Reducing the number of failures during piston ring production

Bachelor thesis

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Zuigerverenfabriek Rottink BV | Darwin 12, Almelo

RESEARCH INFORMATION

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Reducing the number of failures during piston ring production

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PREFACE

Dear reader,

The document currently in front of you is my bachelor thesis 'Reducing the number of failures during piston ring production', the final assignment of my bachelor Industrial Engineering and Management at the University of Twente. This report aims, as the title also informs you, to reduce the number of failures during piston ring production at Zuigerverenfabriek Rottink BV, located in Almelo.

I want to thank everyone who helped me during writing this thesis. First, I want to thank Dennis Prak, my lead supervisor from the UT, for his time and effort and tips and tricks, as well as for guiding me into really looking at the project from all angles. I would also like to thank my second supervisor Marco Schutten, for his point of view and helpful comments. Second, I would like to thank everyone at Rottink, primarily Kitty Kuipers, Wim Embsen, and Miranda Maathuis, for accommodating me and letting me work in the office at Rottink, as this has helped me to keep the focus on my research. I also want to thank all production employees, who were very open and enthusiastic in answering my questions and providing me with insight into the production. I would also like to thank my buddy, Dagmar Franken, for helping me solve obstacles, for reading my drafts and for providing me with clear feedback.

Marrit Flach

MANAGEMENT SUMMARY

The problem that this thesis investigates was posed by Zuigerverenfabriek Rottink BV, located in Almelo. Rottink produces piston rings, which act as a seal between the piston and the cylinder wall in an internal combustion or steam engine. These piston rings are highly specialised, as they have different characteristics, such as material, type of ring, type of lock and outer diameter. These characteristics depend on the functionality of the specific piston ring. Extra treatments such as surface treatments are also available. Because of this, their production has a high variability, in terms of production time and order of production processes. Currently, Rottink also experiences a high number of failures during production. In this context, a failure is a piston ring that cannot be reworked or repaired but has to be scrapped as they do not conform to the requirements. These failures are registered through a failure registration form, which can either be done by the production employees or the quality operator at the end of the production, depending on where the failure was found. Currently, no clear guidelines on measuring exist within the production.

This research investigates a more efficient way to handle failures within the production, by way of a simulation study. Employees provided more insight into the way failures are currently handled within the production, by participating in interviews. These interviews show that there is a lack of structure and communication between the office and the production, as well as uncertainty regarding the quality checks and how they are performed. On average, quality checks seem to take 2 minutes per ring but as it is unclear when the measuring tools are calibrated, the effectiveness of a quality check is uncertain. Furthermore, a literature study sheds light on the existing knowledge regarding quality checks within a production process. The most useful guidelines from this study indicate that there are different ways to reduce failures, but the most fitting is a simulation study due to the large variability in the production. Furthermore, it is necessary to know where failures are occurring more often, for which a data analysis provides insight. The literature study also further highlights the importance of calibrated measuring tools and the effectiveness of quality checks. Also, since there are so many failures and no fixed quality checks, any change could be an improvement. A random quality check could therefore also be of value at Rottink. The found information is used as input for the simulation study, which uses different configurations based on the found uncertainties, such as a variable detection probability and inspection time. The detection probability represents the probability that a failure will be detected in a quality check. The analysis of where failures happen shows that most failures are registered as 'Other', meaning the location where the failure occurred was unknown. The 'grinding' and 'finish turning small' also show high failure registration numbers. As most failures are registered as 'Other', this leaves some uncertainty about where the failures actually occur, and also raises the question of whether failures occurred where they were found. This leads to two approaches for the simulation. Approach 1 assumes that a failure could have occurred at any of the previous stages from where it was found. Approach 2 assumes that failures occurred where it was registered, as production employees can sometimes tell from the failure where it occurred and then tell that employee to register the failure. Logistic regression analysis provides a way of assigning a failure probability to a piston ring order based on its characteristics.

The simulation calculates the gain of a specific policy, as time saved per order (of preventing a failed ring to go through the remaining stages) minus the time it takes to perform a quality check. Approach 1 shows that the best process to appoint as a quality check would be 'sawing', as this could on average save 03:11:50 per order. Approach 2 found 'deburring' as the best location, saving on average 02:47:07 per order. The average of these two approaches showed that 'sawing' would be the best location for a quality check, saving on average 02:51:49 per order. As these approaches only perform

a quality check at a specific process, and not all orders go through this process, another option is to use an alternative check station. This policy has a preferred process for the quality check, and if that process is not available the quality check moves to an alternative location. This way, every order would be checked within the production. The best options are pregrinding/grinding to size (02:59:01), sawing/deburring (03:06:22), and sawing/milling (03:01:31). A random quality check (at one of the first four processes) also has a positive average gain (02:29:46), as predicted from the literature search.

The research also investigates the threshold of effectiveness, as the 2-minute duration of the quality check is an assumption, and the detection probability is also uncertain. This showed that the duration of the inspection is of greater influence than the quality. An inspection that takes 10 minutes per ring, but has a 100% detection probability has a negative gain, as the long duration does not outweigh the time saved in locating a failure. Also, a 5-minute inspection per ring, with a 100% detection probability has a higher gain than a 6-minute inspection per ring with a 100% detection probability.

The recommendation for Rottink is to implement the pregrinding/grinding to size policy, as this can then be done at the same 'department' within the production, by the same two production employees. The results show that this could save on average 02:59:01 in time per order. An important extra recommendation for this is to implement a clear measuring protocol that states that production employees always need to calibrate their tools when they start measuring for an order, and to always inspect all rings of an order, as the quality can vary within an order. This will need to be closely monitored, as it can then be seen if the quality checks are effective, and as short as has been assumed for this research. Furthermore, production employees should be reminded of the importance of properly scanning their actions, as this plays a huge role in the limitations of this research. Subsequently, the communication between the production and the office should be improved, as this could lead to fewer communications and less frustration on both sides. The production leader plays a big role in this.

TABLE OF CONTENTS

1. INTRODUCTION

This chapter details the contexts of this research. Section 1.1 provides an introduction to the company. Section 1.2 provides the identification of the action problem and the problem cluster. Section 1.3 provides the research questions that guide this research.

