MASTER

Improving the Maintenance Scheduling Strategy at Bosch Transmission Technology

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Improving the Maintenance Scheduling Strategy at Bosch Transmission Technology

Master's Thesis

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All data in this thesis is scaled or normalized and meant to visualize results. No data is representative for information of Bosch Transmission Technology.

Abstract

Production locations with long production lines and highly dependent machinery have very rigid planning opportunities for preventive maintenance. The goal of this thesis was to provide companies with a case-study on how to improve maintenance scheduling based on production volume in production settings with high number of machines that are dependent on one another. Maintenance planning must consider production requirements and mechanic man hours capacity. So a mathematical model was developed to optimize maintenance planning over maintenance costs, holding costs, and demand penalty costs. The output of the mathematical model strongly suggests to use overcapacity of production time to execute maintenance tasks as close to their deadline as possible. The mathematical model can be used to investigate performance of production and maintenance requirements based on mechanic capacity and demand forecast.

Executive Summary

This master's thesis has been conducted at Bosch Transmission Technology in Tilburg. The company produces pushbelts for the continuously variable transmission primarily for Asian car brands. Bosch Transmission Technology is at a crucial point in their business with scaling up new business and decreasing demand for pushbelts. As a result utilization of production equipment is decreasing and an improved maintenance scheduling strategy is needed to decrease maintenance expenditures and improve maintenance fit to current production volumes. Within the loop factory, MSE2, long production lines with highly dependent machinery produce loops continuously. Currently, maintenance is executed in a strict four-weekly time interval planning, causing inflexibility in maintenance planning, highly fluctuating mechanic man hours demand, and inefficient maintenance frequency for individual machines. A shift to flexible planning might be a better fit with current production volumes. Therefore, the following main research question has been proposed:

How to improve the maintenance scheduling strategy for MSE2 in terms of total maintenance costs?

The goal of this thesis is to provide companies with highly dependent machines in production lines with a case-study on how to schedule maintenance. The research consists of several steps to answer the main research question. First, the problem has been investigated and defined. It showed that the maintenance frequency does not move with production volume and that demand for mechanic man hours is highly fluctuating over time. Secondly, a literature study has been conducted on maintenance planning, production planning, and dependent production steps to study current knowledge in the field of maintenance planning with highly dependent machinery. Thirdly, a data analysis has been performed to identify the gap between current maintenance frequency and the potential maintenance frequency if another maintenance scheduling strategy would be adapted. This has been done by setting maintenance standards based on maximum production volume and reflecting current production volumes upon the standards. Fourthly, a deeper understanding of the production lines at Bosch TbP is gained to investigate how a new maintenance scheduling strategy needs to be designed. The relation between production and maintenance has been investigated. This has lead to the conclusion that volume based maintenance scheduling potentially improves maintenance scheduling strategy significantly. Finally, a mathematical model has been developed to identify the theoretical improvement of a maintenance scheduling strategy based on production volume. This model includes the relationship between production line availability, maintenance requirements, and mechanic man hours capacity. The model optimizes total costs considering production requirements. The costs to optimize over are maintenance task costs, holding costs, and demand penalty costs. An analysis has been performed on different scenarios in the model. These scenarios include variable mechanic man hours

capacity, variable maintenance deadline margins, and variable production forecast. This analysis is used to answer the main research question.

The mathematical model is used to compare production volume dependent maintenance scheduling strategy with current maintenance scheduling strategy using forecasted demand for 2023. The scenario of no mechanic man hours constraint and no deadline margin is compared with current maintenance scheduling strategy in Table 1.

Table 1: Model output for infinite capacity and margin of 0.0%

Scenario	**Current strategy for 2023**	**Model output for 2023**
2023 maintenance costs	100.00 €	89.27 €
2023 holding costs	N.A.	1.75 €
2023 penalty costs	0.00 €	0.00 €
Number of activities	144	107
Percentage of deadline	76.7%	98.0%
Days left	11.5	1.3
Unique days	25	47
Unique moments	40	71
Mean number mechanics	3.9	1.8
Man hours	626	501
Downtime (h)	104	178

This results in a decrease in maintenance costs of 10.7% in 2023, caused by executing maintenance activities further towards their deadline. In current maintenance scheduling strategy maintenance activities are executed at 76.7% of their deadline, while the mathematical model proposed a maintenance planning with a maintenance deadline of 98.0%. This means that at the moment of execution of each maintenance task it is not due for 11.5 days using current maintenance strategy, which decreases to 1.3 days using the mathematical model. The decrease of maintenance costs for 2023 is 10.7% while the number of activities decreases with 25.7% and the percentage of deadline increases with 21.3%-points. The difference between decrease in costs and decrease in maintenance activities is caused by the highly differing costs of different maintenance tasks. The number of maintenance activities is divided more equally over time, so this gives a better representation of potential improvement. It is expected that the average yearly maintenance costs will decrease with up to 28%. The model showed that when forecasted demand is between 10% lower and 10% higher than the 2023 forecast, average yearly maintenance costs will decrease between 17% and 40% compared to current maintenance scheduling strategy.

Additionally, the highly fluctuating demand for mechanic man hours drastically decreased. During maintenance execution moments, current maintenance strategy requires 3.9 mechanics to work on maintenance at the same time on average whereas the model requires only 1.8 mechanics to work on maintenance at the same time on average. This indicates that less mechanics are needed throughout time, so there is less overcapacity during times of few maintenance activities as well as there is no need to hire external mechanics during periods of high demand for mechanic man hours. Furthermore, demand penalty costs are equal to 0.00 € in all scenarios, which corresponds to Bosch Transmission Technology's priority for customer demand satisfaction. It is not allowed to satisfy customer demand too late. Moreover, the inventory of finished goods has been researched. The model showed that inventory only builds up before maintenance activities. This is to satisfy customer demand during times of less production capacity. So the model builds inventory to satisfy demand timely, which corresponds to the priority for customer demand satisfaction. A point of attention for production capacity and planning is the downtime. In current maintenance strategy planning, yearly downtime is 104 hours. The model proposes a production and maintenance planning resulting in 178 hours of downtime per year. This means that production capacity decreases which may be undesirable. However, this is not necessarily bad in the case of production overcapacity. The maintenance tasks are executed close to their deadlines because there is enough production capacity to spread maintenance tasks over time. There is less time for maintenance task execution if there is more customer demand. This will cause the mathematical model to group the maintenance tasks more to reduce downtime of the production line, which leads to less downtime.

Concluding, the yearly maintenance costs and mechanic man hours demand fluctuation decreases significantly when shifting to a volume based maintenance scheduling strategy. Yearly maintenance activities have decreased from 144 to 107 and the number of maintenance moments increased from 26 to 71. So there are less activities executed spread out over more moments. Moreover, maintenance is executed almost at the due date, which is at 98.0% instead of the 76.7% that the current strategy achieves. Therefore, the recommendation to Bosch Transmission Technology is to adapt to the mathematical model and shift to a volume based maintenance scheduling strategy. The mathematical model can be used to determine the optimal number of mechanics needed depending on production forecast.

Preface

This thesis marks the end of my life as a student. It has been a unique experience to have studied at Eindhoven University of Technology for the past six years. First, as an Industrial Engineering Bachelor student and later as an Operations Management and Logistics Master student.

I want to thank my colleagues at Bosch TbP for the opportunity to execute this thesis in such an interesting company. It has been a great pleasure working with you. Jan, thank you for your help and advise during the project. Also I want to thank Nico and Claudia for their academic guidance and critical view on my project. Special thanks to Nico for always responding so quickly to my questions, no matter the day or time.

Finally, many thanks to my family. Mom and Dad, thanks for always supporting me in my decisions and pushing me to be the person I am today. Gijs and Dirk, thanks for distracting me from the thesis stress now and then. And Gijs, thanks for lending me your super fast laptop when I had some time issues.

List of Abbreviations

Abbreviation	Definition
Bosch TbP	Bosch Transmission Technology Tilburg Plant
CVT	Continuously Variable Transmission
MFE	Manufacturing Engineering department
MFM	Manufacturing Maintenance department
MFO	Manufacturing Operations department
MPS	Master Production Schedule
OOE	Overall Operations Effectiveness
POT	Planned Production Time
SLA	Service Level Agreement

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Chapter 1

Introduction

This chapter encompasses the introduction to the master's thesis conducted at Bosch Transmission Technology. First, the thesis outline is explained, after which a short description of Bosch Transmission Technology and its product is given. Then, the production plant in Tilburg and its characteristics is described. Finally, the focus area of the production plant and the maintenance scheduling strategy are introduced.

1.1 Thesis outline

This section describes the outline of this thesis. In the first chapter, an introduction to Bosch Transmission Technology, the push belt, and their production facility in Tilburg is given. The second chapter introduces the problem and defines the research questions. The third chapter provides a condensed version of the literature review. Then, the fourth chapter contains the data analysis of production volumes after which the fifth chapter explains production and maintenance dependencies. Chapter 6 introduces and explains the mathematical model used for the analysis of the model output in Chapter 7. Finally, Chapter 8 concludes the thesis and provides recommendations to the company.

1.2 Company description

This master's thesis project has been conducted at the Manufacturing Engineering department at Bosch Transmission Technology (Bosch TbP) in Tilburg. This company produces push belts primarily for Asian car brands. Bosch Transmission Technology's headquarters is located in Tilburg and is supported by a manufacturing plant in Ho Chi Minh City in Vietnam. It is part of the Bosch group, a leading supplier of technology and services worldwide. The Bosch Group employs more than 400,000 employees and generated a revenue of 78.7 billion euros in 2021 in four business sectors; Mobility Solutions, Industrial Technology, Consumer Goods, and Energy and Building Technology (BoschGroup, 2022). Bosch TbP is part of the Mobility Solutions group.

1.3 Product description

A push belt is a core component of the continuously variable transmission (CVT), which is an automatic transmission that can operate through a continuous range of gear ratios, allowing an engine to operate with constant rounds per minute while the vehicle operates at varying speeds. A push belt rotates between two pulleys consisting of two conical sheaves located on the input and output shaft to adjust the running radius of the push belt based on speed and torque (BoschGroup, 2022). The CVT is able to put the optimal ratio of required torque to engine speed at all times, thereby reducing fuel consumption and CO_2 emissions. A push belt transfers torque from the engine to the drive axle, which is why it is a key component of the CVT.

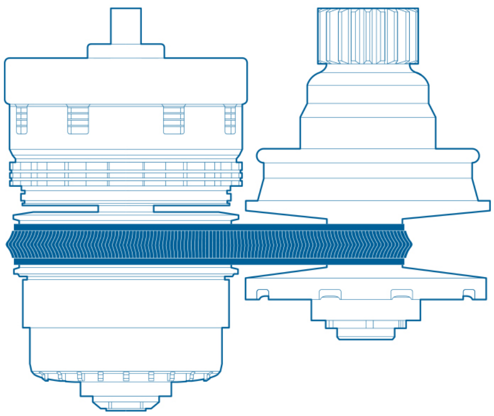

Figure 1.1: Location of push belt in a CVT (BoschGroup, 2022)

Figure 1.1 shows how a push belt is located in a CVT. A push belt consists of steel elements and two sets of high-alloy rings. The combination of these elements and sets of rings make the push belt an extremely robust product that can transmit over 450 Nm of torque optimally from the engine to the drive axle. Figure 1.2 displays a cross-cut of the push belt to show how the elements and sets of rings are placed between the pulley sheaves.

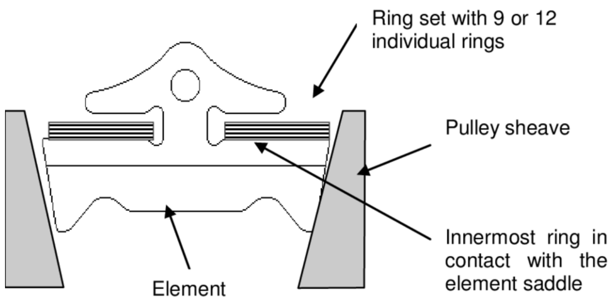

Figure 1.2: Push belt cross-cut (Pennings et al., 2005)

1.4 Production plant

Bosch TbP consists of three production areas, called MSE1, MSE2, and MSE3. Each production area has its own responsibility, being steel element production, ring package production, and assembly. MSE1 and MSE2 are independent from one another regarding production. Downtime in MSE1 does not cause delays in production in MSE2 and vice versa. These general production areas are visualized in Figure 1.3. Obviously, production volumes of MSE1 and MSE2 need to be aligned, which is a dependency. However, this is outside the scope of this research.

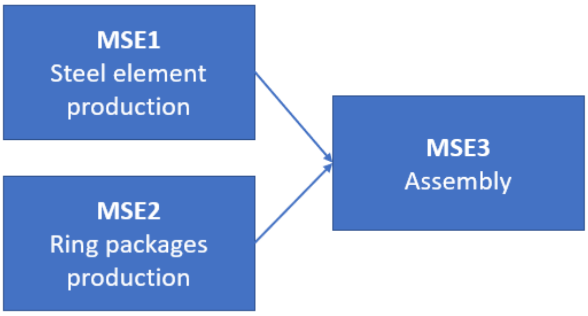

Figure 1.3: Manufacturing areas Bosch Transmission Technology

Maintenance on machines in MSE1 is roughly independent between machines. Every step in the process is decoupled from the next, meaning that production steps can be put on hold for an amount of time to maintain a machine if buffers are used correctly, which is also the case for MSE3. However, MSE2 is designed differently. Its production process is highly automated and the products move through the process without going into buffers. There are transport belts between most production steps, which function as small buffers between machines. In practice, this means that machines can be down for maximally 15 minutes before other machines experience line stops. Some production steps already cause a line stop at other production steps if it is down for 15 seconds. Hence, machinery in MSE2 is heavily dependent on one another regarding productivity. Although the production department wants to use production time as efficient as possible, it experiences significant delays due to maintenance activities. This shows the conflicting interests within the production department. Preventive maintenance ensures production with limited machine failures, while consuming production time. The research is focused on the MSE2 production area.

1.5 MSE2

The MSE2 production process produces loop packages and starts with cutting high-alloy metal sheets. Then, these sheets are bent like a pipe after which they are washed. After washing, the pipes are weld and they undergo an annealing procedure. Thereafter, the pipes are cut into parts that look like small rings. To remove burrs, the small rings are tumbled after which they need to be washed. Then, the rings are rolled so they transform into loops and washed again, whereafter the loops are annealed and calibrated. After this, the loops are loaded into racks to transport through the hardening and nitriding process. The loops are unloaded and their size is measured. Then, the machine selects loops that fit in each other perfectly to form a package, after which an inspection is performed to check for irregularities. Concluding, the production process in MSE2 consists of 17 production steps.

There are over 200 machines divided over three production lines within the MSE2 production department. The cutting, bending, pipe washing, welding, and annealing production steps form the pipeslines and remaining production steps are called the 'loop lines'. These loop lines can operate independently and do not need to produce the same type of loopsets. A global overview of the MSE2 production department is visualized in Figure 1.4. Pipesline 1 produces pipes for Loop Lines 1a and 1b, while Pipesline 2 produces pipes for Loop Lines 2a, 2b, and 3.

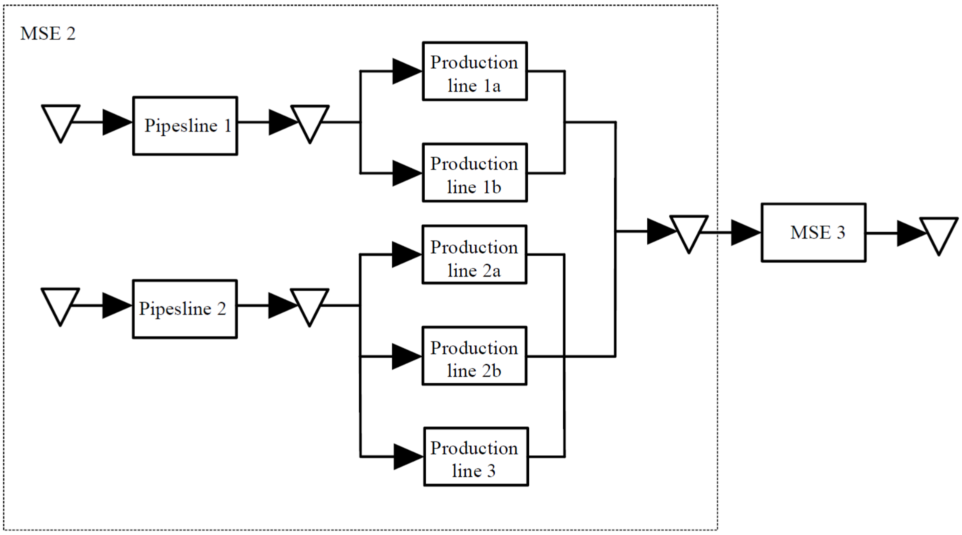

Figure 1.4: Global overview MSE2

1.6 Current maintenance strategy

All machines in the production department are maintained by the Manufacturing Maintenance department (MFM). MFM maintains the machines based on maintenance requirements provided by MFE. These maintenance requirements are called 'stamkaarten' and are to be executed according to a service level agreement (SLA), which describes the number of needed mechanic man hours per maintenance interval. For every individual production step, MFE and MFM agree upon an SLA.

The maintenance requirements for a machine are divided into activities to be executed in time intervals of multiples of four weeks. The choice for maintenance tasks to be divided into a certain fixed-time interval is done by engineers based on experience and machine information. The scheduling of maintenance tasks is designed such that it is easy for maintenance planners to schedule preventive maintenance 6 weeks ahead. For example, a machine can have maintenance activities to be completed every 4 weeks, 12 weeks, and 24 weeks. Some maintenance tasks can only be executed if a machine is down, causing a line stop. To schedule preventive maintenance and its potential line stops easily, 4-weekly maintenance must be scheduled at the same time as 12-weekly and 24-weekly maintenance. To illustrate, a global overview of such maintenance schedule for a machine is visualized in Table 1.1, in which X denotes 4-weekly maintenance, Y denotes 12-weekly maintenance, and Z denotes 24-weekly maintenance. It is noted that workload for the shorter time intervals is also executed at the larger time intervals. Therefore, workload for the maintenance department is fluctuating and experiences peak demand when large time-interval maintenance is due. Moreover, the complete production line causes higher peaks in maintenance demand. This is because all machines in a production line are maintained during the same shift every four weeks.

