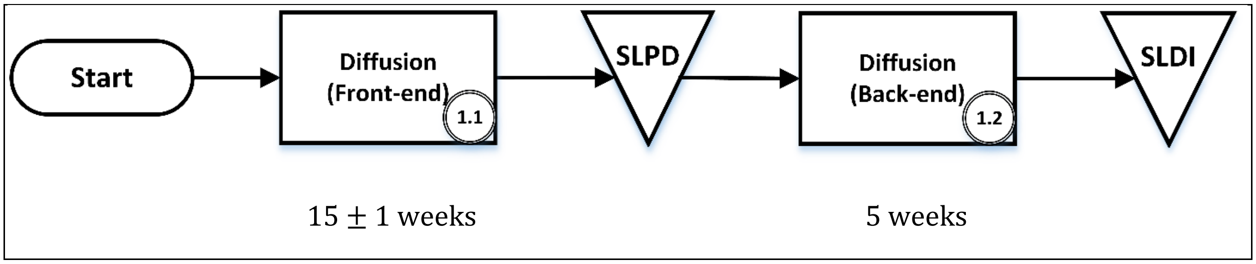


Table 4: Back-end production supply chain for product group 1, lead times of the process steps are stated below. The first buffer (SLDI) is the last buffer of the front-end supply chain from Table 3.

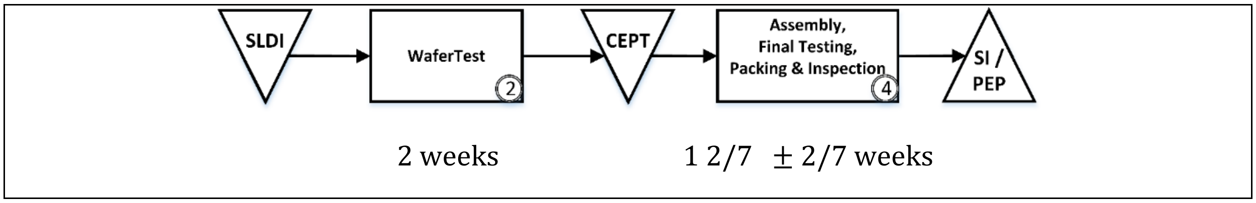


Table 5: Back-end production supply chain for product group 2, lead times of the process steps are stated below. The steps Bumping and WaferTest could be carried out in a different order. Semi-finished products in between would be called CEPT. The first buffer (SLDI) is the last buffer of the front-end supply chain from Table 3.

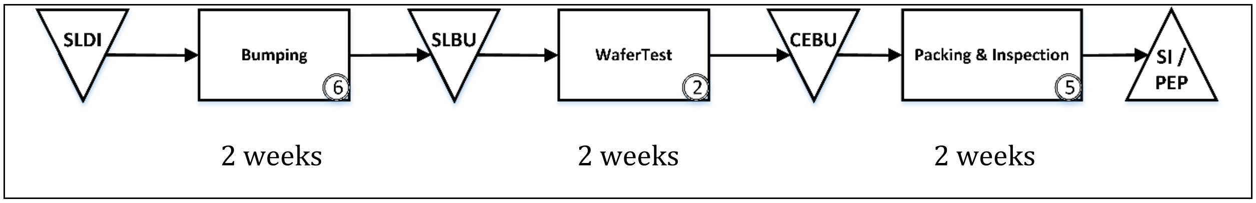
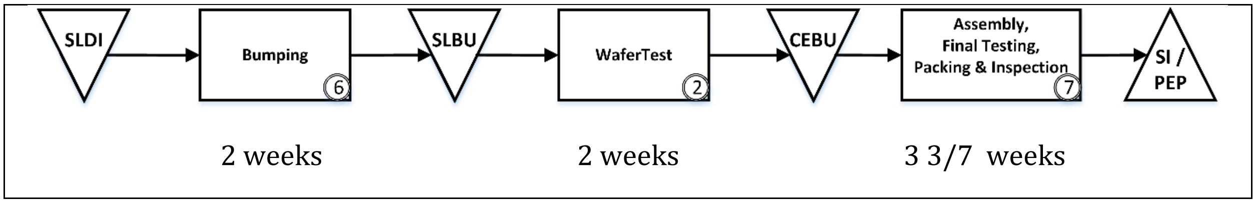


Table 6: Back-end production supply chain for product group 3, lead times of the process steps are stated below. The steps Bumping and WaferTest could be carried out in a different order. Semi-finished products in between would be called CEPT. The first buffer (SLDI) is the last buffer of the front-end supply chain from Table 3.



As can be seen, production supply chains end with the finished goods inventory (SI, Sales Item; PEP; Packed End Product). The process step's lead times in the supply chain, include the transportation times between the production facilities: most of the transportation is done by plane, therefore, it does not take much time when no import/export checks or test have to be done. However, the finished goods inventory as shown in the supply chains, is the inventory at the factory of the final production step. However, after that, the product must go to the customer (directly or indirectly), or can be stored at the company's warehouse, which is in Malaysia. For the lead times as observed by the customer, the transportation times need be considered. An indication for those lead times, is stated in Table 7.

Table 7: Mean times for transportation of PEP, after finishing the production.

Description	**Mean time (days)**
Transportation from final manufacturing stage to company warehouse (Malaysia)	2-3
Transportation from final manufacturing stage to customer	2-10
Transportation from Malaysia to customer	4-7

Other extensions for the supply chain would be a distributor or a VMI (Vendor Managed Inventory). A distributor is a separate company, who sells the company's products to customers. The company is often in contact with the customer for the product, so the desired inventory levels at the distributor are known / can be forecasted. Since inventory leftovers are often returned to the company, this could be seen as an additional (own) warehouse. Moreover, the VMI is a different inventory location, directly located at the customer, but managed by the company. This could also be seen as an additional inventory location within the supply chain.

B.4. Customer Order Decoupling Point

The customer order decoupling point (CODP) is the point in the supply chain, up till where products are manufactured to stock: make-to-stock. After the CODP, production is only continued when customer orders are present (make-to-order). Exceptions are made (pre-building in most of the cases), but the rule is that no production without customer orders occurs after the CODP.