1.1 Company introduction

Zuigerverenfabriek Rottink BV (henceforth referred to as Rottink) produces piston rings. Piston rings act as a seal between the piston and the cylinder wall within an engine. The purpose of a piston ring is to seal the combustion chamber to minimise loss of gas, improve heat transfer from the piston to the cylinder wall, and regulate the oil levels and consumption. The piston rings that Rottink produces are highly specialised in size, kind of cut, surface treatments, and pre-tension (space between the cut ends before installation). This makes their products highly specialised. The production team consists of about 20 people. Their products are delivered all over the world. Bernhard Rottink founded Rottink in 1948. Since then the company has grown, and since the start of 2020, Rottink is located at the XL Businesspark in Almelo to accommodate that growth. To remain a market leader, they want to improve their company. Rottink values its customers and wants to deliver the best piston rings to them. The products they produce have certificates to ensure precision production and environmental and working conditions. For this reason, they would like to decrease the 'failures' within the production. Section 1.2.1 further elaborates on this.

1.2 Identification of action problem

Rottink wants to bring down the number of failures that occur within the production. A failure is either a product that breaks during production, or that does not conform to the desired measurements. Rottink keeps track of these failures by letting the production employees fill in a form when a failure occurs. In this form, they fill in their name, the order information, the number of failures, the reason for failure, an explanation for the failure, and where the failure occurred. In 2018, they have registered 283 failures this way, in 2019 310 failures were registered, in 2020 they registered 553 failures, and in 2021 they have registered 411 failures. So far, in 2022 (until the 31st of March) they have registered 148 failures. When a piston ring breaks, they have to throw it away. Due to this, they lose time and money. To combat the number of failures, they start the production process with 10% extra rings, which also leaves more room for failure. These extra rings can be used as a 'setting ring', used to properly adjust the machine to the right setting. This is also a measure of preventing failures. All failures registered in the failure registration form are actual failures, which means that they cannot be reworked. All products go through quality control at the end of production, the end control. Rottink tries to prevent that there is too much failure at the end control because that would mean that they have to produce new rings to fulfil the order. When there is too much failure such that they cannot deliver enough, they try to spot this as early on as possible, by checking if the number of rings that they currently have in production is enough to satisfy the order. This is a combined responsibility of the production employees and the people in the office, as someone from the office will go into production to ask for clarification when a failure is registered.

1.2.1 Problem cluster and motivation of core problem

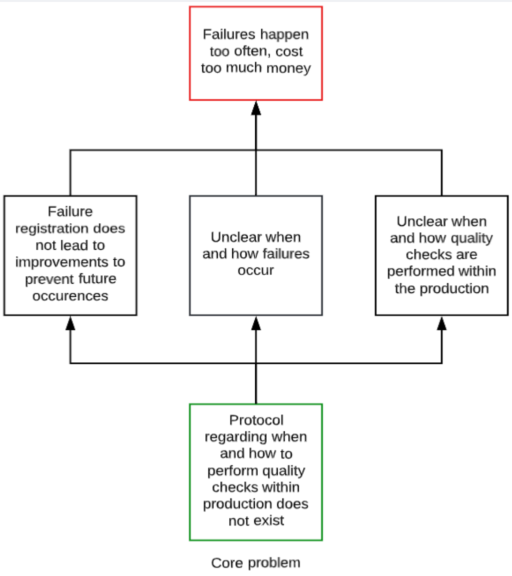

Figure 1.1 Problem cluster

As can be seen in Figure 1.1, the action problem is the fact that failures happen too often and cost too much money. This is not desirable, as failures within a production process limit both the financial performance and responsiveness of the supply chain (Chopra & Meindl, 2016). The registration of failures is done since the start of 2018, and this data is limited. Table 1.1 shows the reasons for failure that production employees can currently select. One of the possible reasons for failure that production employees can select is 'other', which should mean that the failure is caused by a reason that is not on the list. However, when looking at the provided explanations, it can sometimes be attributed to one of the other reasons. 'Other' is by far the most used reason for failure, but it does not provide any insight. The same goes for the location where the failure occurred, this is also most often given as 'other'.

Table 1.1 Reasons for failure

Reasons for failure	Number registered
Total	**1630**
Other	428
Setting error	203
Ground too thin	189
Outside of tolerance	174
Closing play incorrect	130
Spring has come loose	103
Unround	101
Shrinkage cavities	97
Chipped too thin	93
Turned too thin	52
Material not right	28
Broken mill	27
Office, order or drawing not correct	5

Of the 428 times that 'other' was listed as a reason, 52 could immediately be described as another reason. Another 33 are assumed to be setting errors, the remaining are unclear.

Also, the registration of the failures is mainly just that. The registration data is not used to find out what causes the failures but is just used to keep track of how often it happens and what it approximately costs in terms of material costs. To keep track of the costs, the average selling price of a piston ring from 2019 is used, which is multiplied by the number of failed piston rings. Another problem is how the production employees are scanning their actions. Every time a production employee performs a process, they have to scan their name, department, the product, and the assignment number. All of this is registered in their so-called Planbord. Figure 1.2 shows an example of the Planbord. This scanning is not always done properly and can lead to missing information. For example, the number that an employee scans (red column in Figure 1.2) sometimes differs from the actual number of products that is currently in production. Also, the needed number of rings for the order is not visible in this part of the Planbord, only the number that is scanned. Therefore, it is not immediately clear from the Planbord whether extra rings would need to be produced. The needed number of the rings for the order is on the work card that 'flows' with the product.

Werkopdracht	Medewerker	Startdag	Starttijd	Stopdag	Stoptijd	Taak	Artikel	Aantal	Status melding	Status werkopd.
34627-10	[redacted]	01-03-2022	09:00	01-03-2022	09:00	0-Werkopdracht vrijgeven	E34001A0300-002	0	stop	wachten op
34627-10	[redacted]	01-03-2022	09:14	01-03-2022	11:15	1-Voordraaien	E34001A0300-002	4	stop	wachten op
34627-10	[redacted]	01-03-2022	11:23	01-03-2022	13:10	11-Voorslijpen	E34001A0300-002	4	stop	wachten op
34627-10	[redacted]	01-03-2022	13:15	01-03-2022	14:02	14-Afbramen binnen	E34001A0300-002	4	stop	wachten op
34627-10	[redacted]	01-03-2022	15:38	01-03-2022	16:16	2-Nadraaien buiten	E34001A0300-002	4	stop	wachten op
34627-10	[redacted]	01-03-2022	19:01	01-03-2022	19:02	21-Gloeien	E34001A0300-002	4	stop	wachten op
34627-10	[redacted]	03-03-2022	10:04	03-03-2022	13:03	12-Op maat slijpen	E34001A0300-002	3	stop	wachten op
34627-10	[redacted]	03-03-2022	13:04	03-03-2022	13:06	12-Op maat slijpen	E34001A0300-002	0	stop	wachten op
34627-10	[redacted]	04-03-2022	07:49	04-03-2022	08:04	31-Extra controle	E34001A0300-002	2	stop	wachten op
34627-10	[redacted]	04-03-2022	08:05	04-03-2022	08:05	31-Extra controle	E34001A0300-002	5	stop	wachten op
34627-10	[redacted]	04-03-2022	08:24	11-03-2022	11:28	25-Uitbesteding	E34001A0300-002	4	stop	wachten op