Table 1.1: Visualization preventive maintenance schedule for a random machine

Week	**4**	**8**	**12**	**16**	**20**	**24**
4-weekly	X	X	X	X	X	X
12-weekly			Y			Y
24-weekly						Z
Total	X	X	X + Y	X	X	X + Y + Z

The current maintenance strategy has advantages in terms of ease of planning. The maintenance planning can be anticipated for timely as every activity is known to be executed in a fixed-time period. Maintenance capacity can be planned ahead, spare parts can be purchased in time, and production can be scheduled accordingly. Concluding, the maintenance planning is very straightforward and all necessary planning activities can be aligned timely. However, current maintenance strategy also has disadvantages. As shown in Table 1.1, maintenance activities for a machine are fluctuating causing peak demand for mechanics over time. Therefore, the maintenance department needs to be extremely flexible in terms of capacity to be able to execute all planned maintenance activities. Additionally, maintenance activities do not adjust to production quantity. This means that maintenance planning assumes a constant production rate, which is not always the case. Hence, maintenance activities might not match the degree to which machinery is deteriorated. Therefore, preventive maintenance on machines may be too extensive and parts are replaced too early. If maintenance is too extensive, maintenance costs for Bosch TbP are unnecessarily high due to mechanic man hours as well as spare part purchasing costs. Moreover, maintenance activities lead to loss of production time, which influences the production department's capacity. Concluding, the advantages of current maintenance strategy are the ease of planning and the ability to anticipate for maintenance planning timely. However, the disadvantages are peak demand for mechanics and too extensive maintenance efforts.

Chapter 2

Problem Definition

The first step in the problem solving cycle as defined by Van Aken & Berends (2018) is to compose a problem definition, which is presented in this chapter. Subsequently, the problem setting is provided, which includes an extensive explanation of the current situation at Bosch. Thereafter, the problem is visualized and validated using data. Then, the scope of the research is defined, after which the research objective and corresponding research questions are listed.

2.1 Problem setting

Production of push belts is a core activity at Bosch TbP and its demand used to be very high ensuring full utilization of the production lines. Demand for push belts decreased and part of the production is relocated to the manufacturing plant in Vietnam, which brings new types of challenges to the manufacturing plant in Tilburg. One of these challenges is maintenance planning.

Production used to be running continuously at full capacity and preventive maintenance was planned in fixed-time intervals. Currently, production is running only 6 days per week and the speed of production lines can be adjusted to obtain necessary capacity to meet demand. Hence, machinery is loaded less heavily compared to past situation so less maintenance might be needed. However, preventive maintenance planning strategy has not changed. As explained in Section 1.6, maintenance activities are divided into multiples of four-weekly maintenance requirements. The maintenance requirements were set based on production quantities when production used to be running at full capacity. Currently, the maintenance planning has not changed while production time as well as production quantity decreased. Hence, production quantity during preventive maintenance intervals decreased, which is why maintenance is presumed to be too extensive for current production schedule. One would presume maintenance is to be performed according to maintenance needs, thus performing maintenance as late as possible while the machine is still operating within specifications. In general, one would expect that maintenance efforts move with production volume but this is not the case at Bosch TbP when using current maintenance planning strategy.

As discussed in Section 1.6, MFM experiences highly fluctuating demand for preventive maintenance hours. This is undesirable as this causes MFM to have ample capacity during periods of low demand for preventive maintenance hours and a shortage of capacity during peak demand periods for preventive maintenance hours. To cover maintenance demand during peaks, external mechanics are hired. Hiring of external mechanics is more expensive than internal mechanics. Moreover, during periods of low maintenance demand, there is ample capacity which needs to be paid for as well. Therefore, preventive maintenance planning is preferred to be levelled over time to be able to avoid periods of over- and undercapacity. As explained in Section 1.6, maintenance activities for a machine are always combined. Additionally, when maintenance activities cause a line stop, as many machines as possible on that production line are maintained at the same time. Therefore, a peak of demand for mechanics is usually dedicated to one production line. This means that other production lines are still in operation and are subject to unexpected failures. If such failures happen, corrective maintenance is required but the mechanics may be occupied by preventive maintenance activities of the production line undergoing maintenance to ensure this production line is running as soon as possible. Hence, these peaks in demand may extend the time until a mechanic can perform corrective maintenance on another production line. This means that current preventive maintenance strategy might unintentionally cause production lines to experience longer line stops due to failures.

Concluding, the problem setting for the maintenance strategy at Bosch TbP is twofold. Firstly, maintenance activities are not aligned with machine deterioration, so maintenance activities do not move with production volume. Secondly, demand for mechanics is highly fluctuating, which is undesirable for capacity reasons. Additionally, it might increase the risk that other production lines having unexpected break downs cannot be maintained due to insufficient available mechanics. So utilization of machines decreased while maintenance efforts have not changed so maintenance is executed earlier than necessary. Also, a decrease in utilization of machines reduces the necessity to minimize total downtime.

2.2 Problem validation

To validate the problem, an initial data analysis is performed. Section 2.1 indicated that the alignment between production and maintenance volume is non-existent, which is analyzed first. Then, the highly fluctuating demand for mechanics is analyzed. For both problems, the planned preventive maintenance hours of MSE2 for the period January 2021 to September 2022 are used.

First, the alignment between production and maintenance volume is analyzed. As discussed in Section 2.1, Bosch TbP presumes maintenance activities are too extensive for current production schedule. The ratio of production output and planned maintenance hours visualizes relative efforts in maintenance activities compared to production volume. It shows the extend to which preventive maintenance is moving with production output. If the number of produced loops per maintenance hour is fairly stable over time, maintenance efforts move with production quantity. Figure 2.1 shows how many loops are produced for each planned hour of work by MFM. Note that planned maintenance hours actually contain actions for MFM to execute, thus are not postponed due to production numbers. As MFM has agreed upon SLAs with MFE to maintain machines, they are obliged to do so. Therefore, planned maintenance hours provide an accurate estimation of actual maintenance hours.

The number of loops produced for each hour of planned preventive maintenance is fluctuating over time. In quarter 2 of 2022, production of loops decreased significantly due to global supply chain issues caused by China's lockdown. The graph in Figure 2.1 shows that the produced loops per maintenance hour decreased significantly too so the planned maintenance activities did not adjust to production quantities. Ideally, maintenance efforts move with production quantities to avoid maintaining the production lines too extensively and replacing parts too early. Therefore, the graph in Figure 2.1 should be fairly horizontally over time.

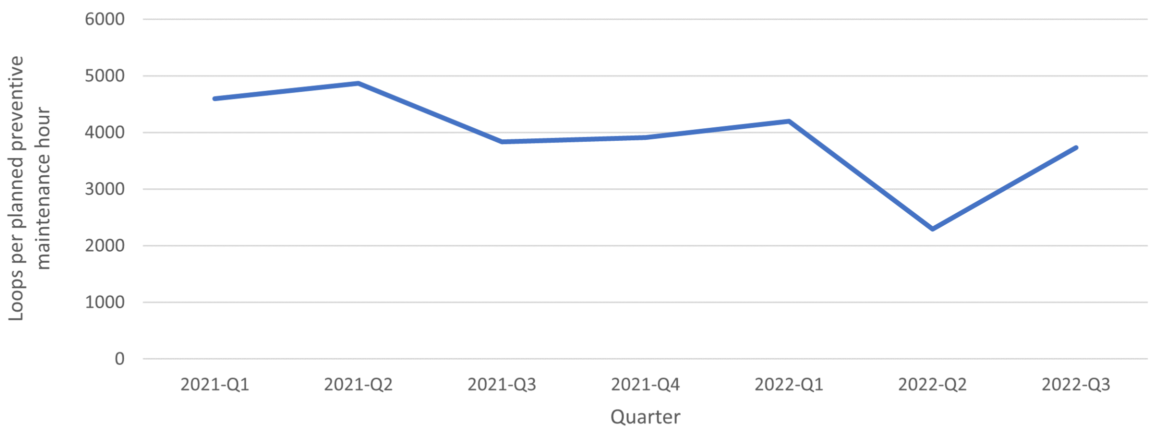

Figure 2.1: Number of loops produced divided by planned maintenance hours over time

Secondly, the fluctuation in demand for maintenance hours is analyzed. As explained in Section 2.1, MFM experiences high fluctuation in demand for maintenance hours. This pressures maintenance capacity heavily during these peak demand periods. The planned preventive maintenance hours are visualized in Figure 2.2 and show a four-weekly pattern in which highs and lows are succeeding one another repeatedly. If the four weekly pattern is separated per week, the difference within the pattern can be seen. Table 2.1 shows the average planned preventive maintenance hours for each group of weeks. So, week $1 + 4X$ means week 1, 5, 9, and so on. It shows that within every four weeks, the planned maintenance hours for MSE2 are fluctuating highly, which indicates why MFM experiences difficulties in managing its capacity planning.

Table 2.1: Average planned preventive maintenance hours

Week	**Average planned preventive maintenance hours MSE2**
Week 1 + 4X	231
Week 2 + 4X	334
Week 3 + 4X	222
Week 4 + 4X	102
Average	222

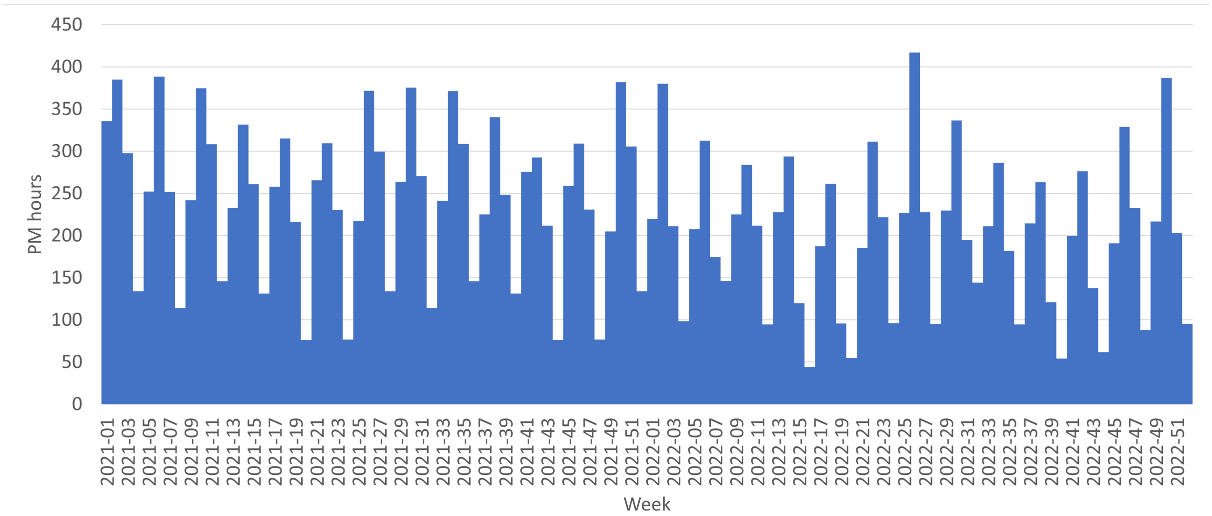

Figure 2.2: Planned preventive maintenance hours for MSE2

Concluding, the planned preventive maintenance tasks do not move with production volume, which is shown by visualizing the ratio between produced loops and planned preventive maintenance hours. Logically this corresponds to the way maintenance is currently planned. Additionally, the demand for preventive maintenance hours is fluctuating over time, which is inefficient for maintenance capacity planning and causes peaks in workload for mechanics. These two issues are not desirable and are directly linked to current maintenance planning strategy used by Bosch TbP.

2.3 Scope

This thesis aims to improve the maintenance scheduling strategy for the loop factory (MSE2) within Bosch TbP. The factory's strategy is to be reassessed to improve alignment of production and maintenance activities. Figure 1.4 shows a global overview of MSE2 and its connection to MSE3. Pipesline 1 produces pipes for Production Line 1a and 1b while Pipesline 2 produces pipes for Production Line 2a, 2b and Production Line 3. Production Lines 1a, 1b, 2a, and 2b are very similar but Production Line 3 is not. An analysis on all of these production lines would be infeasible within time limits of this thesis. Therefore, one of the production lines is chosen as a primary focus.

As mentioned before, Production Lines 1a, 1b, 2a, and 2b are very similar. Production Line 3 will be phased out in the near future so is taken out of scope. As Production Line 1 has the highest output and will produce most products in the near future, part of this production line will be analyzed. The first part of the production line includes the pipesline. This part of the production line can be decoupled from the rest completely. Moreover, it has huge overcapacity and there is a decoupling point between the pipesline and the rest of the production line. Therefore, the pipesline can be analyzed seperately and the focus will be on Production Line 1a. Production Line 1a consists of 29 machines making it more scalable to analyze and is visualized in Figure 2.3 and includes approximately 10% of the machines of MSE2. Decoupling points are noted as Di and production steps are noted as Pi, with i being an index. So, there are four decoupling points and thirteen production steps. Additionally, it shows which production steps have multiple machines in parallel. Note that Figure 2.2 shows preventive maintenance hours for MSE2, which is the complete factory. Appendix B shows that the demand for mechanic man hours is fluctuating similarly for Production Lina 1a as it does for MSE2.

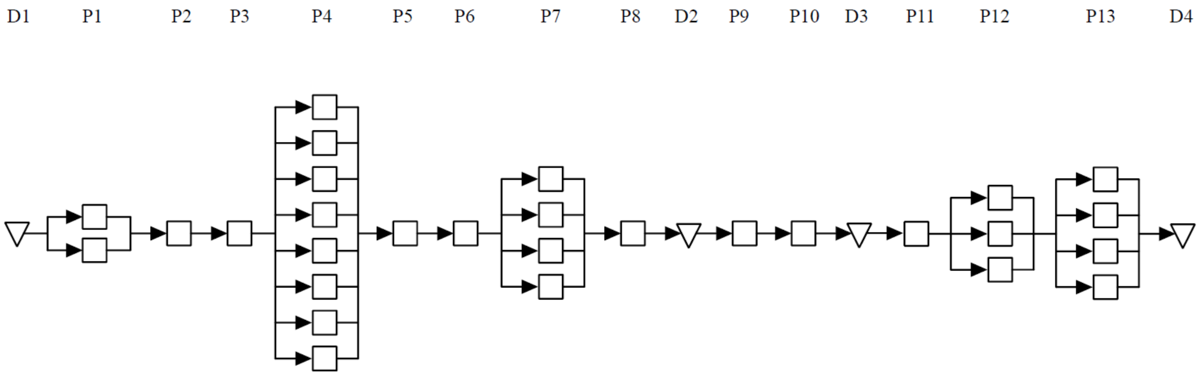

Figure 2.3: Production Line 1a

For this research, spare part availability is not considered, as improved maintenance planning strategy is expected to lead to less preventive maintenance activities rather than more. This means that less spare parts will be needed than in current situation. So, the assumption in the thesis will be that spare parts are available similarly as they are now and is to be researched after the results of this thesis.

2.4 Research Objective

Many organizations have production lines consisting of multiple machines in series. Some production processes do not allow for buffering, so these organizations might have inflexible preventive maintenance planning opportunities. Especially, in the process industry if production is continuous and cannot be stopped at any time, maintenance planning can be difficult and challenges such as described in Section 2.1 may arise. These challenges include fluctuating production volume, mechanic capacity constraints, among others. Additionally, the strategic use of production steps with multiple identical machines in parallel while other production steps operate in series is considered. The objective of this research is to provide organizations with general solutions as well as a case-study to improve such maintenance planning challenges.

2.5 Research Questions

Now the problem statement and problem background have been elaborated on extensively, the main research question is defined. To answer the main research question, sub-research questions are composed. The sub-research questions support the main research question and provide focus of the different areas within the research. The main research question as well as the sub research questions and their respective goals are explained in this section. The main research question is formulated as follows:

How to improve the maintenance scheduling strategy for MSE2 in terms of total maintenance costs?

The total maintenance costs consists of maintenance material costs and mechanic man hours costs. To answer the main research question, several sub-research questions are formulated. A manufacturing site only makes profit when production is running. Hence, production line availability is one of the most important KPIs of a factory. Therefore, the first sub research question is defined as:

1. How to ensure sufficient production capacity while complying to maintenance requirements?

When answering this question machine dependencies in terms of production capacity, production sequence, and machine stops need to be considered. Production can only run when machines are active, which is of high criticality in production lines in series. If Production Step 1 is down, all production steps located after Production Step 1 do not receive any new products to process and experience a line stop. Hence, machine dependencies and its resulting line stops are to be considered.

Then, the second sub research question regards maintenance man hours demand fluctuation. Currently, MFM hires external mechanics to cover peak demand for preventive maintenance hours. Due to scarcity of personnel, this becomes more expensive. Bosch TbP wants to be less dependent on external mechanics, so peaks should be avoided.

2. How to decrease usage of external mechanic man hours?

The third sub research question includes demand forecast. Maintenance activities directly decrease available production time. Hence, the moment of maintenance could be disturbing to satisfy demand. Currently, demand is known a month ahead and production forecast is made one year ahead, meaning that maintenance schedule and production schedule can be aligned to decrease disturbances of maintenance during critical production time.

3. How to use production demand forecast to schedule maintenance?

The final sub research question concerns flexibility of maintenance planning. Currently, Bosch presumes that maintenance is executed too extensively and it would be valuable to be able to adapt maintenance activities to production volume. This means that maintenance will be executed based on production volume or production time instead of fixed-time intervals.

4. How to adapt maintenance activities to production volume?

Summarizing, this thesis encompasses the research to a maintenance scheduling strategy that adapts to production volume. In doing so, Bosch TbP aims to reduce maintenance frequency. Besides adapting maintenance frequency to production volume, the demand for preventive maintenance hours is to be planned such that external mechanic man hours can be decreased. Finally, the production forecast is included in the research to be able to adapt maintenance to production volume.

Chapter 3

Literature Review

This chapter provides a condensed version of the literature review written for the course 1ML05. After this, the theoretical contribution of the thesis is given. The literature review consists of three main areas of focus, which are maintenance planning, production planning, and dependent production steps.