As stated in section B.3, production lead times are currently roughly 23, 26, or 28 weeks. Customers do not accept order lead times this long because of two reasons: most of them are not sure what they need such a period ahead, and competitors can offer shorter lead times. Therefore, the customer order lead time is set to 13 weeks. This is in line with the market. Please note this is the standard time; some customers are allowed to place orders later, some products are only made to order.

For the current lead times as stated in section B.3, combined with the standard order lead time of 13 weeks, the CODP should always be placed at the SLPD. So, wafer starts (production until the metal-bank), needs to be done on forecast. In case other customer order lead times (COLTs) are used, it is possible the CODP position in the supply chain must be switched. For example, when a COLT of four weeks is used, the CODP needs to be located after probing (CEPT / CEBU). Of course, the CODP can differ per product, customer and supply chain.

B.5. Demand Management

As stated in the previous section, it is stated that before the CODP, production must be started on forecasted demand, since actual orders are not in yet when production needs to be started. Therefore, demand must be forecasted. The products of the Business Line, can be divided into three segments: Internet Everywhere, Mobile, and Multi Market, which have all different demand characteristics. The used forecasting techniques differ per product group:

- New Product Introduction (NPI)
  These are newly developed products and are produced upon information from the BL Marketing. Approximately 40% of the total demand is for NPI. The made forecasts are checked by account managers, together with the customer(s).
- Key running products
  These are products which aren't new to the market but are running (being produced and sold for a certain time), and are expected to be running for a certain time. How long this time is, depends on the product's product life cycle length. These products cover approximately 40% of the total demand. Key inputs for the demand forecast are from account managers and Sales Based Forecast (SBF). For different forecasting horizons, some different forecasting methods are used:
  - Short term (≤ 13 weeks): For these horizons, customer forecast (EDI) is used, in combination with customer orders and inputs from account managers.

  - Mid term (> 13 weeks; ≤ 6 months): Inputs from account managers (based on customer information) and information on running products is used.
  - Long term (> 6 months): Own demand model used for various customers, filled with information from account managers.
- Multi market and mass market and mass market.
  For these kind of products, demand is present over a long time. The products are general applicable products, which can be used in various applications. Therefore, the demand is (in comparison to the other product groups) flat. The market share is around 20% (14% in 2018). Forecasting is (mostly) done with statistical models and these are reviewed monthly. Moreover, regional marketing managers inputs are used.

Demand forecasting is done on end-products: the actual products which are sold to customers. Converting this demand on end-products into demand for semi-finished products, is done by production planning (and the production planning engine).

Since demand must be forecasted, the correctness of this forecasts is important. Unfortunately, forecast accuracies are not that high. In the past, project have been initiated to increase forecast accuracies, with minor results. It is known, gaining high forecast accuracies is hard (Business to Business environment, high quantities, long horizons, highly fluctuating demand). Low forecast accuracies in combination with products with relatively short product life cycles, result in high risks on left-over inventories.

Within the company, forecast accuracy was measured with an own KPI: FCACC. Up to September 2018, this KPI was used. The FCACC used an adapted version of the MAPE (Mean Absolute Percentage Error). The adapted version of the MAPE differed from the original by considering the error (difference between forecast and actual demand) differently: the error was not always compared to the actual demand, but to the maximal value of the forecast and the actual demand. This results in a non-symmetrical valuation of the error: in case the forecast is higher than the actual demand, the accuracy is higher than by using the original MAPE. If the forecast is higher than two times the actual demand, the MAPE will be higher than 100%. Calculation the forecast accuracy, will result in negative values. After September 2018, the company will use the original MAPE for determining the forecast accuracy. However, when the error is larger than the actual demand, the forecast accuracy will be stated as 0%, not a negative number.

Within the company, the forecast accuracy is measured for two forecast horizons: six and three months ahead. These numbers are chosen companywide, since they can be related to the start of wafer production and start of back-end production for most business lines (in the business line where the project is conducted, the production lead times are longer). The three month ahead forecast is evaluated the most since this is also related to the customer order lead time. For evaluation, numbers used for the forecast accuracy are averaged over three months, to level out the effect of having demand

	FCACC	FCACC (New)	MAPE	1-MAPE	# largest FC,CO
February	**54%**	**46%**	**76%**	**24%**	**140**
FC > CO	*61%*	*45%*	*102%*	*-2%*	*69*
CO > FC	*48%*	*48%*	*52%*	*48%*	*71*
March	**50%**	**43%**	**109%**	**-9%**	**143**
FC > CO	*47%*	*30%*	*220%*	*-120%*	*55*
CO > FC	*51%*	*51%*	*49%*	*51%*	*88*
April	**51%**	**44%**	**85%**	**15%**	**143**
FC > CO	*49%*	*33%*	*148%*	*-48%*	*59*
CO > FC	*52%*	*52%*	*48%*	*52%*	*84*
May	**53%**	**47%**	**75%**	**25%**	**144**
FC > CO	*58%*	*43%*	*113%*	*-13%*	*61*
CO > FC	*50%*	*50%*	*50%*	*50%*	*83*
June	**54%**	**49%**	**70%**	**30%**	**142**
FC > CO	*60%*	*47%*	*105%*	*-5%*	*57*
CO > FC	*50%*	*50%*	*50%*	*50%*	*85*
July	**54%**	**49%**	**95%**	**5%**	**142**
FC > CO	*61%*	*50%*	*165%*	*-65%*	*57*
CO > FC	*49%*	*49%*	*51%*	*49%*	*85*
Grand Total	**53%**	**46%**	**85%**	**15%**	**854**

Table 8: Forecast accuracies at BL, from February 2018 to July 2018. The forecast accuracies are shown per month (numbers of the current and two previous months used). Per month, the accuracies are divided into two groups; where the forecast was larger than the customer orders (FC>CO) vs. forecasts lower than the customer orders (CO>FC). Looking at the forecast measure (1-MAPE), it can be seen that when the forecast is larger than the actual demand, the accuracy is valued with a negative number. The new forecast measurement (FCACC (New)) is also shown and negative MAPEs are not considered (set to 0%). It can be seen, that the previous measurement for the accuracy (FCACC), provides larger values.

just after the months end. Moreover, the forecast accuracy is measured on two different ways: for customers and on product groups. The customer specific forecast accuracy is also measured on product group level but specified for customers. Looking at the forecast accuracies for the from February 2018 to July 2018, the forecast accuracy using the MAPE[2], is on average around 15%, which is very low. The new measure for the forecast accuracy[3], provides the value of 46%, which is still better than considering the actual accuracy using MAPE, but gives a better image of the forecast incorrectness than the old measure. It can be concluded that the forecast accuracy is low.