Figure 1.2 Example of the Planbord

It is currently also unclear when and how checks are performed within the production. However, it is known that production employees often just go to the end control to get the product checked. This takes away the responsibility from the production employees and consumes more time. Production employees have measuring tools available in their department within the production, but these do need to be calibrated, however, it is unclear when this is done.

The use of a so-called 'setting-ring', which is used to get the right settings on a machine, also has no clear protocol. Some production employees also count these when registering the number of products on the Planbord.

1.3 Operationalisation of the core problem

Figure 1.3 BPM of current situation shows the current situation of the production process at Rottink. Since the production process is highly specialised, there is no fixed order in which stations are visited. Instead, there is a loop, which just shows that the rings will move on to the next process if there is one. Since production employees currently only perform checks indicatively, they either can immediately see that a product is broken, or notice a failure when they happen to perform a check. Since it is unclear when production employees perform checks or calibrate measuring tools, there is no clear method for the performing of checks. There is also a quality control at the end, where a quality operator will check for failures with calibrated measuring tools. This could result in too many failures at the quality control, which means that new rings will have to be produced. This is of course not desirable. These different 'departments' are also visible in Figure 1.4, with the complete map of the production facility. Based on the registration data since 2018, Rottink has had failures occurring in about 10% of their orders.

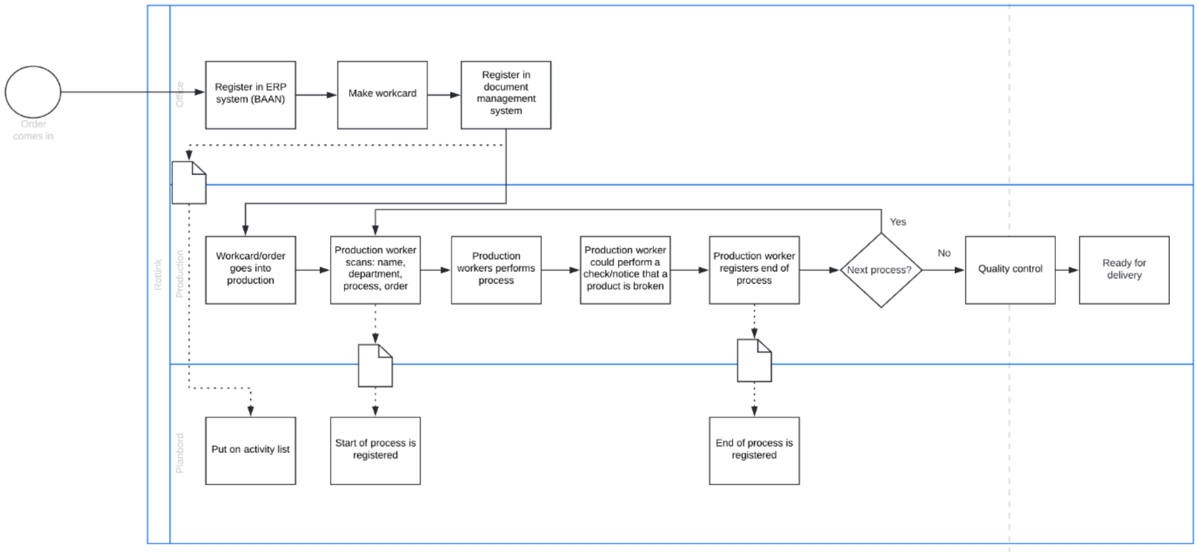

Figure 1.3 BPM of current situation

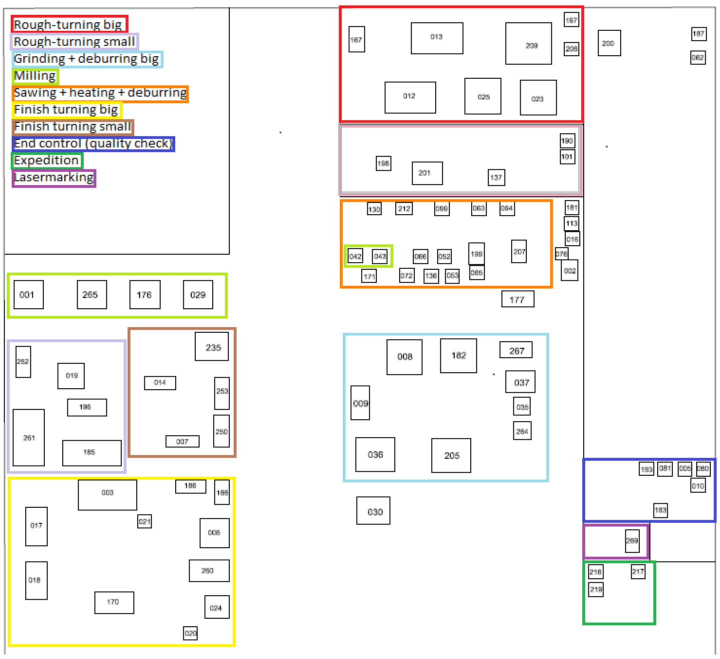

Figure 1.4 Production processes

The production starts with rough-turning a rough tube of material. The material is turned and then the rings are parted from this, both in diameter and width. If there is a finish turning step in the process, then the rough-turning is not directly done to the right tolerance. After rough-turning the piston ring goes to pregrinding. The function of this is to ensure the right axial height of the ring. It is also possible, later on, to go through another grinding process, to remove any inconsistencies. The next step is usually sawing. The sawing process saws a 'lock' into the piston ring. Depending on the type of lock, the piston ring goes to milling, where they determine the right axial height of the lock. Then the piston rings usually go to deburring, to remove small burrs on the material. After, the heating of a piston ring ensures the right kind of tension of the ring and consequently the proper functioning. At the end of every production process, the order goes to the end control for a quality check. After this, they are ready for delivery.