3.1 Maintenance planning

Arts (2014) divides maintenance strategies into three different types, which are modicative maintenance, preventive maintenance and breakdown corrective maintenance. Modicative maintenance concerns interchanging a part to make equipment perform better. Preventive maintenance aims to replace parts before a failure occurs. Obviously, a part may break before its preventive maintenance and corrective maintenance must be performed. Arts (2014) divides preventive maintenance into usage based and condition based maintenance, in which usage based uses a threshold such as time or number of operations while condition based maintenance monitors for a certain condition either continuously or in time-intervals. Usage based maintenance for car tires is the distance driven, for example. Condition based maintenance can be used when a certain condition can be discovered, such as cracks or vibrations in a part of a machine. Koochaki et al. (2008) state that this is not necessarily advantageous to complete production lines, while it is advantageous to single machine performance. More specifically, usage based maintenance can be divided into component replacement and block replacement strategies. Component replacement replaces individual components while block replacement uses the replacement moment to replace multiple components at the same time. Additionally, condition based maintenance can be divided into condition monitoring and periodic inspections, in which condition monitoring examines a condition continuously while periodic inspections does this on predetermined time intervals.

According to Nyman & Levitt (2010) it is essential that the annual maintenance master schedule is aligned with the production planning schedule. There may be periods with low production numbers, which create opportunities to schedule maintenance such that production is less affected. Then, maintenance tasks should be planned during such opportunities and the peaks in maintenance demand should be minimized. Additionally, the annual maintenance calendar lists major events that influence the maintenance schedule heavily. These include yearly scheduled shutdowns and known large projects, for example. To design such schedule, major maintenance events, major production events, specific individual events for technicians such as vacations, training and temporary assignments, big events for the plant, and holidays are to be identified.

Maintenance is directly related to reliability. Besides quality of a machine, reliability can also be seen for a production step having multiple machines. Some production steps at Bosch contain multiple identical machines in parallel. Should production not need all machines to produce customer demand, a k-out-of-n redundant system can be used (Yang et al., 2022). Such redundant systems are used in complex systems to improve reliability. These systems use k out of a total of n machines to operate, and can switch to the machines that sum to k in order to keep production running while maintenance can be executed on the other machines.

For parallel production, two types of studies can be distinguished, which are fixed and flexible. This refers to fixed and flexible start or completion times. If maintenance planning is fixed, this means that production scheduling is subject to availability constraints (Kaabi & Harrath, 2014). However, maintenance planning can also be flexible. Several different algorithms are proposed in literature to approach such maintenance planning problems. For example, Xu et al. (2008) propose a polynomial time algorithm to minimize the makespan, which is the completion time of the last finished maintenance task. Additionally, Maecker et al. (2022) apply a variable neighborhood search to minimize weighted tardiness. Similarly, Costa et al. (2016) do this with genetic algorithms and Ying et al. (2012) develop a simulated annealing method to minimize tardiness considering setup times. These setup times might be useful for the research at Bosch because maintenance activities that require line stops need time before it actually stops, which includes the cooling of an oven, for example. Similarly, such ovens need time to warm up again before starting production. So, maintenance has setup times as well as some kind of setup time at the end. Furthermore, studies approach flexible maintenance assuming predefined time windows in which maintenance tasks are to be scheduled (Touat et al., 2017). Obviously, such time window is larger than the maintenance task to be able to plan.

3.2 Production planning

Planning is performed according to three hierarchical levels; strategic, tactical and operational (Rezg et al., 2016). Strategic planning includes policy making, such as investing in certain machinery. Furthermore, the tactical level encompasses the procedure, which includes priority setting between production lines, for example. Finally, operational level considers the execution, such as daily maintenance planning. This thesis mostly considers tactical and operational levels. Firstly, the tactical level of the research at Bosch may include determining dependencies of maintenance activities or setting priorities between such activities. Secondly, the operational level may include the way maintenance is to be scheduled. This means that procedures for maintenance planners are included in the operational level.

Furthermore, Pochet & Wolsey (2006) propose several ways to model production planning. These can be rewritten to maintenance variants for the purpose of this research. For example, customer-service level can be interpreted as service level to the production department, in which the service level is the percentage of available production time.

Additionally, availability of resources such as machine hours and workforce are similar in both production planning as maintenance planning. Similarly, production planning deals with size of batches and time of production, while maintenance planning deals with maintenance frequency and time.

Research into production planning commonly assumes full availability of production lines, while it is realistic that machines experience failures and are not available continuously. The model proposed by Rezg et al. (2016) considers a manufacturing system with two machines and two buffers. The objective is to reach the best trade-off between cost, availability and quality. The production system makes a single type of product and the machinery experiences an increasing failure rate over time. Machinery is maintained subject to an age-type preventive maintenance policy to improve machine availability and reduce production of non-conforming parts. It then proposes an analytical control strategy for stochastic multi-machine multi-product systems by considering maintenance time intervals, buffer stocks, production capacity, demand, and average cost of preventive and corrective maintenance.

Organizations usually operate under uncertainty. Customer demand fluctuates and influences production needs. As sales directly influence production needs, industrial activities depend on future sales. Therefore, forecasting plays an important role in development of future plans and can be used for decision-making. An accurate forecast ensures companies to adjust production plans to future demand so to satisfy customer demand as well as minimize overproduction, which is direct loss (Kiran, 2019).

Obviously, forecasting plays an important role in production planning, which means it also has an important role in maintenance planning. Therefore, it is to be included in the research for Bosch as an input for the improved maintenance strategy. The demand forecast is provided by Bosch as an input for the model, so different methods of forecasting and literature research regarding this subject are excluded from this literature review.

3.3 Dependent production steps

The third main area of interest for the research at Bosch is the dependency between production steps. The production lines are serial, meaning that production steps are heavily dependent on each other if there is limited buffer space. The buffer space that is available for production lines is mostly the transport belt between machines, covering up to 15 minutes of production. However, some production steps contain multiple machines and are in parallel. Therefore, it is important to search for literature for both serial production lines as well as parallel production lines.

Many literature works regarding maintenance on production lines assume that usage of buffers is possible after each production step. For example, Kenné et al. (2007) and Chelbi & Ait-Kadi (2004) research optimal buffer stock to plan maintenance activities while keeping production time optimal. Li et al. (2009) explain that there are three aspects in developing the optimal preventive maintenance policy for a serial production line. Firstly, it is important to evaluate how much production time is influenced when a specific machine is interrupted due to maintenance. When both preventive maintenance and corrective maintenance costs in terms of time can be determined mathematically, the production losses caused by preventive maintenance can be outweighed by corrective maintenance. Secondly, the complexity of a production line needs to be considered. Usually, preventive maintenance strategy is developed for individual machines, which may not be the optimal strategy for the production line as a whole. Additionally, individual maintenance plans usually ignore machine dependencies. The complexity of the production line leads to a complex state space, which is why new methodologies emerge, such as Artificial Intelligence (AI) and machine learning (ML) (Li et al., 2009). Thirdly, such AI and ML methods may provide very unsatisfactory outcomes as they rely fully on data that may be unclear for its purpose. Furthermore, according to Fitouhi et al. (2017), the different machine speeds are important. This is because machines usually do not have exactly the same processing time, which can be used in the preventive maintenance strategy.

Obviously, parallel production lines are less dependent on each other than serial production lines. Should all lines work on 100% capacity, shutting down a parallel part of the line will only decrease output but might not influence all production steps. A lot of research has been conducted on parallel production lines. Such as in Liu et al. (2021), the focus is on no-waiting of production, hence designing production and maintenance such that production keeps running.

3.4 Theoretical contribution

This research encompasses maintenance planning under highly dependent production steps. Additionally, it touches upon production planning. To identify the theoretical contribution, the literature in these three areas of interest is briefly explained.

The maintenance planning at Bosch is very complex. The production lines contain 17 production steps, in which some production steps consist of multiple machines that can be located in series or parallel. Additionally, there are almost no buffers which causes maintenance activities to be critical to production line availability as maintenance on one machine can cause a full production line to be unavailable. Different production designs and their reliability are researched (Manzini et al., 2010). For example, parallel production is advantageous for production line availability and reliability. Specifically the line availability is interesting in the case of Bosch because parallel production allows for maintenance on machines separately while the production line is not fully down. Therefore, the thesis will propose a scheduling strategy considering difficulties in terms of planning, machine dependencies, machine stops, and capacity.

Production planning at Bosch is less complicated. Only two types of products are manufactured. Additionally, production runs continuously for six days per week. Demand for next month is known two weeks before the month starts, so production planning can be made timely. For the production planning, maintenance planning is assumed to be given and fixed. Concluding, production planning is not complex and is planned around maintenance activities. This means that production sees maintenance planning as capacity constraints. Therefore, if maintenance planning can use forecasted demand and designs a maintenance planning at least two weeks before the beginning of a month, production can consider maintenance planning and design a production planning accordingly.

Most literature considers only one production step or two production steps with buffers. Furthermore, literature covering more than one production step mostly focuses on buffer size (Rezg et al., 2016), (Kenné et al., 2007), (Chelbi & Ait-Kadi, 2004). Generally, theory is focused on maintenance planning and strategy on one production step or usage of buffer space. However, many manufacturing sites such as Bosch have long production lines and are struggling to find the optimal maintenance strategy. The theoretical contribution of this thesis is aimed at smart planning of maintenance under highly dependent production steps consisting of a mix of serial and parallel machine configurations. This includes investigating whether maintenance activities can be scheduled such that different production steps can temporarily operate with fewer available machines to maintain the other machines at the same time. Additionally, a complex production system might experience a line stop due to unexpected failures. Maybe, planned maintenance within a certain threshold can be executed at the same time as the repair of unexpected failures.

Concluding, the theoretical contribution encompasses the maintenance planning and strategy for a highly dependent production line. This includes the consideration of the needed production capacity, historic production data, machine dependencies, maintenance requirements and mechanics capacity.

Chapter 4

Analysis Production Volume

This chapter describes the production volume and maintenance requirements for Production Line 1a. First, the production during times of high volumes is discussed, which is during 2017 and 2018. Thereafter, the production during times of low volume is discussed, which is in 2019 to 2022. The production during times of high volumes is used to quantify maintenance requirements because they are based on high volume production. Thereafter, this is compared to low production volume to see potential improvement.

The maintenance requirements are divided into multiples of four-weekly time intervals. The maintenance activities have deadlines corresponding to the production volume in the length of the interval. Hence, if a maintenance activity is due every four weeks and during 2017 and 2018 the production volume was 100 units every four weeks, this means that the maintenance activity is assumed to have a deadline of 100 units. Therefore, these standards will be used to quantify improvement for maintenance planning strategy in later chapters of this thesis. First, this chapter discusses the high production volume in 2017 and 2018. Secondly, it discusses the production volume in 2019 to 2022 and the forecast for 2023.

4.1 Production 2017 - 2018

In this section, the production volume of 2017 and 2018 is analyzed. This is done for all production steps of Production Line 1a as shown in Figure 2.3. In Production Line 1a, there are two types of production steps, which are serial and parallel. The serial machines simply process all units that are produced during a time period, whereas machines in parallel might not have the same workload. Therefore, a division is made between the two types to analyze production numbers per machine. The production steps have been introduced in Section 2.3 and are visualized in Figure 2.3. Production during 2017 and 2018 is considered to be high volume and is the standard for maintenance requirements. Also, the machines with highest production volume in a production step are part of the base scenario.

4.1.1 Serial production steps

The serial production steps are $P2, P3, P5, P6, P8, P9, P10$, and $P11$. These production steps consist of either one machine or several machines in series. Therefore, these machines process all items that are produced by a production line. Hence, production of Production Line 1a must have passed all machines in the serial production steps. The average yearly production volume in 2017 and 2018 was 11,138,285 units, which is the base for serial production steps. As maintenance requirements are divided into four-weekly maintenance intervals and there are roughly 13 intervals per year, the intervals are calculated by setting one four-weekly interval to $\frac{1}{13}$th of 11.14 million units. Hence, a maintenance interval for a serial production step due at four weeks contains a maintenance deadline when 856,791 are produced. The difference between production volume in 2017 and 2018 is caused by producing a different product mix on Production Line 1a. Bosch TbP believes that the combination of production in 2017 and 2018 are a firm basis for the maintenance requirements.

Table 4.1: Production volume serial production steps

Yearly production volume (units)			
Serial	**2017**	**2018**	**Average**
Production volume	12,515,301	9,761,269	11,138,285

4.1.2 Parallel production steps

The parallel production steps are $P1, P4, P7, P12$, and $P13$. These production steps all have several identical machines. Within each production step, a product only needs to be processed by one machine and it does not matter which one. All these production steps contain machinery, except for $P13$. This step is a final inspection step, and is not included in the volume analysis as it does not contain any maintenance tasks. This section discusses the production data for the individual machines in the parallel production steps and sets the standard for the maintenance requirements for all machines in the production step. If there is a difference between production volume of machines within a production step, the machine with the maximum workload is considered to be the standard for the maintenance requirements. The maximum is chosen as all machines within a production step are identical and have the same maintenance requirements. So it is assumed that all machines in a production step can handle the same workload and have the same deterioration related to this workload.

Production Step $P1$ contains two identical machines. For both machines the operating time is available. This is the amount of time that a machine is actively in operation. Unfortunately, the number of items processed per machine is not known, but the active production time provides an estimate of the proportion of products produced per machine as cycle times for both machines are identical. Additionally, the total number of products manufactured on Production Line 1a is known. Therefore, an estimate of the workload per machine can be determined. Table 4.2 shows the production hours for the machines in Production Step $P1$. It shows that Machine 0978 processes a slightly higher workload than Machine 0996. So the base scenario equals 4884 production hours per year for $P1$.

Production Step $P4$ contains eight identical machines. The exact number of processed items per machine is known and noted in Table 4.3. The machines are sorted based on decreasing production volume. The M is an abbreviation for millions and K is an abbreviation for thousands of units. For Production Step $P4$, the machine with the lowest

Table 4.2: Production time in hours for step $P1$

Yearly production time (hours)			
Machine	**2017**	**2018**	**Average**
0978	5388	4379	4884
0996	5226	4187	4706
Δ%	-3.0%	-4.4%	-3.6%

workload during 2017 and 2018 processes 21.3% less items than the machine with highest workload during this time period. This is caused by the way the loop distributor works. At the start of the production step, a loop distributor is located. It distributes the loops between the machines according to an allocation rule considering transport belt length to the different machines. This causes the differences in usage of machines, which should be taken into account when performing maintenance equally. The base for $P4$ equals 1.56 million units per year.

Table 4.3: Production volume for step $P4$

Yearly production volume (units)			
Machine	**2017**	**2018**	**Average**
0914	1.72M	1.39M	1.56M
0917	1.61M	1.50M	1.56M
Δ%	-6.8%	+7.5%	-0.2%
0916	1.57M	1.29M	1.43M
Δ%	-9.0%	-6.5%	-8.1%
0918	1.56M	1.23M	1.40M
Δ%	-9.8%	-11.2%	-10.5%
0913	1.56M	1.20M	1.38M
Δ%	-9.8%	-14.0%	-11.5%
0904	1.56M	1.15M	1.36M
Δ%	-9.8%	-17.8%	-12.9%
0915	1.43M	1.04M	1.23M
Δ%	-17.3%	-25.2%	-20.8%
0903	1.49M	0.96M	1.23M
Δ%	-13.5%	-30.8%	-21.3%

The next parallel production step is $P7$, which contains four identical machines. The exact number of processed items per machine is known, which is visualized in Table 4.4. This shows that the machines are not in full utilization during 2017 and 2018, while this is the period with high demand. The difference in production volume between the machines can be explained by the design of this production step. The rings arrive at $P7$ by a transport belt. If the first machine is available it picks the ring from the transport belt. Else, if the first machine is already occupied with another ring, the next machine picks the ring from the transport belt. This continues until the last machine. Therefore, the first machine always has a higher workload than the last machine. The first machine is Machine 0976, the second is Machine 0992, the third is Machine 1081, and the last is Machine 1082, which is confirmed by the processed workload per machine. The difference in production numbers should be considered to perform equal maintenance. The base for Production Step $P7$ equals 3.88 million units per year.

Table 4.4: Production volume for step $P7$

Yearly production volume (units)			
Machine	**2017**	**2018**	**Average**
0976	4.17M	3.59M	3.88M
0992	3.85M	3.23M	3.54M
Δ%	-7.7%	-9.8%	-8.7%
1081	3.18M	2.27M	2.72M
Δ%	-23.6%	-36.8%	-29.7%
1082	1.24M	606K	924K
Δ%	-70.2%	-83.1%	-76.2%

The final parallel production step to be analyzed is $P12$. This production step consists of three identical machines. The production volumes for these machines are shown in Table 4.5. This visualizes very similar usage of Machines 0943 and 0942. However, Machine 0838 shows very different production volumes. This is because there is more than 3 months of data missing from this machine. However, Machine 0838 shows similar production volumes to the other machines in all other months. This corresponds with the way that loops are fed to these machines, which is done by distributing the loops in racks equally. So, the base for $P12$ equals 3.97 million units per year.

Table 4.5: Production volume for step $P12$

Yearly production volume (units)			
Machine	**2017**	**2018**	**Average**
0942	4.42M	3.52M	3.97M
0943	4.62M	3.31M	3.96M
Δ%	+4.5%	-6.0%	-0.1%
0838	4.59M	*1.98M*	*3.28M*
Δ%	+3.8%	*-44.8%*	*-17.3%*

The parallel production Steps show large differences in usage between machines. Within Production Step $P4$, the difference between the highest and lowest workload of machines is 21.3%, whereas for Production Step $P7$ this is 76.2%, and 17.3% for $P12$. However, all machines within a production step are maintained according to the same requirements. So, Machine 1082 processed roughly four times less rings than Machine 0976 but received exactly the same amount of maintenance. This shows that maintenance strategy not only needs to be flexible regarding production volume over time, but also between machines during a certain period of time. Using the available production volume information of 2017 and 2018, it can already be seen that there are opportunities to improve maintenance strategy in the base scenario. The maintenance requirements are designed for full production, so the machine with most production in a production step is assumed to be the standard for maintenance requirements. Then, Tables 4.2, 4.3, 4.4, and 4.5 indicate that the theoretical improvement for a new maintenance strategy would be a reduction of activities on several machines. The theoretical improvement opportunities for the base scenario are shown in Table 4.6.