B.6. Production Planning

Production planning is another department within the company. Their job is to align supply with demand. Since the production supply chain is large and complicated and production lead times are long, there is some uncertainty in supply. Minor disruptions in production, can lead to large effects in supply of end product.

As inputs for what should be produced, demand forecast, and customer orders are used. Moreover, customer programs, flex demand and safety stocks are used. Customer program (also VMI, Vendor Managed Inventory) are inventory locations at (important) customers, where specific types of product should always be available in agreed quantities. Flex demand is demand which is marked by marketing (or on other information) that there will be demand, although this is not observed in the forecast (yet). In that case, preparations are carried out to ensure the supply will be possible if the demand appears. From the perspective of slow moving and non moving inventory, this should also be done for products where the demand is low or is likely to disappear. Then, inventory levels could be adjusted for example. Currently, this is not done in practice. For safety stocks, demand is also created. As explained in section B.2, inventory levels can be defined in multiple ways. In case the inventory level is based on demand, demand for (semi-finished) products from the past week is used to determine the inventory levels. If these levels are higher than the actual number of (semi-finished) products in inventory, products must be produced for inventory (safety stocks).

Once a week, a production engine run is carried out. During the weekend, a production plan proposal is created by the production engine, considering all information mentioned above. One run is carried out, and this provides information on what products should be produced where to meet all demand. Then, another run is carried out, considering constraints (production capacities, priorities, stock settings, etc.). Then, the difference between the outcomes of those runs can be evaluated. This is done by production planning, production orders are sent out to the different production facilities. To start producing wafers, the Business Planner(s) should first agree on the proposal. Back-end is done without check.

During a weekly meeting, the S&OP-meeting (Sales and Operation Planning), the differences between the two runs are discussed for the current quarter and for the coming quarters. When (large) gaps exist between demand and possible supply and these are unwanted, actions must be taken. These can be of different kinds; yield improvements can be investigated, but these are often not possible within a short period of time. Capacity increases are often not possible since the lead times for capacity increase are longer and structural shortage in capacity is needed for getting approval for capacity increase. Finally,

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[2] $\text{forecast accuracy} = 1 - MAPE$ for every period. Then, these values are averaged over all product groups.

[3] $\text{forecast accuracy new} = (1 - MAPE)^{+}$ for every period. Then, these values are averaged over all product groups.

two options remain: not fulfilling demand (not delivering products) or pre-building. Pre-building is discussed in section B.7.

Once a quarter, the current inventory (mainly on slow moving and non moving inventory), is discussed. This meeting hosted by the production planning, and all relevant roles within the BL take part in the meeting.

B.7. Pre-building

Pre-building is defined as (early start) producing product to fulfill end product demand or safety stock levels, before needed considering only the production lead times. This can be done in the front-end and the back-end of production. Pre-building is not started automatically, it must be manually decided to start pre-building. Three reasons to initiate pre-building can be defined:

- Future production capacity is not sufficient at a certain location.
- Commit to contractual (minimum) loading of suppliers.
- *End of production line.*

In the first case, when the pre-building is not done, there is a high risk of not fulfilling demand. For example; the capacity needed to fulfill the (forecasted) demand three quarters from now, is not available then, but at this moment capacity is sufficient. In that case, it can be decided to start production for this product now to ensure supply in the future. However, it is possible the forecast is incorrect and the supply is still too short (forecast to low) or supply is too high (forecast to high). The decision needs to be made on these scenarios and consequences of these decisions. As stated in the previous section, others solutions to ensure supply in the future or to enable production postponing, are often not possible or too risky.

For the second case, pre-building is not done to fulfill future demand, but to use currently available production capacity. In case capacity needed at a certain (part of) a production process is lower than the forecasted and (contractual) reserved capacity, this capacity is unused (where it could be used for other production). When this capacity is at company-internal production facilities, production for other business lines could have been scheduled there, where capacities for those products is already gained somewhere else (possibly at third party). Therefore, capacity will be unused, which is undesirable. Moreover, from a strategic point of view, the capacities will not be (completely) reserved for the BL in the future (with the risk of ending up with capacity shortages). In the case the capacity is not reserved at company-internal facilities (but at third party), contracts for those capacities exists. In that case, when less capacity is used than agreed upon, financial penalties will have to be paid by the BL to those third-party companies. This is undesired since these costs are pure loss. On the contrary, is incorrect decisions are made and unsellable products are produced, this also leads to costs (production & scrapping).

In the third case, a production line will be (partially) shut down and no production of product is possible in the future. In that case, if there is still demand for that product, the choice can be made to pre-build as much as the demand prediction is for the complete product life cycle length for the product, possibly with some extra. In that case, the inventory will be large and is highly likely to become obsolete. However, when pre-building is not executed, selling the product is not possible and customers will complain. This pre-building can also occur ‘naturally’; if customers know a product is EOL (End of Life), then may buy more product to create inventory for themselves. The less extreme version of this third pre-built case, is when there is a temporary capacity shortage of a changeover in production line / location. In that case, the time with less or no capacity needs to be bridged.