1.4 Problem-solving approach and research questions

To solve the problem at Rottink, a problem-solving approach is necessary. To find a more efficient way of handling the failures, it is first and foremost necessary to know how these failures are occurring, where they are occurring the most, etc. Next to this, it is also important to know how the failure registration process is handled. The main research question is, therefore:

"How can the number of failures during production at Rottink be reduced?"

The approach for solving this action problem is the Managerial Problem-Solving Method (Heerkens & Van Winden, 2017). The other research questions follow from this approach.

1.4.1 Main research question

The main research question is the following:

"How can failures be detected as efficiently as possible?"

By finding a more efficient way to detect failures, and as early as possible, with time the number of occurrences should also go down. In turn, this could also save material and costs, as the 10% extra is not necessary anymore.

1.4.2 Sub research questions

1. Where does failure occur the most?
2. What does the production of a piston ring look like (sequence and production time)?
3. How do production employees currently register failure?
4. How and when do production employees calibrate their measuring tools and perform checks?

These first four sub-research questions serve to provide a better picture of the current situation at Rottink. The failure occurrence analysis provides a distribution of where failures occur. To monitor the gain of different quality check policies, it is necessary to know what the production of a piston ring looks like in terms of sequence and production time. The influence of implementing a certain quality check policy can then be monitored. The failure registration and quality check procedure shed light on how long it takes to perform a check. This helps decide the effectiveness of a quality check. Chapter 2 provides these answers.

5. What guidelines exist on quality checks in production?

A theoretical framework provides insight into the guidelines that exist for implementing quality checks in production. Chapter 3 provides the answers to this knowledge question and serves as input for implementing quality checks at Rottink.

6. What is the influence of the various piston ring characteristics on the failure probability?

This research question serves to find a relation between the piston ring characteristics and their failure probability, based on the available failure registration data. Chapter 4 provides a regression analysis that shows this relation.

7. What is the expected gain of the checking policy?

The best quality check policy depends on the gain of implementing that policy. Chapter 5 provides the results of the different quality check policies, and in turn, provides the best quality check policy for Rottink.

8. How can the solution be implemented?

Chapter 25 provides an implementation strategy for the quality check policy for Rottink. The implementation strategy serves to provide the best results for Rottink.

9. Is the implemented check policy effective?

This research question falls outside the scope of this research but aims to analyse the provided solution. This is something Rottink should monitor. Chapter 6 details how best to do this.

1.4.3 Deliverables

The deliverables are as follows:

- Heatmap of the current failure occurrence situation
- Quantitative cause analysis of the available data
- Regression analysis on the relation between piston ring characteristics and failure probability
- Recommendation of when and how to implement checks within the production based on a simulation of the production process based on where and when failures are occurring more often.

1.5 Conclusion

Chapter 2 describes the current situation at Rottink. Chapter 3 details the findings from literature regarding the implementation of quality checks within the production. Chapter 4 provides the regression analysis and the failure probability calculation and further inputs for the simulation. Chapter 5 shows the results of the simulation. Chapter 6 provides a conclusion to the research and a recommendation for Rottink, as well as a discussion and options for further research.

2. CURRENT SITUATION

This chapter explores and details the current situation of the production process at Rottink. This chapter provides the answers to the following research questions:

- Where does failure occur the most?
- What does the production of a piston ring look like?
- How do production employees currently register failure?
- How and when do production employees calibrate their measuring tools and perform checks?

Section 2.1 shows where failures occur the most. Section 2.2 shows the structure of the production process. Section 2.3 provides insight into how failure is registered, and how checks are done, using input from the production employees.

2.1 Failure occurrence

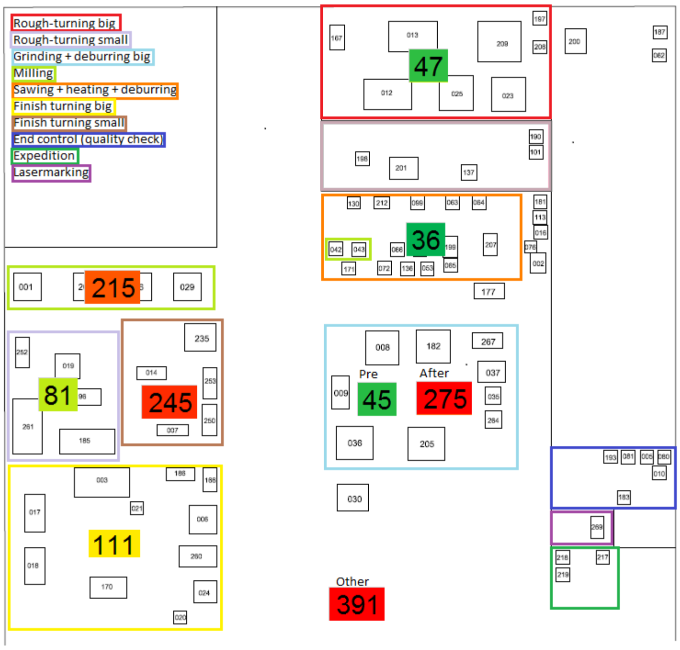

Figure 2.1 Registered failure per process

Figure 2.1 shows where all the registered failures have been found. As can be seen, the highest number of failures are registered as 'Other' (location unknown), since most failures are registered by the quality control at the end and it is for them not always clear where the failure occurred. This is also sometimes used when other processes find a failure and know they did not cause it but also do not know who did. A failure can therefore be wrongly registered at a location if it already occurred before but was not yet found. However, according to the production most of the time this often corrects itself since they can deduce where the failure must have occurred based on the defects. This leads to two approaches. Approach 1 assumes that a failure could have happened anywhere before registration, and approach 2 assumes that the failure occurred where it was registered. Both of these approaches are used in Section 4.2.3.

To find out if the type of material, type of ring, or type of cut has any influence on the occurrence of failures, the article numbers are split into the different characteristics. These numbers contain the necessary information about the final product. Figure 2.2 shows an example of an article number.