Table 4.6: Theoretical improvement opportunity in base scenario

Production step	Machine	Potential maintenance reduction
P1	0996	3.6%
P4	0916	8.1%
	0918	10.5%
	0913	11.5%
	0904	12.9%
	0915	20.8%
	0903	21.3%
P7	0992	8.7%
	1081	29.7%
	1082	76.2%
P12	0838	17.3%

The maintenance requirements are based on high production output. This corresponds to the average production volume of 2017 and 2018, which is quantified in this section. There is already improvement possible within the base scenario. As shown in Table 4.6, some machines can be maintained less extensively due to differing usage of machines in parallel production steps. Concluding, this indicates that a more flexible maintenance planning strategy would theoretically decrease maintenance activities and thereby reducing workload for mechanics. When production runs at full capacity the machines have different workloads, which means that theoretically there is room for improvement regarding maintenance planning in the base scenario.

4.2 Production 2019-2022

The production volume for the base scenario is known and can be compared to the average production volume of 2019 to 2022, when demand started decreasing. In case of a parallel production step, the comparison is done with the most used machine in the production step from the base scenario. In doing so, the potential gain in previous years can be identified to show the total potential improvement. Additionally, the forecast for 2023 is included, which is used to quantify the potential improvement for 2023. The forecast for Production Line 1a is known and equals 9,630,994 units in 2023. For the serial production steps, all these units will be processed by the machines. For the parallel production steps, the units will only be processed by one machine. As discussed in Section 4.1, not all machines in a production step have equal workload. Therefore, the historic machine data of 2017 to 2022 is used to make an estimate for the division of units between machines on a parallel production step. Then, the difference between the forecast and the base scenario indicates the maximum theoretical decrease in maintenance activities if maintenance can be adapted to production volume.

4.2.1 Serial production steps

The base production numbers from 2017 and 2018 are compared to the production numbers in the years after 2018 to see what the potential improvement for the serial production steps is. The difference denotes the potential improvement for decreasing the number of maintenance tasks to the same frequency as in the base scenario. However, it should be noted that some machines such as an oven deteriorate independent of production volume but rather based on production time. The production volume for the years 2019 to 2022 and the forecast is compared to the average production volume of 2017 and 2018 in Table 4.7. We see that the production numbers significantly decrease over time from 2019 to 2022.

Table 4.7: Potential improvement maintenance tasks serial production steps

Yearly production volume (units)						
Base	**2019**	**2020**	**2021**	**2022**	**Yearly average**	**Forecast 2023**
11.14M	10.59M -5.0%	9.94M -10.7%	8.83M -20.8%	5.79M -48.0%	8.79M -21.1%	9.63M -13.5%

4.2.2 Parallel production steps

For the parallel production steps, the machines are compared to the theoretical base value for volume based maintenance requirements as defined in Section 4.1. This means that the yearly base for $P1$ is 4884 production hours, for $P4$ is 1.56 million units, for $P7$ is 3.88 million units, and for $P12$ is 3.97 million units. Then, the theoretical improvement in terms of maintenance frequence can be identified for all individual machines in the parallel production steps. All parallel production steps are discussed below.

The number of operating hours for Production Step $P1$ is compared and shown in Table 4.8. This shows that the number of operating hours decreased significantly over time. The machines in this production step deteriorate based on production volume, which means that maintenance requirements are dependent on usage. Therefore, the difference in production volume provides a good estimation of potential maintenance frequency reduction. The base for this production step is 4884 hours operating time on a yearly basis. Table 4.8 shows that both machines could have been maintained with less maintenance. On average, Machine 0978 could have been maintained by 18% less and Machine 0996 could have been maintained by 32% less on a yearly basis.

Table 4.8: Potential improvement maintenance tasks for Production Step $P1$

Yearly production time (hours)							
P1	**Base**	**2019**	**2020**	**2021**	**2022**	**Yearly Average**	**Forecast 2023**
0978	4884	4512 -7.6%	4049 -17.1%	3651 -25.2%	3751 -23.2%	3991 -18.3%	4315 -11.7%
0996	4884	4424 -9.4%	3796 -22.3%	3317 -32.1%	1660 -66.0%	3229 -32.4%	3744 -23.3%

Production Step $P4$ has detailed production data for each machine including exact production numbers. Based on Section 4.1.2, the base scenario for all machines in Production Step $P4$ is 1.56 million processed units per year. Table 4.9 shows the production numbers on a yearly basis for each machine in 2018 to 2022 compared to the base scenario. This indicates that all machines in Production Step $P4$ have been maintained too extensively. From 2019 until 2022, the production volume significantly decreases every year. The machines in this production step deteriorate by production volume so the machines in Production Step $P4$ could have been maintained less. The machine that had the highest workload in 2019 to 2022 was Machine 0914. This machine could have been maintained less by 17% on a yearly basis. Moreover, Machine 0903 processed the least workload of Production Step $P4$ between 2019 and 2022. The maintenance frequency for this machine could have been reduced by 46% on a yearly basis. Concluding, the machines in Production Step $P4$ have been maintained too extensively over the period 2019 to 2022 on average.

Table 4.9: Potential improvement maintenance tasks for Production Step $P4$

Yearly production volume (units)							
P4	**Base**	**2019**	**2020**	**2021**	**2022**	**Yearly Average**	**Forecast 2023**
0914	1.56M	1.29M -16.9%	1.42M -8.7%	1.32M -15.2%	1.15M -26.0%	1.30M -16.7%	1.39M -10.9%
0913	1.56M	1.11M -28.5%	1.37M -11.9%	1.33M -14.5%	1.23M -21.2%	1.26M -19.0%	1.31M -16.0%
0917	1.56M	1.47M -5.4%	1.35M -13.2%	1.30M -16.8%	0.91M -41.4%	1.26M -19.2%	1.37M -12.2%
0918	1.56M	1.53M -1.8%	1.36M -12.9%	1.16M -25.4%	0.42M -73.2%	1.12M -28.3%	1.22M -21.2%
0916	1.56M	1.45M -6.8%	1.17M -24.7%	1.12M -28.2%	0.71M -54.7%	1.11M -28.6%	1.23M -21.2%
0904	1.56M	1.14M -26.7%	1.29M -17.5%	1.00M -36.0%	0.37M -76.3%	0.95M -39.1%	1.09M -30.1%
0915	1.56M	1.33M -14.7%	0.99M -36.7%	0.82M -47.5%	0.62M -60.3%	0.94M -39.8%	1.04M -33.3%
0903	1.56M	1.25M -20.0%	0.99M -36.4%	0.78M -50.0%	0.38M -75.5%	0.85M -45.5%	0.98M -37.2%

For Production Step $P7$ the exact production numbers are known too. The base scenario for all machines in this production step is 3.88 million processed units on a yearly basis. Table 4.10 shows the production numbers on a yearly basis for the years 2019 to 2022 compared to the base scenario and indicates that the machines have been maintained too extensively. Differences with the base scenario are very high for this production step, which is caused by the production step design as explained in Section 4.1.2. Especially when production volume is lower, the machines at the end of the queue will receive less products to process. Machines still have the same production capacity so the machines at the front of the queue are able to process relatively more of the total amount of products. Compared to the base scenario, Machines 0976, 0992, 1081, and 1082 could have been maintained less on a yearly basis by 17%, 27%, 50%, and 80% on average during 2019 to 2022, respectively.

Table 4.10: Potential improvement maintenance tasks for Production Step $P7$

Yearly production volume (units)							
P7	**Base**	**2019**	**2020**	**2021**	**2022**	**Yearly average**	**Forecast 2023**
0976	3.88M	3.56M -8.1%	3.24M -16.3%	3.08M -20.6%	2.96M -23.5%	3.21M -17.1%	3.47M -10.6%
0992	3.88M	3.44M -11.1%	3.08M -20.6%	2.73M -29.4%	2.00M -48.5%	2.81M -27.4%	3.09M -20.4%
1081	3.88M	2.52M -34.9%	2.35M -39.4%	2.00M -48.2%	0.82M -78.8%	1.93M -50.3%	2.22M -42.8%
1082	3.88M	0.95M -75.6%	1.14M -70.5%	0.87M -77.5%	0.17M -95.5%	0.78M -80.0%	0.84M -78.4%

For Production Step $P12$, the exact production numbers are known. The base scenario for all machines in this production step is 3.97 million processed units yearly. Table 4.11 shows the yearly production volumes for the machines in Production Step $P12$, which indicates that the machines in this production step have been maintained too extensively as well. The differences between these machines are less high due to the distribution of units over the machines, which is equal when all machines are active. On average, Machines 0942, 0943, 0838 could have been less maintained by $23\%, 27\%$, and 28%, respectively.

Table 4.11: Potential improvement maintenance tasks for Production Step $P12$

Yearly production volume (units)							
P12	**Base**	**2019**	**2020**	**2021**	**2022**	**Yearly average**	**Forecast 2023**
0942	3.97M	3.72M -6.0%	3.45M -12.9%	3.01M -24.0%	2.07M -57.7%	3.07M -22.8%	3.35M -15.6%
0943	3.97M	3.47M -12.4%	3.29M -16.9%	2.82M -28.9%	1.96M -62.7%	2.89M -27.3%	3.16M -20.4%
0838	3.97M	1.63M -8.3%	3.16M -20.3%	2.93M -26.1%	1.69M -63.8%	2.85M -28.1%	3.12M -28.1%

Summarizing, the data showed that there is room for improving the maintenance scheduling frequency in the base scenario for the parallel production steps. Furthermore, the period of 2019 to 2022 shows a decrease in production volume, which provides more room for improvement for the parallel production steps, but also shows that the serial production steps could have been maintained less frequently. The data shows that shifting from strict maintenance scheduling in four-weekly intervals to a volume based maintenance scheduling strategy might significantly decrease the amount of maintenance executed in periods of low demand.

4.2.3 Time or volume based maintenance

For Production Steps $P1, P4, P7, P8, P11$, and $P12$ it is known that the deterioration of machines is volume based, so the production numbers shown in previous sections provide theoretical improvements in terms of maintenance frequency that could have been achieved for past years. For Production Steps $P2, P3, P5, P6, P9$, and $P10$ it is known that the deterioration of machines is operating time based, meaning that the difference in workload did not affect those machines. Rather the number of hours in production deteriorate the machines. Therefore, these machines cannot be maintained less by the same amount that production decreases, but it should be based on time.

4.2.4 Production to maintenance ratio conclusion

Summarizing, the serial production steps have a theoretical potential to reduce their maintenance load significantly. If the machine deterioration in these production steps are production volume dependent rather than production time dependent, the average yearly maintenance activity reduction for the years 2019 to 2022 is 21%. Obviously, to operate within maintenance requirements, this is a theoretical maximum reduction and is only achieved upon optimal maintenance task planning. Similarly, for the parallel production steps, there is high potential to reduce maintenance load. All parallel production steps deteriorate depending on production volume and their potential average yearly improvement for the period 2019-2022 ranges up to 32% for Production Step 1, up to 46% for Production Step 4, up to 80% for Production Step 7, and up to 28% for Production Step 12. Concluding, this section shows the theoretical improvement that flexible planning of maintenance activities can achieve. It shows high potential to decrease maintenance efforts significantly for MSE2.

Chapter 5

Production or Maintenance

This chapter aims to provide the basis to answer sub research question 1; "*How to ensure sufficient production capacity while complying to maintenance requirements?*". This is done by explaining the machine dependencies within Production Line 1a. Each individual machine's influence on total line capacity is presented. Then, the line stops are investigated.

5.1 Dependencies

The machines in Production Line 1a are located as shown in Figure 2.3. If a machine is down the machines in previous production steps cannot move their products to the next step so they need to stop producing. Moreover, the production steps after the machine that is down do not get any new products. So machines in a serial production line are highly dependent on one another and cannot continue producing once a machine is down. Although there is buffer space between $P8$ and $P9$ and between $P10$ and $P11$, production steps are highly dependent on one another. Additionally, production steps $P9$ and $P10$ have very specific maintenance requirements that are executed just once every 18 months and are explained in more detail later.

The impact of an individual machine being down on the capacity of the production line is needed to see dependencies between machines. Bosch TbP produces two types of push belts, both having different characteristics. Therefore, some production steps have different cycle times for producing these items, thereby influencing the capacity per type of product. Table 5.1 shows the capacity for each machine when either of the products is produced. It shows that $P5$ and $P6$ are the bottleneck if Product Type 076 is produced whereas $P2$ is the bottleneck if Product Type 082 is produced. Additionally, the difference between the output of the two different product types is significant. If Type 076 is produced, the capacity of Production Line 1a equals 2237 loops per hour, whereas the capacity is only 1585 loops per hour if Type 082 is produced, which is shown in Table 5.1.

As shown in Table 5.1, the capacity per machine differs for the different product types. This is caused by product characteristics, which are different between the two types. To see the impact on production capacity if one machine of a production step is turned off, the remaining capacity of the production line is shown. The maximum capacity is 100% and this is based on the maximum capacity of the bottleneck production step. Hence,

Table 5.1: Machine capacities

Production step	Number of machines	Machine capacity (loops/hour)		Total capacity (loops/hour)	
		076	082	076	082
P1	2	1244	1160	2488	2320
P2	1	2494	1585	2494	1585
P3	1	2463	2463	2463	2463
P4	8	298	265	2387	2117
P5	1	2237	2237	2237	2237
P6	1	2237	2237	2237	2237
P7	4	588	548	2353	2191
P8	1	3268	3195	3268	3195
P9-P10	1	3746	2325	3746	2325
P11	1	2398	2403	2398	2403
P12	3	811	811	2433	2433
P13	4	3011	3011	12042	12042

100% capacity for Product Type 076 means that 2237 loops per hour can be produced. Additionally, 100% capacity for Product Type 082 means that 1585 loops per hour can be produced. Tables 5.2 and 5.3 show the remaining production capacity of a production line if machines of a production step are turned off. This information is valuable to see whether line stops can be avoided. This might be done by maintaining machines of parallel production steps one by one and thereby reducing line capacity temporarily while production keeps running. The design of parallel production steps allows for shutting down individual machines while other machines are still active. In doing so, production stops might be avoided while the average output over time is not influenced. Additionally, MFM demand might be leveled and variation decreases.

Table 5.2: Production line remaining capacity when machines are turned off for product 076

076	Production capacity left							
Production step / **Machines turned off**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
P1	56%	0%	-	-	-	-	-	-
P2	0%	-	-	-	-	-	-	-
P3	0%	-	-	-	-	-	-	-
P4	93%	80%	67%	53%	40%	27%	13%	0%
P5	0%	-	-	-	-	-	-	-
P6	0%	-	-	-	-	-	-	-
P7	79%	53%	26%	0%	-	-	-	-
P8	0%	-	-	-	-	-	-	-
P9-P10	0%	-	-	-	-	-	-	-
P11	0%	-	-	-	-	-	-	-
P12	73%	36%	0%	-	-	-	-	-

Table 5.3: Production line remaining capacity when machines are turned off for product 082

082	Production capacity left							
Production step / **Machines turned off**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
P1	73%	0%	-	-	-	-	-	-
P2	0%	-	-	-	-	-	-	-
P3	0%	-	-	-	-	-	-	-
P4	100%	100%	83%	67%	50%	33%	17%	0%
P5	0%	-	-	-	-	-	-	-
P6	0%	-	-	-	-	-	-	-
P7	100%	69%	35%	0%	-	-	-	-
P8	0%	-	-	-	-	-	-	-
P9-P10	0%	-	-	-	-	-	-	-
P11	0%	-	-	-	-	-	-	-
P12	100%	51%	0%	-	-	-	-	-

5.1.1 Production Steps $P9$ and $P10$

Production Steps $P9$ and $P10$ consist of the hardening and nitriding process, which consists of enormous ovens. These machines are not included in the preventive maintenance schedule but are maintained every 18 months by the manufacturer of the machines. Hence, these production steps are taken out of the preventive maintenance planning model. Whenever the machines in $P9$ and $P10$ need to be maintained, the ovens cannot be used for production for 2 to 3 weeks due to the extensive maintenance and the cooling down and warming up process. This has a huge influence on the production output. However, Production Line 3 will not be used in the future anymore but the hardening and nitriding process of Production Line 3 is still available to cover production capacity during the maintenance of Production Steps $P9$ and $P10$ on the other production lines. During times of such maintenance, an operator needs to transport the loops to the hardening and nitriding process of Production Line 3, but production capacity is not influenced. In case Production Line 3 is fully removed and its hardening and nitriding process cannot be used as a back up for Production Lines 1 and 2, the demand for the impacted weeks is distributed over previous months or it is included in the production forecast for other production lines to satisfy demand in time. This is possible due to the production overcapacity. Therefore, the production loss for the maintenance of the hardening and nitriding process is negligible.

5.2 Line stops

Line stops may be reduced or shortened by taking advantage of the parallel production steps. All machines within a parallel production step are identical, so it does not matter which machine processes the product. The parallel production steps are designed such that machines within the production step can be shut down individually. Tables 5.2 and 5.3 show that machines of a parallel production step can be shut down without it influencing production capacity. For example, if Product Type 082 is produced Production Step 4 can operate with six out of eight machines and still have enough capacity to process all units. Additionally, Production Step 7 can operate with three out of four machines without causing production capacity loss. Similarly, Production Step 12 can operate with two out of three machines and still ensure 100% production capacity of the production line. Therefore, maintenance activities on machines of these production steps can be taken out of the four-weekly maintenance shift without influencing production capacity. Maintenance activities on Production Steps $P4$, $P7$, and $P12$ can be executed whenever MFM has enough mechanic capacity and production is not influenced.

Moreover, the production lines at Bosch TbP currently have overcapacity regarding customer demand. This means that production lines are restrained to a lower capacity occasionally. When reducing production line output, parallel production steps have more overcapacity than shown in Tables 5.2 and 5.3. Then, the execution of maintenance activities of these production steps can be executed such as explained in previous paragraph.