When pre-building is done to prevent supply shortages in the future, the product which needs to be build is clear. When pre-building is done to prevent getting loading penalties, it needs to be chosen which products are produced upfront. These decisions are mostly made on gut-feeling by Business Planning, based on information of other people in the BL. In this case, products which are at that time produced in large quantities and where demand is present for a long horizon, will most of the time be chosen. An addition check by Demand Management is carried out. However, since the forecast horizon is longer than the actual production lead times, forecast accuracies are often low (the possibility on demand drops or change of product are high).

Pre-building can be chosen for all manufacturing stages. When loading of a factory is needed, loading that specific factory is important. Depending on inventories before and after that location, production of new wafers needs to be done. When pre-building is needed to prevent supply shortages at a moment in the future, production for that product (from waferstarts) needs to be done.

App. C. Extensive study on existing inventory

App. C. Evaluating existing slow moving and non moving inventory

In this section, the currently existing inventory will be reviewed. First, the total inventory levels will be reviewed. From there, the inventory composition will be explained. Then the causes for slow moving and non moving inventory are explained and the currently existing SNMI is reviewed, given the causes.

C.1. Evaluating existing inventory levels

Inventory will be present at different inventory locations in the supply chain, as stated in section B.2. Inventory targets are also set; however, targets are not always met (due to production priorities). As stated earlier, Inventory targets are set to have sufficient inventory to keep service levels higher than the target.

Looking at how much inventory would be healthy for the business (industry standards), it is known that for semi-conductor companies with own production facilities, 90 to 95 DIO (Days of Inventory Outstanding), would be healthy. Figure 1 shows the history of the DIO at the BL (actual inventories, not targets). As can be seen, this number is higher than desired. Important to note is that the DIO-calculation is a financial measure for inventory; it used the COGS (Cost of Goods Sold). Drawing conclusions directly from the DIO would be incorrect since current changes in COGS also drive changes in DIO. However, DIO can be used as a good indicator of healthiness in inventory.

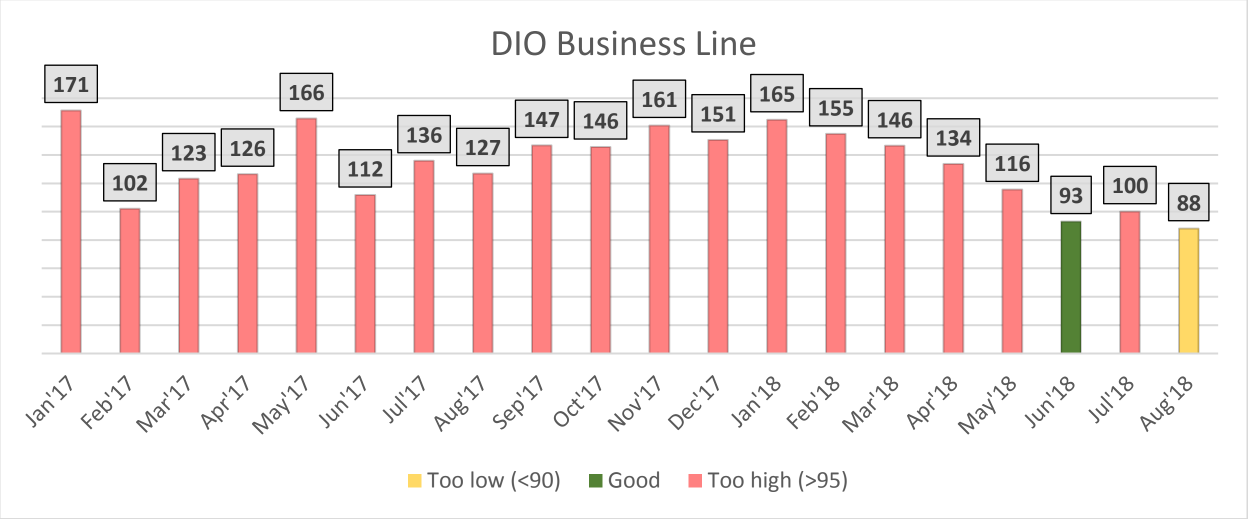

Figure 1: DIO-numbers for the Business Line from January 2016 up to August 2018, based on actual levels (not targets). Inventory too low (according to the benchmark) is depicted in yellow, inventory too high in red and correct levels in green. The value of DIO is put as a label to the bars.

Another measure used at the company is the Entitlement Model. This model creates a target inventory value per product, using different inputs (inventory targets, production lead times, orders and demand, etc.). Looking at the numbers for the BL, it is observed that the Entitlement Value was lower than the actual inventory value for almost the complete (known) history. The last two quarters in 2018, the Entitlement Value is larger than the actual value. This is due to sales which exceed forecasts and therefore, some capacity shortages occur and fulfilling demand is prioritized over building inventory. Moreover, the conclusion can be drawn (looking at the Entitlement Value together with the DIO), that inventory is too high, even if the inventory targets are incorrect since inventory targets are considered in the Entitlement Model.

C.2. Evaluating existing inventory structure / composition

As concluded in section C.1, at the BL, inventory levels are too high (looking at system settings and industry standards). Therefore, the conclusion could be drawn that the original business problem is not found in the inventory level targets and/or settings, although they appear to be not maintained and set in an efficient way. Some deeper evaluation of the inventory composition is needed.

To evaluate the inventory, three categories of inventory are created: Non moving, slow moving, and moving. The intuitive definition would be: inventory which is already there for a long time, inventory with a low run rate, inventory which is sold normally, respectively. However, within the company, there are other definitions for these categories:

- Non moving inventory: no demand for the product the next 22 weeks.
- Slow moving inventory: the weeks of supply on hand is larger than 26 weeks.
- Moving inventory: the weeks of supply on hand is smaller than or equal to 26 weeks.