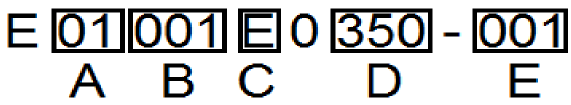

Figure 2.2 Example of article number

An article number always starts with the letter E. The following parts of the article number are established as follows:

- A: type of material: steel (01-04), bronze (10-26), or cast steel (27-99)
- B: type of ring
- C: type of cut
- D: outside diameter (mm)
- E: serial number

Appendix A contains a complete overview of all the piston ring characteristics. Article numbers that contain SP are 'specials'. Example: E01SP0086-002. These are not considered for the simulation as the type of ring and type of cut are not known from these article numbers. Only complete orders from the available data have been used. These are orders that were completely done within the period of 15-10-2019 to 16-09-2021. The failure data has been taken from the same period.

2.2 Production process

As the production process is highly specialised, there is no fixed sequence of assignments within the production. The production sequence refers to how an order goes through the assignment numbers shown in Table 2.1. During the production process, the sequence is also sometimes adjusted, for example, if a product needs extra work done. The production can be as short as only the quality control if it is a ring from inventory or a very complicated process with more than 10 different processes. Table 2.1 shows an overview of the different assignments and their corresponding assignment number.

Table 2.1 Assignments per number

Assignment #	Process
0	Cleared assignment
1	Rough-turning
2	Finish turning outside
3	Finish turning inside
4	Grinding round
5	Turning other
6	Milling step cut
7	Milling lock step
8	Milling gastight
9	Milling crescents
10	Milling other
11	Pregrinding
12	Grinding to size
13	Deburring outside
14	Deburring inside
15	Drilling
16	Pressure blasting
17	Stamping
18	Sawing
19	Deburring cut
20	Deburring automated
21	Annealing
22	Soft annealing
23	Other production
24	End control (quality check)
25	Outsourcing
26	From inventory
29	Laser marking
30	Correcting
31	Extra check
32	EDM

The shortest possible process is 'producing' a ring from inventory, then it will only be the clearing of the production order (0) and then the end control (24), sometimes followed by the laser marking (29) process. As these different processes are divided over the different 'departments' of the production process, as well as in the failure registration form, they have also been divided the same way for the analysis. Table 2.2 shows an overview of the 20 most occurring production sequences, with how often they occur. This again shows the variability of the production sequence, as this is from a total of 2525 production sequences, and yet the most occurring sequence only occurs 227 times.

Table 2.2 Most occurring processes

20 most occurring processes		
1	0-24-29	**227**
2	0-24	**45**
3	0-1-12-18-8-2-3-14-21-24-29	**39**
4	0-1-12-14-18-21-24-29	**39**
5	0-1-12-18-8-2-3-14-13-21-24-29	**32**
6	0-1-12-14-13-18-21-24-29	**22**
7	0-1-11-18-8-2-3-14-21-12-24-29	**22**
8	0-1-12-18-8-2-3-13-14-21-24-29	**21**
9	0-1-11-18-8-2-3-14-12-24-29	**17**
10	0-1-11-18-8-2-3-12-24-29	**17**
11	0-1-12-18-8-2-3-21-24-29	**16**
12	0-1-12-18-6-2-3-14-21-24-29	**16**
13	0-1-12-14-18-21-24	**16**
14	0-1-5-11-18-8-2-3-14-12-24-29	**13**
15	0-1-12-14-21-24-29	**13**
16	0-1-12-14-2-18-21-24-29	**10**
17	0-1-12-13-14-18-21-24-29	**10**
18	0-2-24	**9**
19	0-1-5-11-18-8-2-3-14-13-12-24-29	**8**
20	0-1-5-11-18-8-21-23-2-3-12-24-29	**8**

As the focus is on failures occurring within the production, the research only considers production sequences that produce piston rings, not rings taken from inventory. Some orders also contain repeating parts in the production sequence. An example:

0-1-12-18-2-3-2-3-23-24-29 (finish turning inside and outside takes place over multiple scan actions)

The flow through the production is the same as for the following order:

0-1-12-18-2-3-23-24-29

This is because assignment numbers 2 and 3 are from the same department and are usually either performed by the same person or done simultaneously. For the sake of the simulation, they are therefore considered as the process 'finish turning'. The same goes for the different kinds of 'milling' and 'annealing'. Table 2.3 shows the result of limiting the production sequences to the 'processes' they pass through.

Table 2.3 Top 20 occurring production sequences when only considering 'processes'

1	0-1-12-18-6-2-21-24	160
2	0-1-12-14-18-21-24	103
3	0-1-12-18-6-2-14-21-24	32
4	0-1-5-11-18-6-2-14-12-24	31
5	0-1-11-14-23-25-23-12-24	27
6	0-1-14-11-18-6-2-14-6-21-12-24	25
7	0-1-11-14-1-2-18-21-24-31-25-12-24	24
8	0-1-11-14-1-2-18-21-31-25-12-24	23
9	0-1-11-18-6-2-6-2-14-12-24	20
10	0-1-5-12-18-6-2-14-21-24-16	15
11	0-1-12-2-18-21-24	13
12	0-1-11-14-2-18-21-16-6-31-25-31-12-24	13
13	0-1-12-2-14-19-18-21-24	11
14	0-1-11-14-2-14-18-21-12-31-25-24	11
15	0-1-12-14-18-23-24	10
16	0-1-12-18-6-2-14-2-14-21-24-16-24	10
17	0-1-21-12-18-6-2-14-23-21-24-16-24	10
18	0-1-11-18-6-2-14-12-21-31-25-24	9
19	0-1-12-14-18-24	9
20	0-1-5-21-5-2-31-25-24	9

2.3 Interviews with production employees

To get as complete a picture as possible of the problem within the company, some production employees were interviewed about their opinions.

2.3.1 Interview questions

<u>Measuring</u>

1. *When do you perform a quality check?*
2. *Which measuring devices do you have?*
3. *When do you perform calibration?*
4. *How long does it take to perform a quality check? (Including calibration and measuring)*
5. *Could you do something else at the same time?*
6. *How often do you go to the end control?*

<u>Failure</u>

1. *What do you do when you notice a failure?*
2. *How do you register the failure?*
3. *What do you do in doubt?*
4. *How do you think failure can be prevented?*

2.3.2 Interpretation of the answers

<u>Measuring</u>

1. *When do you perform a quality check*?