Contrarily, line stops still occur as there are also maintenance activities on serial production steps. When executing maintenance on serial production steps, the production line experiences line stops. Within MFM capacity, these line stops must be used as efficiently as possible to reduce further production time interruptions. This means that whenever a linestop occurs, this downtime should be used as optimally as possible and as much maintenance activities that are due must be executed to avoid line stops in the near future. This new way of planning maintenance activities can cause MFM demand to be less fluctuating over time while production capacity is influenced as least as possible. This shows the relation between line stops, maintenance requirements, and mechanic capacity. We do not want too many line stops to avoid unsatisfied demand, we want to maintain machines as late as possible to decrease average maintenance costs over time, and we have capacity constraints regarding mechanics so we cannot execute all maintenance at the due date. Therefore, a mathematical model is developed in Chapter 6 and will be analyzed.

5.3 Conclusion

Production triggers maintenance requirements. If production volume and time increase, the amount of necessary maintenance also increases. Quality is of high importance to Bosch TbP and maintenance requirements are strictly related to amount of production, either in time or in volume. Therefore, maintenance activities are seen as constraints in production planning. The relation between production line availability, maintenance requirements, and mechanic capacity is a challenging case for Bosch TbP. This chapter shows that the production capacity of parallel production steps may be used in an advantageous way. Also, if line stops occur they must be used to its full extend to decrease further decrease of production capacity. Then, the answer to sub research question 1; "*How to ensure sufficient production capacity while complying to maintenance requirements?*" lays in the balance between production line availability, maintenance requirements, and mechanic capacity. These three components are included and explained in the model presented in Chapter 6 and the model will balance the components.

Chapter 6

Model

This chapter contains the mathematical model that is used to analyze the potential improvement for changing the maintenance scheduling strategy. In Chapter 4 we have seen that enormous improvements in terms of maintenance frequency can be achieved if maintenance is based on production volume. Moreover, Chapter 5 explains the relation between production line availability, maintenance requirements, and mechanic capacity. Also it shows a new way of planning maintenance and using mechanic capacity by taking advantage of parallel production steps. The huge potential of volume-based and time-based maintenance needs further investigation, which is done by using a mathematical model. In Chapter 2 we have seen that there is high fluctuation in demand for mechanic man hours. This is included in the mathematical model and an important variable for the analysis presented in Chapter 7. The combination of volume-based and time-based maintenance planning, production forecast, and mechanic capacity calls for an investigation into a change of maintenance scheduling strategy. The current maintenance scheduling strategy is very strict and does not consider machine deterioration adequately. Therefore, the maintenance scheduling strategy to be investigated does not consider the fixed four-weekly time intervals but rather plans based on machine usage, needed production capacity, and mechanic capacity.

The mathematical model is used to analyze the potential improvement for changing the maintenance scheduling strategy from using fixed four-weekly time intervals to a flexible scheduling strategy. The goal is to find a minimum in costs considering maintenance task costs, mechanic man hours costs, penalty costs for late demand satisfaction, and holding costs. Each variable and parameter used in the model is explained in Table 6.1 and the explanation for each line in the model is provided in Table 6.2. The model is designed for generic production lines and can be used by production facilities having serial production lines. This thesis uses the production facility at Bosch TbP as a case-study. It is designed such that it is easy to focus on Production Line 1a but can be expanded to a complete production line as described in Section 2.3. The mathematical model is designed to be discrete, meaning that it iterates over time in hours. Additionally, the model assumes that the time provided in the SLAs of the maintenance requirements are accurate and discrete. Hence, the duration of a maintenance task will take exactly the amount of time that is provided by the SLAs. Similarly, other parameters such as production rates of machines are discrete. The model also assumes no unexpected failures. The model provides a planning for one year ahead so it is assumed that downtime of the production line does not cause additional costs such as idle operators because they can be assigned other tasks timely. This is similar to current maintenance planning strategy.

6.1 Mathematical model

First, the symbols of the variables and parameters used in the model are described in Table 6.1. Then, the mathematical model is presented and every line is explained in Table 6.2.

6.1.1 Introduction symbols

Table 6.1: Notation for mathematical model

Symbol	Description
$t \in$ {0,1,...,T}	Time in hours with horizon T
$a^E \in$ {4E, 8E, 16E, 24E, 48E}	Set of electrical maintenance activities A^E
$a^M \in$ {4M, 8M, 16M, 24M, 48M}	Set of mechanical maintenance activities A^M
$i \in$ {076, 082}	Set of products I
$s \in \{P1, P2, ..., P13\}$	Set of production steps S, with S^N volume-based and S^{TI} time-based
$b \in \{D1, D2, D3, D4\}$	Set of buffer steps B
$x \in \{D1, P1, P2, P3, P4, P5, P6, P7, P8, D2, P9, P10, D3, P11, P12, P13, D4\}$	Combined set of production steps S and buffer steps B in production line sequence X
$c \in \{M, E\}$	Capacity or skill of mechanics C, which is mechanic or electric
$m_{P1} \in \{0979, 0996\}$	Set of machines in production step $P1$
$m_{P2} \in \{0979\}$	Set of machines in production step $P2$
$m_{P3} \in \{1133\}$	Set of machines in production step $P3$
$m_{P4} \in \{0903, 0904, 0913, 0914, 0915, 0916, 0917, 0918\}$	Set of machines in production step $P4$
$m_{P5} \in \{2295\}$	Set of machines in production step $P5$
$m_{P6} \in \{1002\}$	Set of machines in production step $P6$
$m_{P7} \in \{0976, 0992, 1081, 1082\}$	Set of machines in production step $P7$
$m_{P8} \in \{1158\}$	Set of machines in production step $P8$
$m_{P9} \in \{1003\}$	Set of machines in production step $P9$
$m_{P10} \in \{1005\}$	Set of machines in production step $P10$
$m_{P11} \in \{1159\}$	Set of machines in production step $P11$
$m_{P12} \in \{0838, 0942, 0943\}$	Set of machines in production step $P12$
$\{P1, P2, P3, P4, P5, P6, P7, P8\} \in D1$	Set of production steps between two decoupling points
$\{P9, P10\} \in D2$	Set of production steps between two decoupling points
$\{P11, P12\} \in D3$	Set of production steps between two decoupling points

$c_{m,a}$	Cost maintenance activity a on machine m
c^h	Cost per working hour of a mechanic
c_i^p	Penalty cost unsatisfied demand of product i
c_i^{hc}	Holding cost product i
$D_{i,t}$	Demand for product i to be satisfied during time t
$TI_{m,k}^{EM}$	Number of hours machine m is in production at time k, electrical and mechanical maintenance variant
$N_{m,k}^{EM}$	Number of items machine m processed at time k, electrical and mechanical maintenance variant
$\Delta_m^{N^{EM}}$	The maximum number of items produced between two succeeding electrical and mechanical maintenance tasks on machine m
$\Delta_m^{TI^{EM}}$	The maximum number of production hours between two succeeding electrical and mechanical maintenance tasks on machine m
$p_{m,i}$	Production rate in products per hour for machine m when producing item i
$P_{s,i,t}$	Production rate production step s for product i at time t
$P_{i,t}^L$	Total production rate on the production line for product i at time t
$U_{s,t}$	Utilization of production capacity of production step s at time t
$Y_{x,i,t}$	Number of incoming items i to production step x at time t
$Z_{x,i,t}$	Number of processed items i at production step x at time t
$I_{x,i,t}$	Inventory item i at production step x at time t
$\Theta_{i,t}$	Number of items i taken from inventory of last production step to satisfy demand
$Buffer_x$	Buffer capacity of production step x
$Cap_{t,c}$	Number of mechanics with capacity c available during time t
$n_{m,a,c}^{min}$	Minimum number of mechanics with capacity c that can work on maintenance task a on machine m
$n_{m,a,c}^{max}$	Maximum number of mechanics with capacity c that can work on maintenance task a on machine m
$n_{m,a,c,t}$	Number of mechanics with capacity c working on maintenance activity a at time t
$L_{m,a}$	Duration of maintenance activity a on machine m
$\delta_{m,a,c,t} \in \{0,1\}$	Machine m is maintained during time t for maintenance activity a and needs mechanic capacity c while production is stopped
$\Phi_{m,a,c,t} \in \{0,1\}$	Machine m is maintained during time t for maintenance activity a and needs mechanic capacity c while production does not need to be stopped
$\gamma_{m,a,t} \in \{0,1\}$	Machine m started maintenance activity a at time t
$\phi_{m,i,t} \in \{0,1\}$	Machine m is in production during time t producing item i

$\omega_{m,i,t} \in \{0,1\}$	Ramp-up and ramp-down loss for machine restarts regarding maintenance tasks

6.1.2 Mathematical model flexible scheduling

Now all parameters and variables are introduced, the model can be presented. Equation 6.1 is the objective and all other equations are constraints of the model.

$$\min \quad \sum_{m\in M}\sum_{a\in A}\sum_{t\in T}(\gamma_{m,a,t}\cdot c_{m,a}) + \sum_{m\in M}\sum_{a\in A}\sum_{t\in T}\sum_{c\in C}((\delta_{m,a,c,t}+\Phi_{m,a,c,t})\cdot n_{m,a,t,c})+ \sum_{i\in I}\sum_{t\in T}(D_{i,t}-P_{x_{last},i,t})\cdot c_i^p + \sum_{i\in I}\sum_{t\in T} I_{x_{last},i,t}\cdot c_i^{hc} \tag{6.1}$$

$s.t.$

$$N_{m,t}^{EM} = \left(N_{m,t-1}^{E} + (1-\omega_{m,i,t}\cdot 0.2)\cdot \phi_{m,i,t}\cdot p_{m,i}\cdot U_{s,t}\right)\cdot(1-\gamma_{m,a,t}) \quad \forall m\in s, \forall s\in S^N, \forall t\in T \tag{6.2}$$

$$TI_{m,t}^{EM} = \left(TI_{m,t-1}^{E} + \phi_{m,i,t}\cdot p_{m,i}\right)\cdot(1-\gamma_{m,a,t}) \quad \forall m\in s, \forall s\in S^{TI}, \forall t\in T \tag{6.3}$$

$$\sum_{m\in M}\sum_{a\in A_c} n_{m,a,c,t} \le Cap_{t,c} \quad \forall t\in T, \forall c\in C \tag{6.4}$$

$$\sum_{t=k-\frac{L_{m,a}}{n_{m,a,c}^{min}}}^{k}(\delta_{m,a,t,c}+\Phi_{m,a,t,c})\cdot n_{m,a,t,c} = L_{m,a}\cdot\gamma_{m,a,t} \quad \forall m\in M, \forall a\in A, \forall c\in C \tag{6.5}$$

$$(\delta_{m,a,c,t}+\Phi_{m,a,c,t})\cdot n_{m,a,c}^{min} \le n_{m,a,c,t} \le n_{m,a,c}^{max}, \forall m\in M, \forall a\in A, \forall t\in T \tag{6.6}$$

$$\gamma_{m,a,t}\cdot\Delta_m^{N^{EM}} \ge N_{m,a,t-1}^{EM} - \Delta_m^{N^{EM}} + 1 \quad \forall m\in M^N \tag{6.7}$$

$$\gamma_{m,a,t}\cdot\Delta_m^{TI^{EM}} \ge TI_{m,a,t-1}^{EM} - \Delta_m^{TI^{EM}} + 1 \quad \forall m\in M^{TI} \tag{6.8}$$

$$\sum_{i\in I}\phi_{m,i,t} \le (1-\delta_{m,a,c,t}) \quad \forall m\in M, \forall t\in T, \forall a\in A, \forall c\in C \tag{6.9}$$

$$\sum_{c\in C}\delta_{m,a,c,t}\cdot\Phi_{m,a,c,t} \le \sum_{t-L_{m,a}}^{t}\gamma_{m,a,t} \quad \forall m\in M, \forall a\in A, \forall t\in T \tag{6.10}$$

$$P_{s,i,t} = \sum_{m\in s}(1-0.2\cdot\omega_{m,i,t})\cdot\phi_{m,i,t}\cdot p_{m,i} \quad \forall t\in T, \forall i\in I, \forall s\in S \tag{6.11}$$

$$P_t^D = \min_{s\in D}\left(\sum_{i\in I}P_{s,i,t}\right) \quad \forall t\in T \tag{6.12}$$

$$U_{s,t} = \sum_{i\in I}\frac{P_{i,t}^L - (\delta_{m,a,t,c}+\Phi_{m,a,t,c})\cdot p_{m,i}}{P_{s,i,t}} \quad \forall m\in s, \forall s\in S, \forall t\in T, \forall a\in A, \forall c\in C \tag{6.13}$$

$$Z_{x,i,t} = P_{x,i,t}\cdot U_{x,t} \quad \forall x\in S, \forall t\in T, \forall i\in I \tag{6.14}$$

$$Z_{x,i,t} = Y_{x+1,i,t} \quad \forall x\in X, \forall t\in T, \forall i\in I \tag{6.15}$$

$$I_{x,i,t} = I_{x,t-1,i} + Y_{x,i,t} - Z_{x,i,t} \quad \forall x\in X\backslash\{x_{last}\}, \forall t\in T, \forall i\in I \tag{6.16}$$

$$I_{x_{last},i,t} = \sum_{i\in I}\sum_{t'\in t}(P_{x_{last},i,t'} - D_{i,t'})^{+} \quad \forall x\in X, \forall t\in T, \forall i\in I \tag{6.17}$$

$$I_{x,i,t} = 0 \quad \forall x \in S, \forall t \in T, \forall i \in I \tag{6.18}$$
$$I_{x,i,t} \geq 0 \quad \forall x \in B, \forall t \in T, \forall i \in I \tag{6.19}$$
$$I_{x,i,t} \leq Buffer_x \quad \forall x \in B, \forall t \in T, \forall i \in I \tag{6.20}$$
$$I_{x,t,076} \cdot I_{x,t,082} = 0 \quad \forall x \in X, \forall t \in T \tag{6.21}$$
$$n_{m,a,c,t} \geq 0, \forall m \in M, \forall a \in A, \forall t \in T \tag{6.22}$$
$$\Theta_{i,t} \geq 0, \forall i \in I, \forall t \in T \tag{6.23}$$
$$\gamma_{m,a,t} \leq \omega_{m,i,t-1} \tag{6.24}$$
$$\gamma_{m,a,t} \in \{0,1\}, \forall m \in M, \forall a \in A, \forall t \in T \tag{6.25}$$
$$\phi_{m,i,t} \in \{0,1\}, \forall m \in M, \forall a \in A, \forall t \in T \tag{6.26}$$
$$\delta_{m,a,c,t} \in \{0,1\}, \forall m \in M, \forall a \in A, \forall t \in T \tag{6.27}$$
$$\Phi_{m,a,c,t} \in \{0,1\}, \forall m \in M, \forall a \in A, \forall t \in T \tag{6.28}$$
$$\omega_{m,i,t} \in \{0,1\}, \forall m \in M, \forall a \in A, \forall t \in T \tag{6.29}$$
$$n_{m,a,c,t} \in \mathbb{R} \tag{6.30}$$

6.1.3 Explanation mathematical model

Now the mathematical model is presented, the objective and all constraints are explained in more detail in Table 6.2.

Table 6.2: Explanation mathematical model

Equation	Description
6.1	Objective function that minimizes over maintenance task costs, mechanic man hours cost, penalty cost of unsatisfied demand, and holding costs
6.2	Number of products machine m processed up to time k for electrical and mechanical maintenance tasks
6.3	Number of hours machine m was in production up to time k for electrical and mechanical maintenance tasks
6.4	The number of mechanics with capacity c active during time t is within capacity of capacity c at time t
6.5	Maintenance task must be executed without interruptions
6.6	Number of mechanics working on maintenance task is within feasible limits for that task
6.7	Succeeding maintenance tasks must be completed before the deadline for mechanical maintenance tasks
6.8	Succeeding maintenance tasks must be completed before the deadline for mechanical maintenance tasks
6.9	Production cannot be running while performing machine-stopping maintenance
6.10	Maintenance start triggers maintenance task
6.11	Production rate for a production step
6.12	Production rate for the production steps between two decoupling points
6.13	Utilization of a production step in terms of full capacity

6.14	Number of items i processed at production step x at time t
6.15	Number of items i processed at production step x at time t proceed to production step $x + 1$
6.16	Inventory item i at production step x at time t equals inventory item i at production step x at time $t - 1$ plus processed items at production step $x-1$ at time t minus processed items at production step x at time t
6.17	Inventory and demand satisfaction at final production step
6.18	No inventory can be held at production steps that contain machines
6.19	Inventory is non-negative
6.20	Inventory must not exceed than buffer capacity
6.21	Production at time t on a production line is one unique item i
6.22	Number of mechanics working on a maintenance task is non-negative
6.23	Number of products of type i used to satisfy demand in time period f
6.24	Binary variable to indicate ramp-up and ramp-down loss due to maintenance tasks
6.25	Binary variable start maintenance task
6.26	Binary variable production active
6.27	Binary variable maintenance with machine stop active
6.28	Binary variable maintenance without machine stop active
6.29	Binary variable for ramp-up/ramp-down for machine
6.30	Number of mechanics is a real number

6.2 Programming

The mathematical model is programmed in Python using Gurobi 10.0.1, which is generally known as one of the best optimizing packages. The program in Python can be used to analyze the maintenance scheduling strategy for MSE2. For example, the model can provide insights in the effects of different capacity levels on the maintenance planning. It can also be used to analyze the effect on maintenance planning if delays in maintenance moments are allowed.

Chapter 7

Analysis Model Output

This chapter presents the analysis on the output of the mathematical model presented in Chapter 6. First, it explains the model's goal and the difference with current maintenance scheduling strategy. Then, the input parameters as used for the case-study at Bosch TbP are introduced. Thereafter, the comparison metrics, which are the different scenarios for the model, are explained. Then, the model output is visualized and a comparison is made between the different scenarios. The objective function of the mathematical model consists of maintenance costs, holding costs, and penalty costs. Each of these three cost components is discussed. The number of mechanics, which is part of the maintenance costs is discussed. Additionally, the demand pattern of mechanic man hours is presented. Then, the holding costs including the inventory level of finished goods are discussed. The third cost component, demand penalty costs, is discussed as well. Finally, a conclusion of the model output is provided.