Weeks of supply on hand (WksSOH) is calculated by using the following formula:

$$\mathrm{WksSOH} = \frac{Inventory}{average\ demand}$$

, where the $average\ demand$ is the average demand for the next 22 weeks. If the $\mathrm{WksSOH} = x$, this would mean (given the average demand), x weeks of demand can be fulfilled with the current inventories. When this value is below 26, the inventory is categorized as ‘Moving’. From the excess inventory point of view, no problem exists (very low inventories can be problematic, but this is not concerned with this approach). When the value is larger than 26 weeks, the inventory is categorized as ‘slow moving’. This means that there is a lot of inventory relative to the forecasted demand, and attention is required; the risk of becoming excessive is higher. For the last case, if there is no demand forecasted for the coming 22 weeks, the inventory is marked as ‘non moving’ (by using the formula for WksSOH, the value would be undefined because of dividing by zero, limit of average demand going to zero would result in infinite supply on hand). This means that the inventory is just there and will probably not be used the coming 22 weeks. When demand exists at a longer horizon, the inventory should be kept. This possibility is not included in the definition, but of importance for scrapping decisions. When there is no demand forecasted in the future, getting rid of the inventory (scrapping), should be considered. Although it seems logical to just leave it in inventory (since the product size, inventory does not consume much inventory compared to the value), however, products can age (and must be scrapped eventually), but also, it still consumes space which can be used for other products.

As stated in the introduction of the chapter, obsolescence costs are mostly the costs of scrapping products and writing off inventory. The current and historic inventory situation at the BL, considering different categories, is shown in Figure 2.

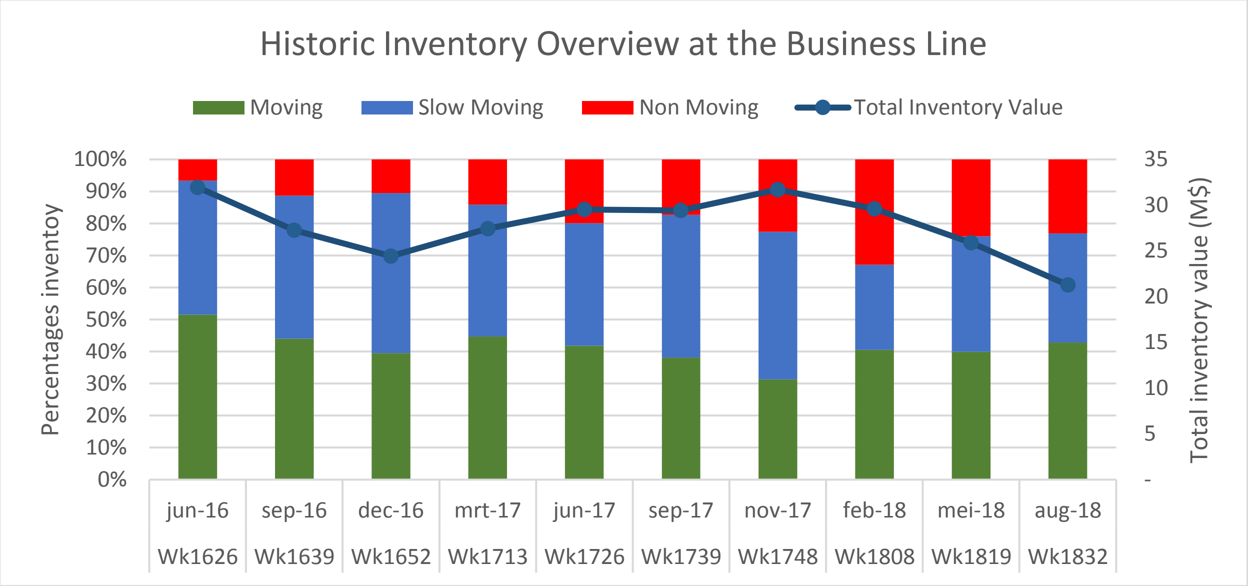

Figure 2: Historic view on inventory from Q2 2016 up to Q3 2018. The percentages Slow moving, non moving, and moving are shown (bars), as is the Total value of the inventory per period (line).

As can be seen, the fraction of slow moving and non moving inventory (SNMI) is large (about 60% of the total inventory). This means, that the 'healthy' (moving) inventory, is only 40%. Moreover, as can be read from the graph, the SNMI represents about 12 million Dollar(!) in August 2018.

Once a quarter, an Inventory Review Meeting is held at the Business Line. During this meeting, slow moving and non moving inventory is evaluated. Given the business characteristics, it is not uncommon to have slow moving or non moving inventory, this is a logical result on fluctuations in demand and the long lead times. However, quantities as observed in the BL are not healthy, particularly the products with large quantities. Therefore, to make the quarterly analysis concise and effective, SNMI is cut into two parts. The cut is made at 100 k$ ($100,000.00): products marked as slow or non moving, with a value of more than 100 k$ (including corresponding semi-finished products), are reviewed. This cut is justified for two reasons. Products with a value smaller than one-hundred thousand dollars, are not reviewed since these are no quantities of a significant size and are considered negative results of doing business. Moreover, the cut is roughly based on the 80-20-rule. Twenty percent of the end products (including related semi-finished products) cause roughly eighty percent of the slow moving and non moving inventory. In 2018 Q1, the products with a total inventory values larger than 100 k$ equals 71% of the total SNMI-value, by 13% of the products. The exact 80-20-cut would have been at 63 k$, however, from the business relevance point of view, these products (with a value between 100k$ and 63k$) are not relevant to look at. Figure 3 shows the Pareto Chart on the SNMI inventory levels in the first quarter of 2018, the products under the cut are grey, the products with a higher value are blue.