This depends on the process. Checking is more important towards the end of the process, as there are more aspects of a ring that need to be checked, like tension, thickness, surface, etc.

2. *Which measuring devices do you have?*

What measuring devices are present also depends on the process, for the same reason as stated above. However, they all agree that the micrometre is the most widely used measuring device.

3. *When do you perform calibration?*

The production employees usually calibrate at least once a day, but often is better, as 'measuring is knowing' ('meten is weten' in Dutch).

4. *How long does it take to perform a quality check? (Including calibration and measuring)*

The process of measuring one ring usually takes about 1-2 minutes, depending on for example the tension.

5. *Could you do something else at the same time?*

While measuring a ring, they could have another ring in the machine. Some machines can also do multiple rings at the same time, depending on the process. However, this is a bit riskier, since they could all come out wrong.

6. *How often do you go to the end control?*

To be sure that a ring is right, they do sometimes go to the end control. The end control usually knows more about what the customer wants and what the exact measurements of a ring should therefore be. The production employees do this more often when they know the ring is expensive.

<u>Failure</u>

1. *What do you do when you notice a failure?*

When they notice a failure, they check if there are still enough rings left to fulfil the order. If not, they go to the end control or the manager, to consult about the next steps, or to see if there are still rings in the inventory.

2. *How do you register the failure?*

When they have a failure, they fill in the failure registration form on the computer of their department. They have to fill this in by hand (also the numbers).

3. *What do you do in doubt?*

When they have doubts about a ring they also go to either the end control or the manager.

4. *How do you think failure can be prevented?*

The production employees also agreed that there seems to be a certain degree of 'sloppiness' when it comes to production. For example, counts often seem to differ between departments. Some employees also said that not all new production employees seem to be as properly educated in the production process. Next to that, the communication concerning the planning between the office and the production hall could be better. A production leader could improve this communication. The production leader could also help with the planning for the production employees. Production employees can choose their tasks based on their own 'to-do list' in the Planbord, but they do not always do this most efficiently. The planning is not evenly divided across days and processes. One department could be drowning in work, while the other department has limited tasks available. Also, sometimes urgent orders have to go first, while they still have a lot of other work to do. They think rushed work also leads to failure.

2.3.3 Management

Management agrees that there is sometimes a miscommunication between the production and the office, as there can be a discrepancy in how the work card is interpreted. Also, as the Planbord is not always up-to-date, there can be a lack of overview of the production. The production leader should be the one to close the bridge.

2.4 Conclusion

The gathered knowledge from this chapter serves as input for the simulation. The different characteristics of the piston rings that Rottink produces are used to determine if certain characteristics cause failures more often, which is then used to simulate the production process in Section 4.3. The 20 most occurring production sequences are used for the simulation in Section 4.2.2. The answers from production employees also serve as input, especially for how long the measuring process takes, as this is needed to calculate the costs and gains of implementing quality checks in the production process at Rottink, as well as the mention of the 'sloppiness' of production employees. The recommendations in Section 6.3 also consider their suggestions for how to reduce the number of failures.

3. THEORETICAL FRAMEWORK

To be able to gain more insight into when and how failures are occurring, it is important to detect the failures properly. For this, quality checks are performed within the production process. Currently, there is no clear protocol for this at Rottink, and there are no guidelines on when these quality checks should be performed. Therefore, the detection of failures is not optimal. This chapter researches the methods and theory of implementing quality checks within the production. Section 3.1 explains the human skill concerned with quality checks. Section 3.2 provides insight into the allocation of quality control systems (AQCS). Section 3.3 explains the uncertainties within a complex production. Section 3.4 details the trade-off between cost versus quality. Section 3.5 provides more information on the logistic regression.

3.1 Human skill

The quality inspection in the production at Rottink is done by the production employees themselves. They have measuring tools that they need to use properly to check the quality of the products. This means that the quality of the quality inspection is dependent on human skill. According to Kang et al. (2018), inspection during a production process can be done 'online' or 'offline'. Online quality inspection is performed during the production process, whereas offline quality inspection is only performed to inspect the quality of finished products. The focus of this research is on implementing online quality inspection. Kang et al. (2018) argue that while it is not necessary to only have 'high-skilled' inspectors, as that would cost too much, it is necessary to have a mix of skill levels. Putting lower and higher-skilled inspectors together will encourage low-skilled inspectors to improve. This in turn shows the importance of training production employees in quality inspection. This could also apply to the current situation at Rottink. The management team is uncertain of how quality inspections are done within the production process.

3.2 AQCS

As one of the variables of the research at Rottink is the total production time, the inspection time is an important aspect to be considered. While improving the quality, inspection is important because it will save material this should not compromise the overall production time. Shetwan et al. (2011) propose a heuristic to improve the efficiency of a production process by dealing with AQCS (allocation of quality control systems), as trying to find an optimum gets increasingly more difficult when the problem size and variability of the production process become larger (Shiau, 2002). Also, inspection policies often do not fully utilise the available financial, equipment and human resources. Ineffective inspection policies lead to 'waste' (defective products, in this context called failures), which is why it is also important to consider the effectiveness of different policies. The simulation considers the fact that inspection is likely not 100% effective and considers the different policies to compare the effectiveness. Important to consider is the influence of the inspection time, as this also influences the quality of the inspection. The simulation also uses this to check for a trade-off between the inspection time and the effectiveness of a quality check. This paper furthermore assumes that each stage has a given probability of producing defective parts. This applies to the situation at Rottink since certain stages have failures more often in the failure registration data. To solve the AQCS problem, this review looks at several different methods, including a heuristic with local search (HMLS), complete enumeration method (CEM), linear programming (LP) and others. None of these properly suit the situation at Rottink as, for example, the production process contains too much variability, in terms of different stages, rings and therefore costs. The article also proposes the possibility of using a Monte

Carlo simulation. A Monte Carlo simulation focuses on the question “what if?”. A Monte Carlo simulation (MCS) is often used as a statistical tool to analyse uncertainties and provide analyses of different scenarios (al Garni & Awasthi, 2020). An MCS approach entails repeatedly generating samples for different scenarios and comparing these, the results of which can be found in Chapter 5.