7.1 Model goal

The maintenance planning at Bosch is presumed to be inefficient in terms of timeliness, MFM capacity planning, and flexibility. The timeliness refers to the fact that maintenance tasks are not executed near the theoretical deadline of the maintenance task. Maintenance requirements were designed for full production capacity while current production volume is significantly lower and maintenance intervals have not changed. In general one wants to execute maintenance tasks as late as possible to reduce average costs per produced unit. The MFM capacity planning and flexibility refer to current maintenance planning strategy, which is very rigid and causes peaks in demand for MFM capacity. To improve maintenance planning in these aspects, the model in Chapter 6 is proposed. The main element that the model proposes is flexible planning. It is not bounded by the four-weekly maintenance shift and plans maintenance tasks by considering maintenance requirements, customer demand, and mechanic man hours availability. This model is implemented in Python using Gurobi optimizer and this chapter provides an analysis on the maintenance planning, the MFM capacity, demand variation, and the deadline of maintenance tasks.

7.2 Input parameters

The model provided in Chapter 6 shows a general mathematical model that can be used by any production organization with serial production lines to plan maintenance activities. Some input parameters are defined specifically for Bosch Transmission Technology. Firstly, the skills of the mechanics are not included as this information was not available. So the model assumes that all mechanics have the knowledge to maintain all machines, including mechanical and electrical maintenance. The time unit used in the mathematical model is four hours. This makes the model smaller and faster to calculate. Current planning preciseness is in weeks so the level of detail of the maintenance planning will significantly increase. The mathematical model decides for every time unit whether production should be run, how much products are produced and whether maintenance should be executed for every individual machine. The problem is very large so the model is run for each month individually and the output of the month is used as input for the next. In doing so, the output of one year of maintenance planning consists of twelve subproblems that are solved. So the optimal solution for a scenario is the sum of twelve local optima. This way the model for 12 months can be run within 8 hours with a computer having 8GB RAM and an Intel(R) Core(TM) i7-7700HQ processor. But it should be noted that the sum of twelve local optima may differ from a global optimum.

The objective function of the model includes material costs, mechanic costs, demand shortage cost, and holding costs. The material costs are based on the actual maintenance task costs but scaled such that the numbers can be compared but no confidential information of Bosch TbP is shown. The hourly mechanic cost is fictionally set to 60 €. Then, demand shortage costs and holding costs are fictional costs as well. The production forecast already includes inventory replenishments. Holding costs are set to 0.0005 € per unit per time unit. The holding cost may seem insignificantly low but due to the high production volume holding cost accumulate quickly. If higher holding cost is chosen the holding cost will become relatively more important than maintenance costs and the model may behave differently and may not represent the improvement of maintenance scheduling. Using this holding cost balances holding costs such that no excessive inventory is build up while it prioritizes maintenance costs. This corresponds to reality as inventory goals are already included in production forecast. Customer needs are among the most important priorities within the company so demand penalty is set to 1,000,000 € per unit of late demand. This extremely high penalty cost is chosen to ensure that the model will only delay customer demand if this is caused by production capacity constraints. This corresponds to Bosch's way of working and its focus on customer needs.

The model uses maintenance task deadlines based on the production volume in 2017 and 2018 as shown in Section 4.1. The machine capacities are provided in Section 5.1. These machine capacities are measured when machines are operating continuously without disruptions. In practice, machines are not able to continuously operate at those levels of production output due to machine hick-ups, unavailability of products on the exact moment that the machine can process the next product, and so on. Bosch strives to operate with an Overall Operations Effectiveness (OOE) of 80%. Therefore, the model assumes production capacity of 80% of theoretical production capacity. The model uses the 'stamkaarten' as maintenance requirements. This includes maintenance task length, costs, and mechanic man hours needed, for example. The model assumes that the time provided in the SLAs of the maintenance requirements are accurate and discrete. Hence, the duration of a maintenance task will take exactly the amount of time that is provided by the SLAs.

The machine counters and next maintenance activity per machine as of January 1st, 2023, are used as starting situation. In doing so, the comparison between the model and the current maintenance planning can be made. So machine data are used to determine the state of all individual machines as of January 1st and historical maintenance data is used to determine which maintenance activity was executed last and on which date.

In addition to the input parameters explained above, there are some practicalities that the model needs to consider specifically for Bosch TbP. Production runs only six days per week, so there is no production on Sundays. Moreover, the mechanics only execute preventive maintenance from Monday to Friday every day between 8:00 and 16:00. So production runs continuously from Monday to Saturday whereas maintenance is only executed on weekdays during the day shift.

7.2.1 MFM capacity

The effect of a varying MFM capacity is analyzed to see to what extend maintenance activities for Loop Line 1a are influenced by capacity of MFM. Additionally, it may be interesting to see whether maintenance tasks can be levelled such that all requirements can be met within different levels of MFM capacity. By reducing the MFM capacity, the maintenance tasks cannot be executed at the same time as is currently done. This forces some tasks to be executed at different times. The MFM capacity levels are chosen to be infinite, 7, and 5 mechanics. When setting mechanic capacity to infinity the model shows that the maximum needed number of mechanics is 10. The minimum capacity is equal to 5 mechanics as the biggest task needs to be worked on by 5 mechanics. A mechanic capacity of 7 is chosen because this is between 10 and 5 mechanics and helps to see the behavior of the model.

7.2.2 Maintenance deadline margin

Maintenance activities are to be executed within a predetermined time frame or before a predetermined production volume. Optimally, a maintenance task is executed at the moment the deadline expires to achieve lowest average cost over time. However, due to MFM capacity constraints and production capacity constraints, maintenance tasks may be executed before the deadline. For example, in case of production capacity constraints, maintenance activities on different machines might need to be planned at the same time to reduce the amount of line stops and thereby reducing production availability interruptions. This means that the machine with the smallest deadline forces the machine with a longer lead time to be maintained earlier than its deadline. Including a maintenance deadline margin allows maintenance tasks to be executed shortly after the deadline to be more flexible in terms of planning. Then, the maintenance activity with the smallest deadline is slightly late while the maintenance deadline of the longer interval is less early. The levels of maintenance deadline margin included in the analysis are 0.0% and 5.0% maintenance deadline margin. The maintenance deadline margin of 0.0% is chosen to see the model's output if maintenance deadline is used as theoretically determined. Most production steps have a maintenance interval of 8 weeks in current maintenance strategy. A maintenance deadline margin of 5.0% is equal to extending the deadline of 8 weeks with 2.8 working days, which is expected to be sufficiently large to see results on a yearly basis.

7.2.3 Demand

Maintenance tasks are dependent on production volume, which is directly related to production demand forecast. The base for the analysis is the production forecast (FC) of 2023. To evaluate the model for different production volumes, the model is also run for a production demand forecast of the 2023 volume minus 10% and plus 10%. In doing so, the maintenance planning can be compared for different production volumes so Bosch TbP has knowledge about the effects of changing production volumes.

7.3 Comparison metrics

As discussed, the model is run for several values of MFM capacity, deadline margin, and production forecast. The MFM capacity (C) is changed for infinite, 7, and 5 mechanics, whereas the deadline margin (M) is changed for 0.0% and 5.0%. All combinations between the varying mechanic capacity and deadline margin are analyzed and the output is shown below. Furthermore, different production forecast scenarios are investigated. The 2023 forecast is run in the model with infinite mechanic capacity and 0.0% deadline while the forecast is changed to 10% less and 10% more than the 2023 forecast. Tables 7.1 and 7.4 show values for several parameters to compare different scenarios of mechanic capacity and maintenance deadline margin to the current maintenance planning. Table 7.7 shows the comparison between the different production forecast scenarios. The parameters are explained next.

First, the *maintenance costs of 2023* is the sum of the material costs and mechanic man hours cost for 2023. The *holding costs* are the total holding costs for inventory and the *penalty costs* are the total penalty costs for unsatisfied demand in 2023. The *number of activities* is self-explaining. Then, the *percentage of deadline* means the fraction of the theoretical maximum value of a deadline for a maintenance task at which the task is executed. So, if a maintenance task must be executed once 10 products are processed and it is executed when only 8 products are processed, the percentage of the deadline equals 80%. This is directly related to *days left*, which is defined as the mean number of days left to execute a maintenance activity on the moment of executing the activity. The *unique days* is the number of unique days that have a planned maintenance activity, whereas the *unique moments* is the number of unique moments that have a planned maintenance activity. A moment is defined as a time unit in the model, which is 4 hours. As maintenance tasks can only be executed between 8:00 and 16:00, every weekday has two moments in which maintenance can be planned. The *mean number of mechanics* is defined as average number of man hours needed per hour of maintenance and the *man hours* is the needed mechanic man hours for 2023. Finally, the *downtime* is equal to the total number of production hours lost.

7.4 Model output

The different scenarios are run in the model and Table 7.1 shows the output for the scenarios in which the margin for the deadline is 0.0% and the mechanic capacity changes for infinity, 7, and 5. Table 7.4 shows the output for a margin of 5.0%. These tables are used to compare the performance of the different scenarios. Note that the holding costs in current scenario are set to not available (N.A.) because no data is available regarding the relation between inventory and maintenance planning. Therefore, we can only compare the maintenance costs in current scenario to the maintenance costs in the model.

7.4.1 Scenarios with 0.0% margin

Current versus model

Firstly, a comparison is made between current scenario and the model output having infinite mechanic capacity and 0.0% deadline. Then, a comparison between the model output with varying mechanic capacity is made.

Table 7.1: Model output for differing mechanic capacity and deadline margin equals 0.0%

Scenario	**Current**	**C=inf M=0.0%**	**C=7 M=0.0%**	**C=5 M=0.0%**
2023 total costs	N.A.	91.02 €	91.43 €	94.50 €
2023 maintenance costs	100.00 €	89.27 €	89.73 €	92.57 €
2023 holding costs	N.A.	1.75 €	1.70 €	1.93 €
2023 penalty costs	0.00 €	0.00 €	0.00 €	0.00 €
Number of activities	144	107	109	112
Percentage of deadline	76.7%	98.0%	97.7%	97.8%
Days left	11.5	1.3	1.4	1.4
Unique days	25	47	67	64
Unique moments	40	71	95	92
Mean mechanics	3.9	1.8	1.3	1.4
Man hours	626	501	504	518
Downtime (h)	104	178	205	225

Currently, the maintenance costs for Line 1a in 2023 are planned to be 100.00 €. In case of a deadline margin of 0.0% and infinite mechanic capacity the maintenance costs are expected to be 89.27 €, which is a decrease of 10.7%. However, the number of planned maintenance activities decreases from 144 to 107, which is a decrease of 25.7%. The difference between these percentages is caused by the distribution of the costs in Production Step 2. At the start of the model run, on January 1, 2023, Production Step 2's next maintenance task is by far the highest cost of all maintenance activities. These costs are made in week 1 of 2023 in both the current maintenance planning and in the model's planning. But, this maintenance activity is due right in the beginning of 2024 for the current maintenance strategy, while it is not due for a longer time according to the model. Moreover, the moment of maintenance task execution increases from 76.6% of the theoretical deadline to 98.0% of the deadline. This indicates that maintenance activities in the model are delayed close to the theoretical optimal moment of maintenance task execution. Although infinite mechanic capacity means that there are sufficient mechanics to execute all maintenance tasks at the theoretical optimal moment of maintenance execution, some tasks are executed before the deadline. This is caused by production capacity constraints and by maintenance execution constraints. The production line needs to produce the demand for products so the production line cannot be shut down at all times. Maintenance can only be executed on Monday to Friday between 8:00 and 16:00, so we cannot execute maintenance at 100% of the deadline if it is due on Saturday or outside the day shift. Maintenance tasks may be grouped and this can cause some maintenance activities to be executed before the deadline.

Furthermore, the unique moments of maintenance execution increases significantly. In current maintenance strategy the number of unique moments is 40, whereas this increases to 71 for the model. So maintenance tasks are spread out over time and are not executed in the strict four-weekly intervals that Bosch TbP currently uses. The mean number of mechanics needed decreases from 3.9 mechanics per hour to 1.8 mechanics per hour, which is a decrease of 53.8%. This indicates that maintenance activities are spread out over time and less mechanics are needed at the same time. Note that this is an average number of mechanics needed during maintenance moments and only the hours that mechanics work on maintenance tasks are considered as costs. Mechanics spend spare hours on corrective maintenance, modicative maintenance, and projects. The decrease in needed mechanic hours indicates the decrease in total workload for mechanics, which is a decrease from 626 hours currently to 501 hours according to the model. So in the model's output we have less total maintenance hours and the maintenance hours are spread out over more moments.

Finally, the total number of hours of downtime is measured. In current maintenance strategy 104 hours of downtime are registered. There are 13 four-weekly intervals in a year, all causing one shift of downtime. So 13 times 8 hours of downtime are registered. However, the number of maintenance moments for current strategy is higher than the 13 days and corresponding 26 moments. The maintenance department decided to schedule some tasks of parallel machines outside the regular four-weekly intervals due to the production overcapacity of these production steps compared to current production volume. The small tasks outside the regular intervals do not cause additional line stops so the downtime hours in current scenario equals 104 hours per year. The model proposes to execute tasks over more moments in time, so the amount of hours that the production line cannot operate on 100% capacity will increase. This leads to an increase of downtime in 2023 to 178 hours. We cannot compare the 178 hours of downtime of the model to the 104 hours of downtime in current maintenance scheduling strategy as the model considers opportunities in production capacity to schedule maintenance, which is then registered as downtime. But current maintenance strategy does not consider opportunities in production capacity. So in current maintenance scheduling strategy we have 104 hours of downtime per year but we do not use the production line for 100% during all available production hours as we simply do not have that much demand. Moreover, an increase in downtime is not necessarily bad in case of production overcapacity such as is the case now. It must be noted that it is assumed that downtime does not cause additional costs in terms of idle operators. As maintenance planning is known far ahead operators can be assigned different tasks timely and no productivity loss of the employee hours are included. This is similar to current maintenance scheduling strategy at Bosch TbP, in which operators are assigned cleaning tasks for example. Concluding, there is enough production capacity left when maintenance tasks are spread out and using production overcapacity advantageously causes additional downtime. The effect of production overcapacity is considered in Section 7.7, where demand variation is evaluated.

Comparison scenarios varying capacity

Several things are noted when looking at the differences between the scenarios with varying mechanic capacity in Table 7.1. Firstly, a decreasing mechanic capacity shows increasing maintenance costs. Increasing maintenance costs are directly related to increasing number of maintenance activities. It is noted that maintenance costs do not increase linearly with number of activities. This is caused by the difference in maintenance task costs. Similarly for the needed mechanic man hours, not all maintenance tasks have the same workload so the number of maintenance activities does not increase linearly with the number of needed mechanic man hours. When mechanic capacity decreases peak demand for mechanic man hours cannot be satisfied so less maintenance activities can be executed at the same time. Some tasks need to be executed earlier due to mechanic capacity constraints when several activities are due at the same time. By executing tasks earlier than their deadline, future activities will be executed earlier causing more activities to be executed on a yearly basis. We do not see a significant decrease in the percentage of the deadline when mechanic capacity decreases. However, we see that the percentage of deadline for capacity of 7 mechanics is slightly lower than the percentage of deadline for a capacity of 5 mechanics. Due to rounding the table shows a difference of 0.1% but the difference between these percentages is 0.05%, which equals 0.62 hours of difference in maintenance activity execution in terms of average maintenance interval in current situation. The activities that differ between the two scenarios are visualized in Table 7.2.

Table 7.2: Different maintenance tasks in scenarios with M=0.0% and C=7 or C=5

Machine	Maintenance task	Deadline	In scenario
0916	8M8	100%	Capacity 7
0838	32E32	100%	Capacity 5
1082	8M8	99%	Capacity 5
1133	4M32	100%	Capacity 5
0979	4M16	96%	Capacity 5

We see that one maintenance task is executed in the scenario with 7 mechanics and four maintenance tasks are executed in the scenario with 5 mechanics. To explain the difference in maintenance task execution, the machine counters of the machines are looked into. When mechanic capacity equals 7 the counter for Machine 0916 at the end of December 2023 is 1,904,689 units whereas this is 1,666,603 units when mechanic capacity equals 5. The sum of the counters of all machines in the production step are equal in both scenarios. So the production step processed an equal amount of products over 2023 but the individual machines processed a different number of products. It does not matter which machine produces what number of products in some months as there is no maintenance activity due during the month. However, demand and production capacity constraints might force all machines to run production in later months, which causes a machine to be maintained slightly earlier. This example illustrates the difference between scenarios that can happen in parallel production steps. This is the case for Machine 0916, Machine 0838, and Machine 1082 in Table 7.2. Machines 0838, 0916, and 1082 are maintained based on processed volume but Machines 0979 and 1133 are maintained based on production time. The production time counters of Machines 0979 and 1133 at the end of December 2023 are shown in Table 7.3. This shows that both machines use more operating time when mechanic capacity decreases while we know that production quantity is equal in the scenarios. Due to the increasing number of maintenance moments and maintenance hours, production capacity of such machines is not utilized to its full extend while operating time is accumulating linearly. To produce enough products at the end of a time period, the machines need to operate more hours. A machine can reach its maintenance deadline earlier due to lower utilization when maintenance is time based. So now we know why scenarios might include some different tasks at the end of the time horizon, which is caused by different use of machines.

Table 7.3: Hourly counter Machines 0979 and 1133 end of December 2023

Capacity	**0979**	**1133**
Infinity	2659	3334
7	2677	3352
5	2711	3386

Furthermore, we see a varying holding cost when mechanic capacity changes. The holding costs slightly decrease when mechanic capacity decreases from infinity to 7 and increases from 7 to 5 mechanics. If we only look into the parallel production steps, the number of unique maintenance moments for an infinite mechanic capacity equals 54, for a mechanic capacity of 7 it equals 79, and for a mechanic capacity of 5 it equals 71. The number of moments for parallel production steps is very high in the scenario of 7 mechanics. The percentage of production capacity loss when there are more maintenance moments for parallel production steps is less when we have more maintenance moments. This explains why holding costs in the scenario with 7 mechanics has slightly lower holding costs.

Further it is noted that the unique days and unique moments roughly increases when mechanic capacity decreases. However, the number of unique days and unique moments when mechanic capacity equals 5 is slightly lower than when capacity is 7 mechanics. This is compensated for a slightly higher mean number of mechanics per hour needed. Also, the number of needed man hours increases when mechanic capacity increases, which is directly related to the increase in maintenance tasks. Moreover, the downtime increases, which is related to the number of maintenance moments and the increase in maintenance tasks.