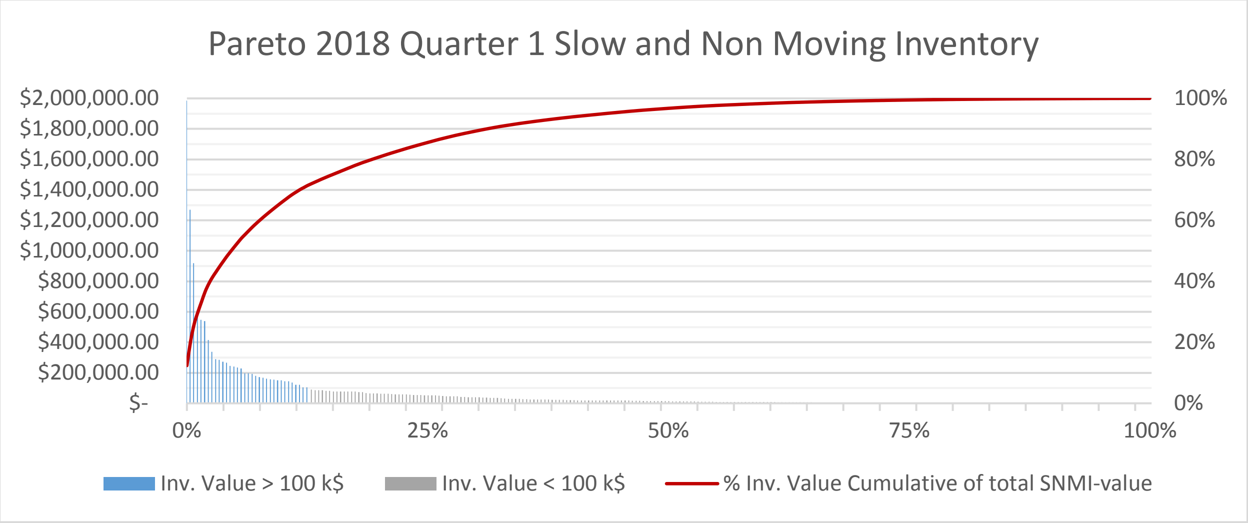

Figure 3: Inventory levels of Slow moving and Non moving inventory at the BL in the first quarter of 2018. On the horizontal axis, the different products (numbered, starting with the product with the highest value). The left vertical axis shows the value of all the products (marked as SNMI). The right vertical axis shows percentages, which defined the red/orange line. This line represents the percentage the cumulative inventory value represents of the total SNMI-value.

In 2018 Q2, the products above 100 k$ equals 15% of the products and represent 75% of the value (the top-20.5% products represent 81.7% of the tot SNMI-value). Finally, in 2018 Q3, products above the cut (13% of the products) represent 71% of the value. 20% of the end-products with the highest values, represent 80.5% of the total SNMI-value.

C.3. Causes for Slow moving and Non moving inventory and occurrences

As found in section C.2, slow and non moving inventory within the business line represents a large value. This value has a high risk of becoming obsolete, which than would become cost of non-quality.

In 2018, looking at the review moments from quarter one to quarter three, there are forty-one unique end-products with value larger than $100,000. For all these products, the reason of existence is searched for. The following reasons / causes appear as reasons for the occurrence for specific products:

1. *Cancelled Orders*
   When customer orders are present, production can start (from the CODP). When orders are cancelled after production start, this can lead to excess inventory. Not all customers have the same rights, but normally, customers can cancel orders within a certain time slot (e.g., until eight weeks before the delivery date).
2. *Large Demand Drop*
   Demand[4] can drop unexpectedly significantly. This can be due to poor forecasting, but often it is unavoidable since most of the demand information is based on input from the customer. Given the business environment (business to business) and industry characteristics (fluctuating demand and short product life cycles), demand is uncertain, also for customers. This results sometimes in large demand fluctuations; where demand increase results in no supply (and poor service levels) and demand drops in SNMI. Therefore, this is marked as cause for SNMI.

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[4] Here, with *Demand* is meant: actual demand (customer orders) and forecast.

3. *Personal Mistakes*
   As explained in section App. B, production orders are created by and inventory targets are set by Production Planners. This means mistakes can be made (a wrong product is ordered or inventory levels are set too high).
4. *Prebuilt (Loading Commitment)*
   As explained in B.7, pre-building can have different reasons. One of the three reasons is loading factories (using capacity) since this is agreed upon. This to prevent financial penalties. When products are produced (when no orders are present), it is possible that no orders will come (due to different reasons) and product end up as SNMI.
5. *Prebuilt (No Loading Commitment)*
   As explained in B.7, pre-building can have different reasons. Another reason than *cause 4*, can be that a capacity shortage is expected in the future. To secure supply, production must be started earlier, when no orders are present. Since this is a temporary inventory built-up, demand drops are possible and products will end up as SNMI.
6. *Ramp-Up*
   When new products are designed, it is unknown what the customer demand will be exactly. Most of the times, products are sold, however, it is possible that no products will be sold (the product doesn't serve a need anymore). In that case, the products produced to sell from introduction, cannot be sold, end up as non moving and will be scrapped eventually.

Important to note: three main reasons for pre-building are mentioned in section B.7 and only two are mentioned in the list above; pre-building because of closing a production line is not mentioned. This is because these pre-building products are not incorporated in the normal inventory reviews and will not appear on the list of slow moving and non moving inventory. The value of the inventory represented by this cause is stated later in 0.

Not all the causes occur equally often. Table 9 provides more insights in the number of occurrences of the cause. As can be seen; cause two (Large demand drop) occurs often compared to the causes. Then, prebuilding occurs often: in 49% $(= 27\% + 22\%)$ of the occurrences of SNMI with a value higher than 100k$, prebuilding was the cause.

Table 10a shows the number of times causes occur together. In

Table 10b, the percentages of occurrences of combinations of causes is shown.

Table 10b shows the unconditional percentages: the percentage of two causes together given the number of products.

Table 10c shows the conditional occurrences. So; in $Z\%$ of the cases, when cause x occurs, cause y occurs also.

Table 10 shows that Personal Mistakes is a standalone cause (is never combined with other causes). Moreover, cause 1, 4, and 5 always occur in combination with (an) other cause(s). Cause 1 always occurs with a large demand drop, the same goes for cause 5. Cause 5 is also combined with cause 2 and 6, once. Cause 4 occurs most of the times with cause 2, but also once with cause 6.

Table 9: Occurrences of different causes. Of the 41 different products with a value higher than 100k$, the different causes are linked a couple of times to products (number of occurrences). Moreover, the percentage is provided.