3.3 Uncertainty

The difficulty of a specialised multi-stage production system lies in uncertainty. This makes it hard to make a simulation or model that is completely accurate and calls the need for simplification. Schotz et al. (2018) provide a simplified methodology for reducing quality-related costs, of which a particular step is to localise the different kinds of failures that can occur in specific processes. This could also be done within the production process at Rottink. Rezaei-Malek et al. (2019) also point out the uncertainty of inspection tools and the importance of calibration, as these can also influence quality inspection. Uncertainty can also be found in the quality of the quality inspection, meaning that a quality inspection might not be 100% effective. The simulation also takes this into account and uses a variable detection probability, which depicts the probability that a failure is found during a quality check.

3.4 Cost versus quality

The cost associated with quality depends on the viewpoint (Hopp & Spearman, 2008). One view is that cost increases with quality, as high quality requires better inspection, such as better inspection tools, or better materials. The other view is the exact opposite, namely, that cost decreases with quality, which stems from the assumption that ‘doing things right the first time’ saves material and labour costs. Neither view can be universally correct, as this of course also depends on the product, production process, etc. According to Hopp & Spearman (2008), it can be argued that if quality improvement can be done by moving some responsibility from end-of-line quality control to in-process inspections, it is likely that the gains from reducing failure costs will outweigh the costs of extra inspections. Furthermore, when the failure costs are high, it is easier to improve with small steps, and a random quality check could also provide improvement. This applies to the situation at Rottink, as currently, the responsibility of the end-control is much higher, and it is unclear when or how inspections during the production process are performed. The simulation therefore also provides results from a random quality check in Chapter 5.

3.5 Logistic regression

A regression analysis provides the relation between characteristics and the probability of a failure occurring based on historic data. As a linear regression is not suitable in this case (the dependent variable, failure, is binary), a binary logistic (logit) regression model is more suitable (Berger, 2017). Additionally, a logistic regression assumes there is no correlation between the independent variables (the characteristics). This can be assumed since every combination of the characteristics is possible in a piston ring. The combined characteristics of a particular order then provide a failure probability.

3.6 Conclusion

The theoretical perspective provides insight into guidelines for reducing the number of failures during production at Rottink. As is to be expected with quality control done by production employees, the level of the quality control is dependent on human skills. This leads to uncertainty about the effectiveness of quality controls. Together with the before-mentioned uncertainty of the production system itself, and the uncertainty of inspection tools, there is quite a lot of uncertainty. This uncertainty serves as input for the simulation in Section 4.2. Furthermore, as Schotz et al. (2018) suggest, the failures are localised to specific processes. The AQCS approach shows which variables need to be considered when trying to find the optimum location for quality control within a multi-stage production system. This is considered when comparing the results of the simulation in Chapter 5.

4. Problem analysis

This chapter describes the performed problem analysis. A simulation study researches the optimal quality inspection policy. Section 4.1 details the inputs needed to construct the simulation. Section 4.2 explains the simulation. Section 4.3 describes the variables for this research.

4.1 Needed inputs for the simulation

This section details the characteristics, regression, detection probability and the probability of a failure at a specific location.

4.1.1 Characteristics and failures

As described in Section 2.1, there are different characteristics of a piston ring, namely the type of material, type of ring, type of lock, and the outer diameter. To find out if, for example, a certain type of lock would fail more often, all piston rings from the available data were analysed on their characteristics. Table B.1 in Appendix B shows an overview of this. This analysis does not consider 'Special' rings, as not all the same characteristics are known from the article number.

4.1.2 Regression

To be able to estimate the expected influence of implementing quality checks in the production line, it is necessary to have information from the real-life production process. For every order (excluding special rings), it was checked if a failure occurred and what the characteristics were of this order. The regression analysis assigns a probability that a failure will occur, based on the characteristics. Table 4.1 shows a small part of this data, Appendix B shows a larger part of the table. The last column indicates if there was a failure or not; 1 means 'yes', and 0 means 'no'. The categorical characteristics (material, type of ring, type of lock) are dummy variables. If the ring is made from steel, that means that the columns for cast steel and bronze both contain a zero. The same applies to rings with a type different from 001, 002, and 401, as well as a lock other than A, D, E or I.

Table 4.1 Part of the data for logistic regression

Outer diameter	Cast steel	Bronze	001	002	401	A	D	E	I	Failure (yes-1/no-0)
250	1	0	1	0	0	1	0	0	0	0
210	1	0	1	0	0	0	0	0	1	0
300	1	0	1	0	0	1	0	0	0	0
75	1	0	1	0	0	0	0	0	0	0
190	1	0	1	0	0	0	0	1	0	0
260	1	0	1	0	0	0	0	1	0	0
93	1	0	0	0	1	0	1	0	0	0

Table 4.2 Result of logit regression

	coefficients
Intercept	*-1.08983*
Outer diam (x_1)	-0.00165
Cast steel (x_2)	-0.01545
Bronze (x_3)	0.209011
001 (x_4)	-0.3811
002 (x_5)	0.382217
401 (x_6)	-0.49779
A (x_7)	0.199383
D (x_8)	0.588522
E (x_9)	0.686246
I (x_{10})	0.64734

Table 4.2 shows the output values of the logistic regression, which indicate the statistical relationships between the different variables. The p-values and the coefficients are the most important (Frost, 2019). The p-value indicates whether or not the hypothesis test results are statistically significant (Frost, 2020). If the p-value is less than the significance level, that means that the null hypothesis can be rejected, which means that there is a relationship between variables. In this case, the significance level is 5%, which means that any p-value below 0.05 indicates statistical significance. This means that for 'Outer diameter', 'D', 'E', and 'I', the results are statistically significant. For the other variables, the null hypothesis, the hypothesis that there is no relation, cannot be rejected. The meaning of the coefficients can be interpreted as follows: a positive value means that the probability of a failure is higher, and vice versa (Frost, 2019). In the case of the continuous variable 'Outer diameter', the coefficient is negative, which means that an increase in outer diameter has a negative influence on the probability of a failure occurring. In other words, the larger the outer diameter, the smaller the probability of a failure. For bronze, the coefficient is possible, which means that a bronze piston ring has a higher possibility of failure than cast steel. The other coefficients can be interpreted in the same way.

To calculate the probability of failure *fp* based on the different characteristics of piston rings, the following formula should be used.

$$fp = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m)}}$$

This is based on the number of explanatory variables. In this case, there are 10 explanatory variables. The coefficients in the tables are the β variables, the intercept is the β_0 variable. Every x in this formula represents either a one or a zero, meaning whether or not that characteristic is present in this particular piston ring.