7.4.2 Scenarios with 5.0% margin

Table 7.4 visualizes the output for scenarios when maintenance deadline margin is 5.0% and a varying mechanic capacity. These scenarios show similar relations between parameters as was explained for Table 7.1 but perform approximately 1% better in terms of costs and number of activities executed. Compared to a deadline margin of 0.0%, the percentage of the deadline increases from around 98% for all mechanic capacities and a

Table 7.4: Model output for differing capacity and margin equals 5.0%

Scenario	**Current**	**C=inf M=5.0%**	**C=7 M=5.0%**	**C=5 M=5.0%**
2023 total costs	N.A.	90.16 €	90.64 €	91.83 €
2023 maintenance costs	100.00 €	88.61 €	89.00 €	90.11 €
2023 holding costs	N.A.	1.55 €	1.64 €	1.72 €
2023 penalty costs	0.00 €	0.00 €	0.00 €	0.00 €
Number of activities	144	106	107	113
Percentage of deadline	76.7%	103.6%	103.1%	101.2%
Days left	11.5	0.1	0.3	1.1
Unique days	25	61	70	64
Unique moments	40	82	97	88
Mean mechanics	3.9	1.5	1.3	1.4
Man hours	626	496	497	507
Downtime (h)	104	176	217	184

deadline margin of 0.0% to around 103% for all mechanic capacities and a deadline margin of 5.0%. This increase is more then the decrease in costs, which is why the expected yearly costs will also decrease slightly more in time as percentage of deadline increased significantly. In general we see that when mechanic capacity decreases maintenance costs increase, the number of of maintenance tasks increases, the percentage of deadline decreases, and the needed man hours increases. However, we see that the number of unique days and unique moments significantly drops when mechanic capacity is 5 instead of 7. More maintenance tasks and mechanic man hours are scheduled in less moments. The percentage of maintenance deadline drops slightly more when comparing mechanic capacity 7 and 5 than when comparing mechanic capacity infinity and 7. This drop is explained by the decrease in unique maintenance moments as this means that more activities are executed at the same time. So more activities are executed before their deadline. This also explains the decrease in downtime hours between capacity of 7 and 5 mechanics.

On a side note, preventive maintenance tasks at Bosch TbP can be electrical or mechanical, which is included in the mathematical model in Chapter 6. It is assumed that mechanics in the model have the knowledge to execute all maintenance tasks including mechanical and electrical tasks. It is not interesting to investigate for electrical mechanics separately as the number of maintenance hours needed for electrical maintenance is relatively low. In both the type of scenarios with 0.0% and 5.0% maintenance deadline margin the number of mechanic man hours needed for electrical tasks was 16 hours when mechanic capacity is infinite or 7 and the number of needed mechanic man hours was 18 hours when mechanic capacity was 5 mechanics. This corresponds to roughly 3.2% of total demand for mechanic man hours and a total of roughly two working days per year.

Summarizing, for both scenario sets with 0.0% and 5.0% maintenance deadline margin we see increasing maintenance costs for decreasing mechanic capacity. The increasing maintenance costs are caused by execution of more maintenance tasks due to earlier execution. In general, we see increasing holding costs when mechanic capacity decreases, which is caused by more interruptions of production. Inherent to these observations the number of needed man hours increases and downtime increases as well.

7.4.3 Maintenance interval length

Tables 7.1 and 7.4 show the maintenance costs and activities for 2023. Due to differing costs and workload for maintenance tasks, these numbers cannot be evaluated unambiguously. Therefore, the average interval length for each production step is evaluated, which is a measure that can be used to compare current maintenance strategy to the model's maintenance strategy. The interval length is the number of weeks between two succeeding maintenance tasks for individual machines. If a production step has multiple machines, the average of the interval lengths for the machines in the production step is taken. Table 7.5 shows the comparison between current scenario and the scenarios of the mathematical model. The average interval length is the average of all intervals of the machines for the production steps of the production line. The comparisons made in these tables are important to evaluate potential improvement of current maintenance strategy.

Table 7.5: Average interval length between succeeding maintenance activities in weeks for 2023

C **M**	**Inf** **0.0%**	**7** **0.0%**	**5** **0.0%**	**Inf** **5.0%**	**7** **5.0%**	**5** **5.0%**	**Current**
P1	8.2	8.2	8.6	8.6	8.2	8.4	8.0
P2	5.1	4.8	4.7	5.2	5.2	5.2	4.0
P3	5.1	4.8	5.0	5.2	5.2	5.2	4.0
P4	9.7	9.6	9.4	10.3	10.0	9.4	8.0
P5	10.0	9.8	10.0	10.3	10.8	10.3	8.0
P6	10.3	9.8	9.8	11.3	11.3	10.0	8.0
P7	12.7	12.0	12.2	12.8	12.4	11.6	8.0
P8	13.3	14.0	11.7	13.7	14.0	11.3	8.0
P12	18.4	18.3	18.0	19.7	19.0	21.0	16.0
Average	11.1	10.9	10.7	11.6	11.4	11.1	8.7

Table 7.5 shows that for the model with infinite mechanic capacity and 0.0% deadline margin the total interval length increased from 8.7 to 11.1 weeks compared to the current maintenance strategy, which is an increase of 27.6%. When mechanic capacity decreases the average interval length decreases as well. This is related to the increased number of executed maintenance tasks as explained before. The output is similar but interval lengths are slightly larger when the maintenance margin deadline is 5.0%. The model output shows huge potential of implementing the volume- and time-based maintenance strategy as proposed by the model.

Concluding, the model shows that maintenance deadline percentage increases from 76.7% to 98.0% resulting in an increase of 27.6% in maintenance interval length and a decrease in maintenance activities is 25.7% for 2023. So the model plans the maintenance tasks much closer to the maintenance deadline and increases the average maintenance interval length. The percentages slightly differ due to the low number of maintenance activities in a year and are expected to converge over longer periods of maintenance planning. In addition, for further research it might be interesting to investigate the effects of the deadline margin on machine performance to make a choice for deadline margin.

7.5 Number of mechanics

One of the cost components of maintenance is the number of mechanic man hours needed, which is an issue in current maintenance planning at Bosch TbP due to the highly fluctuating demand for mechanic man hours. Therefore, a high number of mechanics is needed for maintenance execution. The number of mechanics needed is high due to the fact that all maintenance activities of one production line are to be performed in one shift in current situation. By planning maintenance according to the proposed model in Chapter 6, the number of mechanics needed is expected to decrease. Therefore, the number of needed mechanics in current situation is compared to the number proposed by the model. As explained before, the minimum number of mechanics that can be available must be five as the biggest maintenance task requires five mechanics to work at the same time. The comparison is made for the current situation versus the scenarios with 0% deadline margin and an infinite mechanic capacity as well as a capacity of five mechanics. The number of needed mechanics over the 2023 maintenance planning is visualized in Figures 7.1 and 7.2.

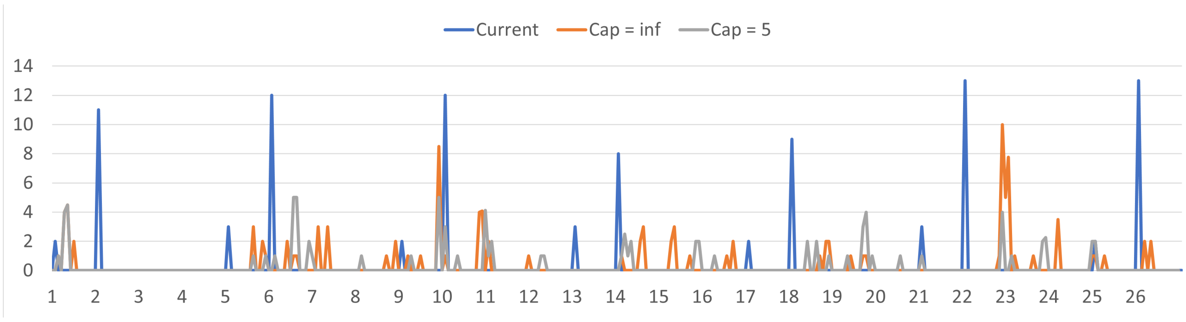

Figure 7.1: Comparison number of mechanics first half of 2023

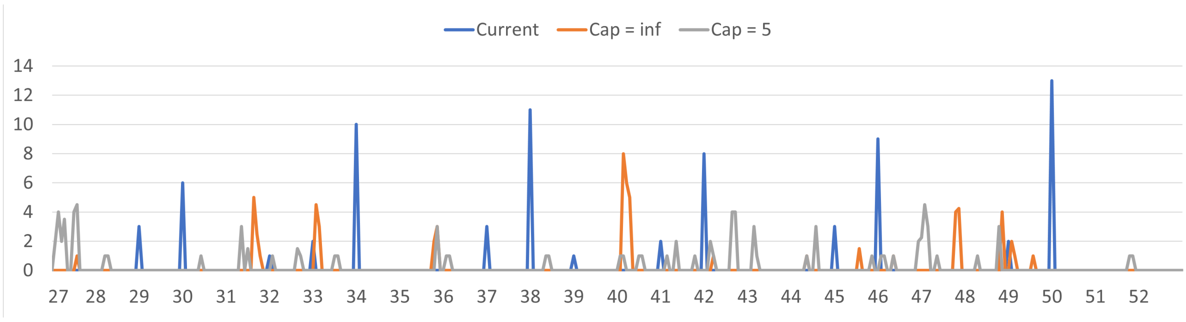

Figure 7.2: Comparison number of mechanics second half of 2023

Figures 7.1 and 7.2 visualize the number of needed mechanics throughout the weeks of 2023. The current situation clearly shows the high peaks every four weeks whereas the number of needed mechanics in the model significantly decreases and is spread out over time more evenly. This shows that the peak demand for mechanics over time is levelled when using the model. This was also confirmed by model output in Tables 7.1 and 7.4, which show the mean number of mechanics needed per maintenance moment decreases in the model output, mainly caused by an increase in maintenance moments.

7.6 Inventory

One of the cost components in the objective of the mathematical model is inventory. As discussed in Section 7.2, customer demand is one of the top priorities at Bosch TbP. To cover for demand fluctuations the inventory goals are included in production forecast. Producing more products than the forecast only yields production costs and additional holding costs as well as it causes maintenance activities to be due earlier, so it does not make sense for the model to produce more than the production forecast. However, throughout time the inventory must be built up to satisfy demand in time if the production line is down for maintenance for a period of time. So demand might be produced slightly before it is due. Therefore, the inventory of loops is analyzed to see how the model handles production and maintenance planning. Figure 7.3 shows the inventory level of finished goods, which is number of loops, over time in 2023 in the scenario with infinite mechanic capacity and a margin of 0.0%.

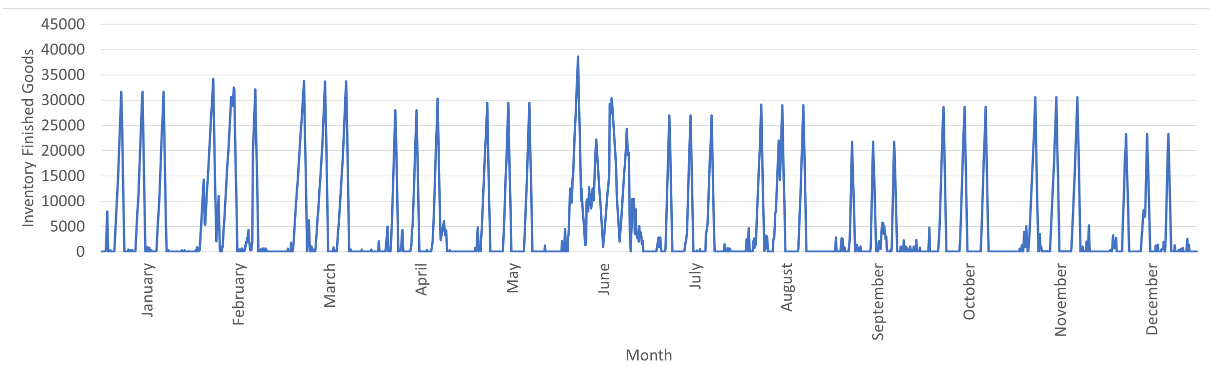

Figure 7.3: Inventory loops 2023

The number of loops as inventory over time in 2023 seems to have peaks at approximately 30,000 units and goes to zero right after such peak. It is expected that these peaks are caused by line stops due to maintenance tasks execution. As demand satisfaction is of extreme importance, inventory will be built up right before line stops to cover demand timely. An inventory level 30,000 is approximately equal to two shifts of full production, which seems logical to build up as a maximum if some maintenance activities are scheduled close to one another over multiple days. The inventory levels of February are zoomed in to exemplify. Figure 7.4 visualizes inventory of loops through February 2023.

To further analyze the inventory level during February, we need to know the downtime caused by maintenance. Table 7.6 shows the downtime moments and the percentage of output loss during those moments. The downtime information for February shows that roughly four moments of high output loss can be identified. The first is at February 6th when the production line is impacted from 8:00 to 16:00. The second is at February 9th when the production line is down from 8:00 to 16:00. The third is during the afternoon shift of February 13th and the morning shift of February 14th. And the final output loss is between February 24th and February 27th, when shifts are impacted partially over time. All of these events impact inventory buildup as visualized in Figure 7.4 with the data labels. Summarizing, inventory levels stay fairly low over time with a maximum of approximately two shifts of production. This is done to build up some stock to satisfy demand during maintenance task execution.

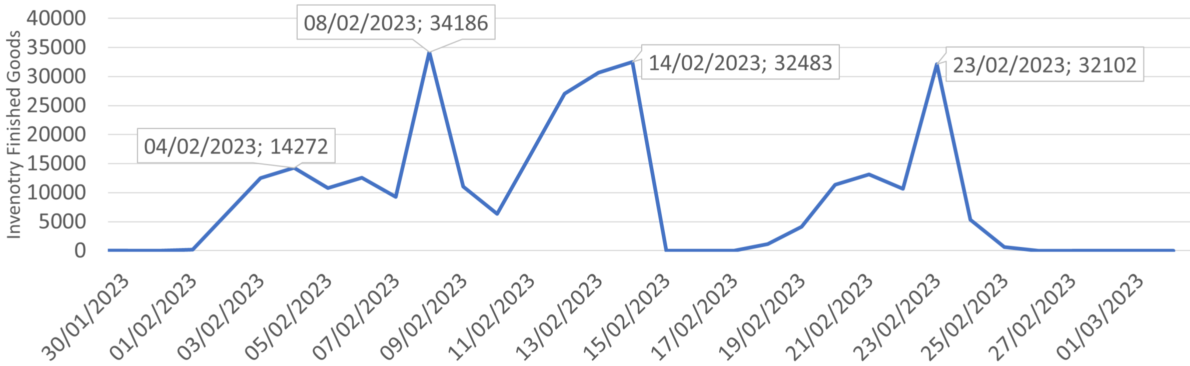

Figure 7.4: Inventory loops February 2023

Table 7.6: Downtime April 2023

Date	Timeframe	Capacity loss
02/02/2023	8:00-12:00	27.3%
06/02/2023	8:00-12:00	100.0%
06/02/2023	12:00-16:00	37.2%
09/02/2023	8:00-12:00	100.0%
09/02/2023	12:00-16:00	100.0%
13/02/2023	12:00-16:00	100.0%
14/02/2023	8:00-12:00	100.0%
24/02/2023	8:00-12:00	25.0%
24/02/2023	12:00-16:00	16.1%
27/02/2023	8:00-12:00	15.0%

7.7 Demand satisfaction

One of the cost components of the objective in the mathematical model is the penalty cost for unsatisfied demand. As discussed previously, the customer demand is of extremely high importance to Bosch TbP. Therefore, the fictional demand penalty cost is set extremely high. This causes the model to produce all demand in time and invest in inventory as shown in Section 7.6. It must be noted that unexpected failures may happen in reality and can cause demand to be delayed. This is excluded from the model and the model shows that it works corresponding to Bosch's customer focus. Model output shown in Tables 7.1 and 7.4 confirm this with penalty cost over 2023 of 0.00 €. This means that all demand is satisfied in time and no penalty costs are incurred. It is interesting to see what the model's output is when demand differs. To see effects of varying demand, the 2023 forecast is changed with 10% less and 10% more demand in the scenario with infinite mechanic capacity and 0.0% deadline margin. The output is shown in Table 7.7.

Table 7.7 shows the model output when demand is 10% higher or 10% lower than the 2023 forecast. It shows that number of maintenance tasks decreases when demand decreases and increases when demand increases. This corresponds to expectation and

Table 7.7: Model output for differing mechanic capacity and deadline margin equals 0.0%

Scenario	Current	C=inf M=0.0% 2023 FC	C=inf M=0.0% 2023 FC - 10%	C=inf M=0.0% 2023 FC + 10%
2023 total costs	N.A.	91.02 €	85.96 €	96.17 €
2023 maintenance costs	100.00 €	89.27 €	84.70 €	94.08 €
2023 holding costs	N.A.	1.75 €	1.25 €	2.08 €
2023 penalty costs	0.00 €	0.00 €	0.00 €	0.00 €
Number of activities	144	107	97	118
Percentage of deadline	76.7%	98.0%	98.0%	98.1%
Days left	11.5	1.3	1.3	1.3
Unique days	25	47	62	70
Unique moments	40	71	67	79
Mean mechanics	3.9	1.8	1.7	1.7
Man hours	626	501	454	534
Downtime (h)	104	178	222	194

how the model would work considering that maintenance is production volume and time based. This directly relates to the difference in maintenance costs, which increases when demand increases and decreases when demand decreases. The same behavior is seen for the needed mechanic man hours. Moreover, we see that the number of downtime hours significantly increases when demand decreases. So less maintenance is executed but more downtime is caused by maintenance activities. The number of activities decreases from 107 to 97, while the number of downtime hours increases from 178 hours to 222 hours, which is an increase of 24.7%. Due to production overcapacity, which increases when demand decreases, the number of affected hours can be higher. When demand increases, we see that the downtime also increases but not as much as in the lower demand scenario. Obviously, the increase in maintenance activities of 10.3% in case of the high demand needs time to be executed. Therefore, the number of downtime hours increase from 178 hours to 194 hours, which is an increase of 9.0%. Also we see that the holding costs decrease when demand decreases and increase when demand increases. Due to the lower number of maintenance activities and lower demand per time unit less inventory needs to be held during less time. Therefore, holding costs moves with demand.