Cause	Cancelled Orders (1)	Large Demand Drop (2)	Personal Mistakes (3)	Prebuilt (LC) (4)	Prebuilt (NLC) (5)	Ramp-Up (6)

Number of occurrences	1	34	3	11	9	6
Percentage of total	2%	83%	7%	27%	22%	15%

Table 10: Occurrences of two causes combined, in percentages. Table (a) provides the number of occurrences together. Table (b) provides the percentage of the total product that a combination of causes occurs (for example: for 2.5% of the products, cause 1 & 2 are the cause). Since the table is symmetrical (1&2 is the same as 2&1), table (c) is only shown half. Table (b) provides the same numbers, however, the point of view is from the cause in the left column. (For example: for cause 1, all the occurrences (100%) are together with cause 2, where for cause 2, cause 1 occurs only in 3% of the cases.). This table is asymmetrical, and therefore shown completely.

(a) Number of occurrences

	1	2	3	4	5	6
1		1	-	-	-	-
2			-	10	9	3
3				-	-	-
4					-	1
5						1

(b) Unconditional percentage

	1	2	3	4	5	6
1		2.44%	0.00%	0.00%	0.00%	0.00%
2			0.00%	24.39%	21.95%	7.32%
3				0.00%	0.00%	0.00%
4					0.00%	2.44%
5						2.44%

(c) Conditional percentage

	1	2	3	4	5	6	*Sum*
1		100%	0.00%	0.00%	0.00%	0.00%	*100%*
2	2.94%		0.00%	29.41%	26.47%	8.82%	*68%*
3	0.00%	0.00%		0.00%	0.00%	0.00%	*0%*
4	0.00%	90.91%	0.00%		0.00%	9.09%	*100%*
5	0.00%	100%	0.00%	0.00%		11.11%	*111%*
6	0.00%	50.00%	0.00%	16.67%	16.67%		*83%*

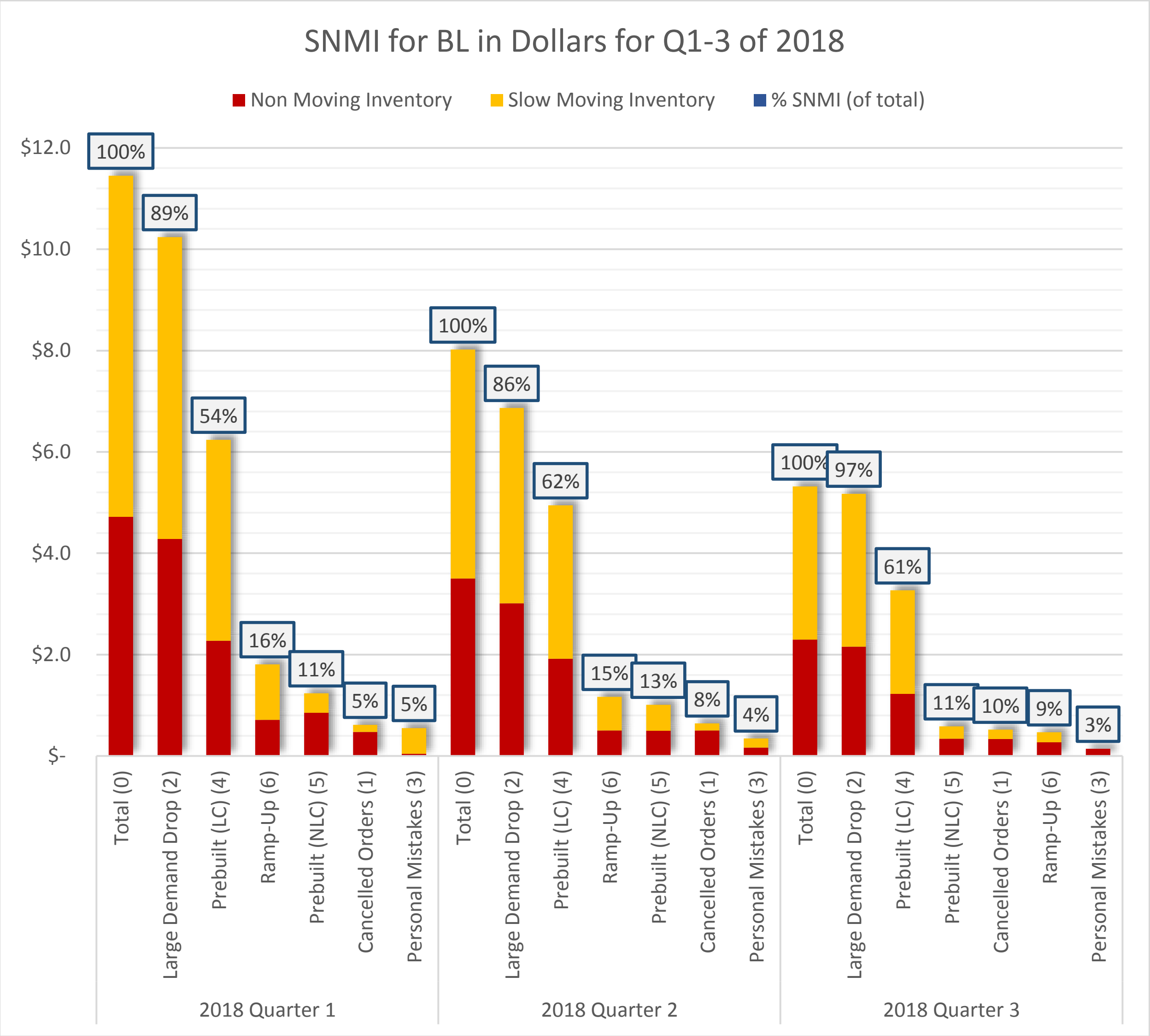


Figure 4: Slow moving and non moving inventory value per end product larger than $100,000, liked to the different causes. On the horizontal axis, quarter one to three of 2018 are shown. In red, the non moving value is shown. In yellow, the slow moving value is shown. Moreover, per cause, the percentage the cause represents of the total value per quarter is shown, depicted above the bars. Per quarter, the total value (number 0) is shown. Then, the value represented per cause is shown, sorted from largest (left) to smallest (right) sum of slow moving and non moving inventory. The numbers with the causes refer to the list of causes with explanation earlier in this section. The values (and percentages) of different causes do not add up to the total value since inventory can be caused by multiple causes and the inventory is considered multiple times. Moreover, it can be notices the total value of slow moving and non moving inventory decreases over the year 2018; it almost halves.

Slow and non moving values per cause

In Figure 4, for quarter one to three of 2018, the value of the SNMI (larger than $100,000), the value per reason is shown; separated in slow moving (SMI) and non moving inventory (NMI). As can be seen, cause two (‘Large Demand Drop’) is linked to most of the value of SNMI, throughout the three quarters. Then, Prebuilt due to Loading Commitments (Prebuilt LC, cause 4) is throughout all quarters the second largest part. Prebuilt, but not for Loading Commitments (Prebuilt NLC), represents also a large value, however, Ramp-up (cause 6) is larger in quarter one and two. The other causes (Personal mistakes (3) and Cancelled orders (1)) are the minor part of the SNMI with a combined value of around $550,000 NMI and around $380,000 SMI.

As stated in section C.3, one cause (prebuild parts because it is not included in the normal Slow moving and non moving review. This is done since this inventory is different from others; since the cause is different and nothing can be changed anymore: no product can be produced since the production line or facility is not there anymore. When a transfer from one production line to another is done, this will be viewed as a temporary capacity restriction (prebuilt product; cause 5).

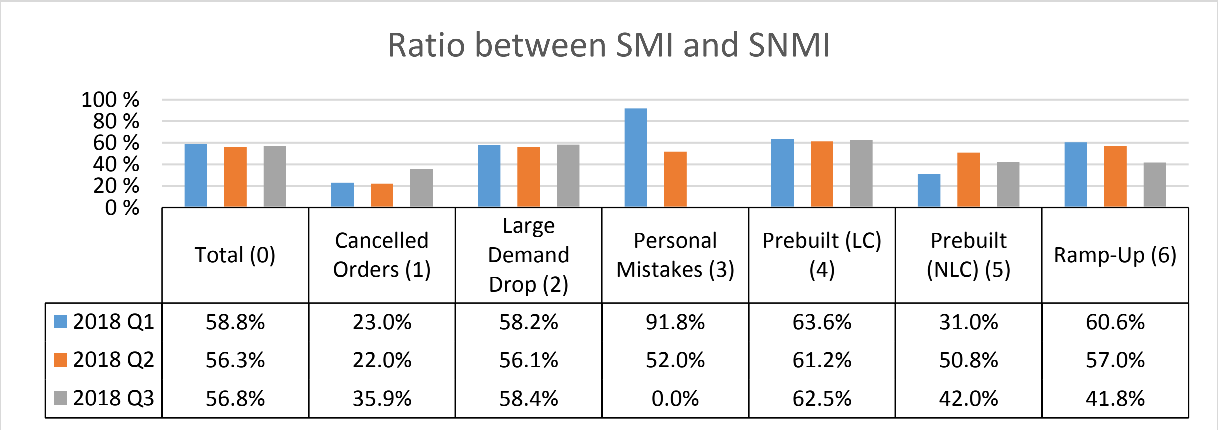
In Table 11, the value of the inventory created by prebuilding because of a production line closure is shown. Here, one can see that the inventory is quite high (4.3 M$ in 2018Q3), but this is a lot lower than the created value in 2013 (when the facility is closed) which was 25 M$. From this it can be concluded, that is was a wise decision to do a prebuild of such volumes. Not the least because there is still some inventory which is moving and there still is demand.

Table 11: Moving, Slow moving, and non moving inventory values due to prebuilding because of closing a production line. As can be seen, the value of the moving value is significantly lower than slow moving and non moving inventory. This is logical, since it withholds products produced in a facility which is closed in 2013. In 2013, an inventory of 25 Million Dollar is built, and in 2018 Q3, this was down to 4.3 M$. The product will not be scrapped, however, financially, the products is already written down because of the age. The product will not be scrapped since there is not option to produce again, and additionally because there is still (low) demand.

	Moving	**Slow Moving**	**Non Moving**	**Total**
2018 Q1	$ 7,030	$ 359,884	$ 4,810,987	$ 5,177,901
2018 Q2	$ 161,361	$ 3,386,873	$ 1,453,398	$ 5,001,632
2018 Q3	$ 176,331	$ 2,973,496	$ 1,190,557	$ 4,340,384

Ratio between slow and non moving inventory per cause

For all the causes, the ratio between slow moving inventory and non moving inventory is shown in Figure 5. As can be seen, the ratio between slow moving and non moving inventory is quite constant through the quarters. This is explainable since the ratio for cause two (large demand drop) is also quite constant and this cause represents a large part of the inventory. Moreover, is can be noticed that the ratio for cause one, is low: cancelled orders result (often) in non moving inventory. Also cause three (personal mistakes) stands out; this one evolves very clearly from slow moving for the larger part (quarter one) to non moving in quarter three. This seems logical, since due to a personal mistake, too much product is produced, where there is not enough demand over the complete horizon. The other



	Total (0)	Cancelled Orders (1)	Large Demand Drop (2)	Personal Mistakes (3)	Prebuilt (LC) (4)	Prebuilt (NLC) (5)	Ramp-Up (6)
2018 Q1	58.8%	23.0%	58.2%	91.8%	63.6%	31.0%	60.6%
2018 Q2	56.3%	22.0%	56.1%	52.0%	61.2%	50.8%	57.0%
2018 Q3	56.8%	35.9%	58.4%	0.0%	62.5%	42.0%	41.8%

Figure 5: Ratio between Slow moving inventory and Non moving inventory, calculated by dividing the slow moving inventory value by the total slow moving and non moving value. As can be seen, the ratios are provided per quarter, sorted per cause.

ratios are quite constant: a bit more than half of the total slow and non moving inventory, is slow moving.