Table 7.8 shows the interval lengths for varying demand when mechanic capacity is infinite and deadline margin is 0.0%. It shows that the maintenance interval length increases from 11.1 weeks to 12.2 weeks when demand decreases with 10%. Additionally, we see a decrease from 11.1 weeks to 10.2 weeks when demand increases with 10%. Current maintenance scheduling strategy does not consider production volume when planning maintenance. The output shows that an increase of production forecast reduces the average interval length, hence reduces the potential reduction of costs. Also it shows that a decrease of production forecast increases the average interval length, so it increases the potential reduction of costs. When production forecast is 10% lower than the 2023 forecast, the potential cost reduction is 40% compared to current maintenance scheduling strategy. If the production forecast is 10% higher than the 2023 forecast, the potential cost reduction is 17% compared to current maintenance scheduling strategy. So potential cost reduction depends on the utilization of production capacity.

Table 7.8: Average interval length between succeeding maintenance activities in weeks for 2023

C **M** **D**	**Inf** **0.0%** **2023 FC**	**Inf** **0.0%** **2023 FC - 10%**	**Inf** **0.0%** **2023 FC + 10%**	**Current**
P1	8.2	9.5	8.5	8.0
P2	5.1	5.6	4.9	4.0
P3	5.1	5.3	4.9	4.0
P4	9.7	10.9	8.5	8.0
P5	10.0	10.3	10.3	8.0
P6	10.3	11.0	9.8	8.0
P7	12.7	14.2	10.5	8.0
P8	13.3	15.0	13.7	8.0
P12	18.4	19.0	17.7	16.0
Average	11.1	12.2	10.2	8.7

7.8 Model output conclusions

The maintenance planning at Bosch is presumed to be inefficient in terms of timeliness, MFM capacity planning, and flexibility. These elements are included in the mathematical model. The timeliness refers to the moment of maintenance task execution, which increases from 76.7% in current maintenance planning to 98.0% in the model's planning. This corresponds to the decrease in yearly maintenance tasks of 26% and an increase of average maintenance interval lengths of 28%. As discussed before, these two percentages slightly differ due to relatively low number of maintenance activities in one year. The two numbers are expected to converge when the maintenance planning is run over a longer period of time. The MFM capacity planning is highly fluctuating, but the model can ensure a decrease in average mechanic man hours demand by spreading out the maintenance tasks over time as it is not bounded by the strict four-weekly maintenance intervals. This causes that the number of moments maintenance tasks are planned increases from 40 to 71, which decreases peak demand for mechanic man hours. Moreover, this provides the opportunity for the model to schedule maintenance tasks further to the end of the deadline. This causes total downtime to increase, which is not bad in case of production overcapacity. Furthermore, the model respects the high priority of Bosch's customer demand by producing all products in time. Concluding, the model improves preventive maintenance scheduling in terms of timeliness, MFM capacity planning, and flexibility.

Improvement of maintenance scheduling is possible due to overcapacity of production lines. The possibilities to schedule individual maintenance tasks on or close to its deadline decreases when utilization of the production line increases. When utilization of the production line increases it is expected to increase yearly maintenance costs. This is seen in in the scenario for which the production forecast for 2023 is increased and decreased with 10%. We saw that the maintenance interval length increased with 9.9% in the low demand scenario and it decreased with 8.1% when demand increased compared to the model's output with 2023 production forecast. Summarizing, yearly maintenance costs are reduced by approximately 28% based on the production forecast of 2023 but this depends on production volume. If production forecast is between 10% lower and 10% higher than the 2023 forecast, the potential cost reduction is between 17% and 40% on a yearly basis.

Chapter 8

Conclusion and recommendations

This chapter concludes the research at Bosch TbP and answers the main research question. The main research question is answered by answering the four sub research questions as defined in Section 2.5. Furthermore, it provides recommendations to Bosch TbP regarding interpretation of the data and using the model.

8.1 Conclusion

The main research question is answered by answering the four sub research questions. The production capacity, external mechanic man hours, production demand forecast, and maintenance adaption to production volume are reviewed in the sub research questions. After answering the sub research questions the output in terms of costs is discussed and a final conclusion is given.

How to improve the maintenance scheduling strategy for MSE2 in terms of total maintenance costs?

1. How to ensure sufficient production capacity while complying to maintenance requirements?

The first sub research question considers production capacity in relation to maintenance requirements. As discussed in Chapter 5, the maintenance planning at Bosch TbP is a challenging case regarding production line availability, maintenance requirements, and mechanic capacity. These three elements are to be in balance in order to have a sustainable maintenance planning. We need mechanic capacity to satisfy maintenance requirements and the maintenance requirements must be met to ensure high quality of machines, which takes production line availability. Therefore, the mathematical model in Chapter 6 is proposed. The results in of this model are of high potential for Bosch TbP. To ensure sufficient production capacity while complying to maintenance requirements, several constraints are added to the mathematical model. Specifically, the demand is ensured by the high penalty cost in the objective function while the maintenance requirements are ensured by Constraints 6.2 and 6.3.

2. How to decrease usage of external mechanic man hours?

Currently, Bosch TbP plans one shift of downtime every four weeks for every production line. All maintenance activities due at that shift are to be executed immediately. Therefore, all mechanics are dedicated to one production line at the same moment in time. This causes fluctuation in demand for mechanics. To cope with such peaks Bosch TbP hires external mechanics. However, this is undesirable for a number of reasons. Firstly, external mechanics are expensive so it is worthwile if hiring can be avoided. Secondly, there is overcapacity of mechanics during times of no planned production stops. This overcapacity is costly and could better be used to maintain machines. Thirdly, it could be advantageous to keep all maintenance knowledge in-house to not be depending on external mechanics in case of emergencies. Therefore, the effect of a lower mechanic capacity is analyzed in Chapter 7 to see what the effect of lower mechanic capacity is while planning maintenance according to the new model. The analysis shows that a lower capacity of mechanics is feasible if maintenance tasks are spread out over time. This is logical as mechanics then have more moments to work on maintenance tasks, so less mechanics are needed at the same time. The model in this research only considers Production Line 1a and shows a decrease in average needed mechanics per moment from 3.9 to 1.8, which is a decrease of 54%. However, the number of maintenance moments increased and we have seen an increase in maintenance interval length of 28%, which is why the number of mechanic hours needed per year can be decreased up to 28%, which may be the complete external hours and a part of the internal hours. To further analyze the needed number of mechanics and the impact of decreasing external mechanics, the complete line needs to be included in the model.

3. How to use production demand forecast to schedule maintenance?

4. How to adapt maintenance activities to production volume?

Sub research questions 3 and 4 are very much related to one another so these are answered together. Maintenance requirements at Bosch TbP are based on production volumes at full capacity, which was the case in 2017 and 2018. The production numbers of these years are considered to be the base for the maintenance requirements. The standard four-weekly intervals are calculated for individual machines in Section 4.1 to use as maintenance deadlines. Production volumes decreased over time but the maintenance planning did not adjust accordingly. The adaptation of maintenance planning to production volume can be done by basing maintenance planning directly on production volume or time. Bosch is able to do so as they installed production counters on most of their machines. To base maintenance planning on production volumes, the standards as explained before are used to define new maintenance task deadlines. Within the production numbers of 2017 and 2018 we saw that there was potential to improve maintenance planning for parallel machines. Not all machines in a parallel production step process an equal amount of products. This can be caused by the way the production line is designed or machine failures for example. Therefore, the machine that processed most of a production step during 2017 and 2018 is considered to be the standard for a production step. So, the maintenance planning can be adapted to production volume by using the standards for maintenance requirements based on full production capacity.

To answer the main research question, the data from Chapter 7 is used. The maintenance scheduling strategy can be improved by using a production volume and production time based model. In doing so, the maintenance requirements are satisfied but minimized over costs. This is caused by delaying preventive maintenance execution until the theoretical deadline. The data shows that in current situation the execution of maintenance tasks is at 76.6% of the theoretical deadline, while the model provides a new maintenance planning that ensures the execution of maintenance tasks at 98.0%. Moreover, the model shows that less mechanics are needed at the same time so the number of external mechanics can be decreased. To illustrate, the number of needed mechanics at the same moment decreases from 3.9 in current maintenance scheduling strategy to 1.8 in the mathematical model. Also, an analysis is done with varying demand. This showed that the model uses production overcapacity advantageously. So maintenance costs can be reduced significantly while demand for mechanics is lower and less fluctuating. The maintenance costs are expected to decrease with 28% based on the 2023 production forecast. If production demand decreases the potential reduction increases and vice versa. So potential reduction is dependent on production demand forecast.

8.2 Recommendations

It should be noted that the analysis in this research is solely based on Production Line 1a. To further investigate the potential impact for Bosch, Production Lines 1b, 2a, and 2b should be included as well. This will yield more extensive results for Bosch TbP to decide upon which parameters to use when planning maintenance. Furthermore, the model will be more precise if all machines are equipped with production counters.

Besides the functional recommendations, the main recommendation is to incorporate the new maintenance planning strategy in the production lines and use the mathematical model to determine an improved planning. The maintenance deadline margin may give an additional opportunity to consider. As seen in the data, for a maintenance deadline margin of 0.0%, the average percentage of the deadline is 98.0%. This means that there is room for extending the deadline on average.

Currently, maintenance requirements for machines are grouped and executed at the same time for a full production line at the same time. The model shows huge potential to schedule maintenance planning more flexibly. However, the maintenance requirements for individual machines are still grouped. So a 'stamkaart' consists of multiple activities to execute at the same time for an individual machine. Maybe a 'stamkaart' could be split into smaller ones to be even more flexible in scheduling. Additionally, this could provide the opportunity to give activities within a 'stamkaart' different deadlines, which is not the case now. This can potentially improve maintenance planning at Bosch TbP even more.

The model optimizes maintenance planning for individual months and uses the month's output as the next month's input. Therefore, the maintenance planning for one year consists of twelve local optima. The choice for running the model for individual months was made to reduce calculation time. It would be interesting to see the difference in performance of the model if a full year could be run together.

The advantages of current maintenance scheduling strategy are ease of planning, predictability of maintenance tasks in the future, and ease of spare parts purchasing. The model proposes a new maintenance planning, so it should still be easy to schedule maintenance. However, it requires flexibility from production and maintenance departments. Additionally, the predictability of maintenance tasks is still secured as a maintenance planning for a full year is determined for one model run so maintenance planning is roughly known one year ahead. This ensures the ease of spare parts purchasing as well. Moreover, maintenance efforts decrease with current production volumes, so it should cause less planning of maintenance and less demand for spare parts. Concluding, the proposed scheduling strategy also includes the advantages that the current maintenance strategy has.

Concluding, the recommendation to Bosch TbP is to use the mathematical model to schedule maintenance activities and to determine the optimal number of mechanics needed depending on production forecast. This means shifting to a volume based maintenance scheduling strategy. This yields a yearly cost reduction of up to 28% in maintenance costs based on the 2023 production forecast. If production forecast is between 10% lower and 10% higher than the 2023 forecast, the potential cost reduction is between 17% and 40% on a yearly basis.

References

Arts, J. (2014). Elementary maintenance models. *Lecture notes for 1CM30-Service Supply Chains for Capital Goods*, 1–43.

BoschGroup. (2022). *The bosch group main website.* Retrieved 2022-09-07, from `https://www.bosch.com/`

Chelbi, A. & Ait-Kadi, D. (2004). Analysis of a production/inventory system with randomly failing production unit submitted to regular preventive maintenance. *European journal of operational research*, *156*(3), 712–718.

Costa, A., Cappadonna, F. A. & Fichera, S. (2016). Total tardiness minimization in a parallel machine system with flexible periodic maintenance. *Journal of Industrial and Production Engineering*, *33*(7), 485–494.

Fitouhi, M.-C., Nourelfath, M. & Gershwin, S. B. (2017). Performance evaluation of a two-machine line with a finite buffer and condition-based maintenance. *Reliability Engineering & System Safety*, *166*, 61–72.

Kaabi, J. & Harrath, Y. (2014). A survey of parallel machine scheduling under availability constraints. *International Journal of Computer and Information Technology*, *3*(2), 238–245.

Kenné, J.-P., Gharbi, A. & Beit, M. (2007). Age-dependent production planning and maintenance strategies in unreliable manufacturing systems with lost sale. *European Journal of Operational Research*, *178*(2), 408–420.

Kiran, D. (2019). *Production planning and control: A comprehensive approach.* Butterworth-heinemann.

Koochaki, J., Veldman, J. & Wortmann, J. (2008). Literature survey on condition based maintenance within the process industry. In *Proceedings of 21st congress of condition monitoring and diagnostic engineering management (comadem 08).*

Li, J., E. Blumenfeld, D., Huang, N. & M. Alden, J. (2009). Throughput analysis of production systems: recent advances and future topics. *International Journal of Production Research*, *47*(14), 3823–3851.

Liu, Y., Zhang, Q., Ouyang, Z. & Huang, H.-Z. (2021). Integrated production planning and preventive maintenance scheduling for synchronized parallel machines. *Reliability Engineering & System Safety*, *215*, 107869.

Maecker, S., Shen, L. & Mönch, L. (2022). Unrelated parallel machine scheduling with eligibility constraints and delivery times to minimize total weighted tardiness. *Computers & Operations Research*, 105999.

Manzini, R., Regattieri, A., Pham, H., Ferrari, E. et al. (2010). *Maintenance for industrial systems*. Springer.

Nyman, D. & Levitt, J. (2010). *Maintenance planning, coordination, and scheduling (2nd edition)*. Industrial Press. Retrieved from https://app.knovel.com/hotlink/toc/id:kpMPCSE003/maintenance-planning/maintenance-planning

Pennings, I. B., Tran, I. M., Derks, I. M., Feijtel, I. J., van Lith, J., Brandsma, I. A. & van Schaik, I. M. (2005). New cvt pushbelt design to cover all front wheel drive powertrains. In *Internationales cti symposium*.

Pochet, Y. & Wolsey, L. A. (2006). *Production planning by mixed integer programming* (Vol. 149) (No. 2). Springer.

Rezg, N., Hajej, Z. & Boschian-Campaner, V. (2016). *Production and maintenance optimization problems: Logistic constraints and leasing warranty services*. John Wiley & Sons.

Touat, M., Bouzidi-Hassini, S., Benbouzid-Sitayeb, F. & Benhamou, B. (2017). A hybridization of genetic algorithms and fuzzy logic for the single-machine scheduling with flexible maintenance problem under human resource constraints. *Applied Soft Computing*, *59*, 556–573.

Van Aken, J. E. & Berends, H. (2018). *Problem solving in organizations*. Cambridge university press.

Xu, D., Sun, K. & Li, H. (2008). Parallel machine scheduling with almost periodic maintenance and non-preemptive jobs to minimize makespan. *Computers & operations research*, *35*(4), 1344–1349.

Yang, A., Qiu, Q., Zhu, M., Cui, L., Chen, W. & Chen, J. (2022). Condition based maintenance strategy for redundant systems with arbitrary structures using improved reinforcement learning. *Reliability Engineering & System Safety*, 108643.

Ying, K.-C., Lee, Z.-J. & Lin, S.-W. (2012). Makespan minimization for scheduling unrelated parallel machines with setup times. *Journal of Intelligent Manufacturing*, *23*(5), 1795–1803.

Appendix A

Assumptions

- *Production in MSE2 is independent of outside factors*
  Only production within MSE2 is in scope. Production in MSE1 and MSE3 is assumed not to influence operations of MSE2.

- *There are no unexpected failures*
  Production lines in MSE2 do not experience unexpected failures. Corrective maintenance is out of scope.

- *Spare part availability is out of scope*
  Supply of materials for maintenance tasks is out of scope. Additionally, maintenance activities are expected to decrease, which is why no hurrying for materials is needed.

- *Machines in a production step have the same maintenance deadlines*
  Machines in a productino step are assumed to be identical. Therefore, they deteriorate similarly over time and have the same deadlines for maintenance tasks.

- *Time is discrete*
  Time is assumed to be discrete and duration of tasks are non-variable. Length of maintenance tasks as agreed upon in the SLAs is discrete and exactly the duration of a task. It is assumed that mechanics take the exact time as the SLA states for a task.

- *Production capacity per machine is discrete*
  Production capacity of machines do not change over time.

- *OOE is equal to 80%*
  Bosch TbP strives to an OOE of 80%, which is assumed as a standard when calculating production capacity in this thesis.

- *Downtime does not cause additional costs*
  As the model provides a maintenance planning for a year ahead, downtime is known timely and it is assumed that there are no idle operators because they can be assigned to different jobs timely. This is similar to current maintenance scheduling strategy at Bosch TbP.

- *All mechanics have the knowledge to maintain all machines*
  The mechanics are not restricted to certain machines when performing maintenance.

Appendix B

Mechanic man hour demand Production Line 1a

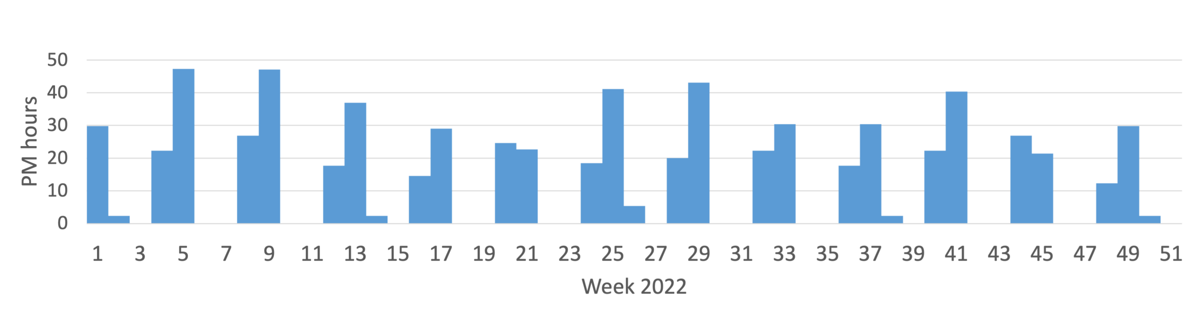

Figure B.1: Planned preventive maintenance hours for Production Line 1a