An example of calculating the failure probability for an order with article number E01001E0130:

$$x_1 = 130, x_2 = 1, x_3 = 0, x_4 = 1, x_5 = 0, x_6 = 0, x_7 = 0, x_8 = 0, x_9 = 1, x_{10} = 0$$

$$fp = \frac{1}{1 + e^{-(-1.08983 + (-0.00165 * 130) - 0.01545 - 0.3811 + 0.686246)}} = 0.266327$$

An example of a different order with a larger outer diameter E01001E0450 (other characteristics kept the same):

$$fp = \frac{1}{1 + e^{-(-1.08983+(-0.00165*450)-0.01545-0.3811+686246)}} = 0.176807$$

This shows that the failure probability does indeed decrease with an increase in outer diameter. 79% of cases are predicted accurately by the model.

4.1.3 Detection probability

The uncertainty of inspection tools and quality of the inspection mentioned in Section 2.3 and Section 3.6 can lead to variability in the 'detection probability'. This means that the probability that a failure is found, is not always 100%. This adds an extra component to the simulation that can be adjusted to see what impact it has on implementing quality checks in the production process.

4.1.4 Failure location

As the production employees can indicate the location in the failure registration form, it should be known where all failures occurred. However, there is the possibility of the failure occurring before that, and only being registered at a subsequent location. Also, as mentioned in Section 2.1, the failure is most often registered as 'other', meaning it was either unknown where the failure occurred, or the actual location is not available in the failure registration form. Therefore, an attempt to correct the failure locations was done, by assuming that the failure could have occurred at any of the locations that were passed before the failure was found, including the location where it was found, with equal probability. With this method, alternative probabilities for the failure location were calculated. As some of the time a production employee may know specifically at which location a failure occurred, it is uncertain which of these methods is most accurate. Therefore, the simulation has been done with both the assumption that the failure occurred according to the failure registration form and with the assumption that it could have occurred at any of the previous locations. Furthermore, the simulation assumes that there is no correlation between the characteristics and where the failures occur as the probabilities are multiplied.

4.2 Simulation

This section explains the different 'building blocks' of the simulation.

4.2.1 Creating an order

For the simulation, it is necessary to know how often different types of piston ring characteristics occur. The tables from Section 4.1 were used as input for this. To create a specific order, every different characteristic is 'drawn' from the possible options for that characteristic. For example, there is a higher probability that an order will be of ring type 001 than type 301. The simulation also generates an order quantity. The failure probability is calculated using the characteristics and the formula from Section 4.1. Table 4.3 shows an example.

Table 4.3 Example of a generated order

Material	Cast steel
Type ring	001
Type lock	I
Outer diameter	45
Quantity	54
Failure probability	0.286333192

4.2.2 Generating the process

Next, the simulation provides the complete production process. This production process is based on the 20 most used process sequences and assumes no relation between the type of ring and the production sequence. These sequences have been mostly limited to the 'department' where they are done, to simplify the process. So, for example, all the different kinds of milling (milling gastight, milling lock step, etc.) are now just 'milling'. The simulation 'draws' a random number, which then corresponds to one of the 20 different processes, based on how often they occur. To simulate production times, the deterministic average production time per piston ring per process has been used, for the processes that were taken together the average production times per ring are added. So for every process, the average production time per piston ring is multiplied by the order quantity.

4.2.3 Generating a failure probability

There are different probabilities for where the failure occurs within the production process. If a certain production stage does not occur in the production process, then the failure can of course also not occur there. Therefore, the probabilities for the occurrence of a failure are adjusted per production sequence and according to the assumptions mentioned in Section 4.1.4. These are also shown in the simulation. Given that a check is performed at a certain stage, the probability of finding a failure is the probability of a failure occurring at that stage plus the probability of a failure occurring at any of the previous stages, multiplied by the chance of a failure occurring. The model, therefore, assumes that a failure can only occur once in a piston ring. The regression generates an overall failure probability, independent of where the failure occurs.

4.3 Variables

The effect of different inspection policies is checked by looking at the costs and gains of implementing the specific policy. The simulation generates *n* = 1000 orders, which each have a failure probability *p* based on their characteristics, and a failure location probability per stage s_i, with a failure detection probability *d*. The probability of finding a failure at station i (with a 100% order check), *f,* can be calculated as follows:

$$f = p * \left(\sum s_i\right) * d$$

The s_i are summed up to and including the stage of the quality check.

The costs *c* are the extra time of inspection multiplied with the failure detection probability *d*, whereas the gain *g* of a policy is time saved by preventing a failed ring from going through the rest of the production process, which is the number of stages, *ns* that is left after the check until the end control multiplied with the average time per process of one ring *pt* multiplied with the number of rings *nr*. The objective function of the gains of an inspection policy can be formulated as follows:

$$g = (f * ns * pt * nr) - (c * d)$$

(the probability of finding a failure * expected saved time) – (expected inspection time * failure detection probability). For the sake of the simulation, this formula uses the average time per process of one ring (00:26:26).

5. Results

This chapter discusses the different configurations of the simulation model, based on the numerous uncertainties and difficulties of the production process at Rottink. Every specific process is taken as a quality check and then simulated a 1000 times so that the results can be compared. The gain from such a check was then averaged over these 1000 iterations and subsequently compared to other locations for quality checks. Section 5.1 shows the results from Approach 1. Section 5.2 shows the results from Approach 2. Section 5.3 shows the average over these two approaches. Section 5.4 shows the results of using an alternative check station. Section 5.5 the effects of the relation between the inspection time per ring and the detection probability. Section 5.6 details the probability of finding a failure per stage. Section 5.7 provides the results of a random quality check.

5.1 Approach 1

Approach 1 assumes that a failure could have happened anywhere before it was registered, and therefore uses the corrected failure probabilities for the location of failure. The simulation has been run with a quality check at a specific process, with the assumption of a check time of 2 minutes, based on the production employees' input, and a 100% detection probability. If the specific process is not in the production sequence, then there is no quality check. If the process occurs multiple times, then the first occurrence is taken. Therefore, this configuration takes into account that performing a quality check at a specific process is more profitable if that process occurs often in the production sequence. The gain represents the average time saved per order as opposed to not checking.

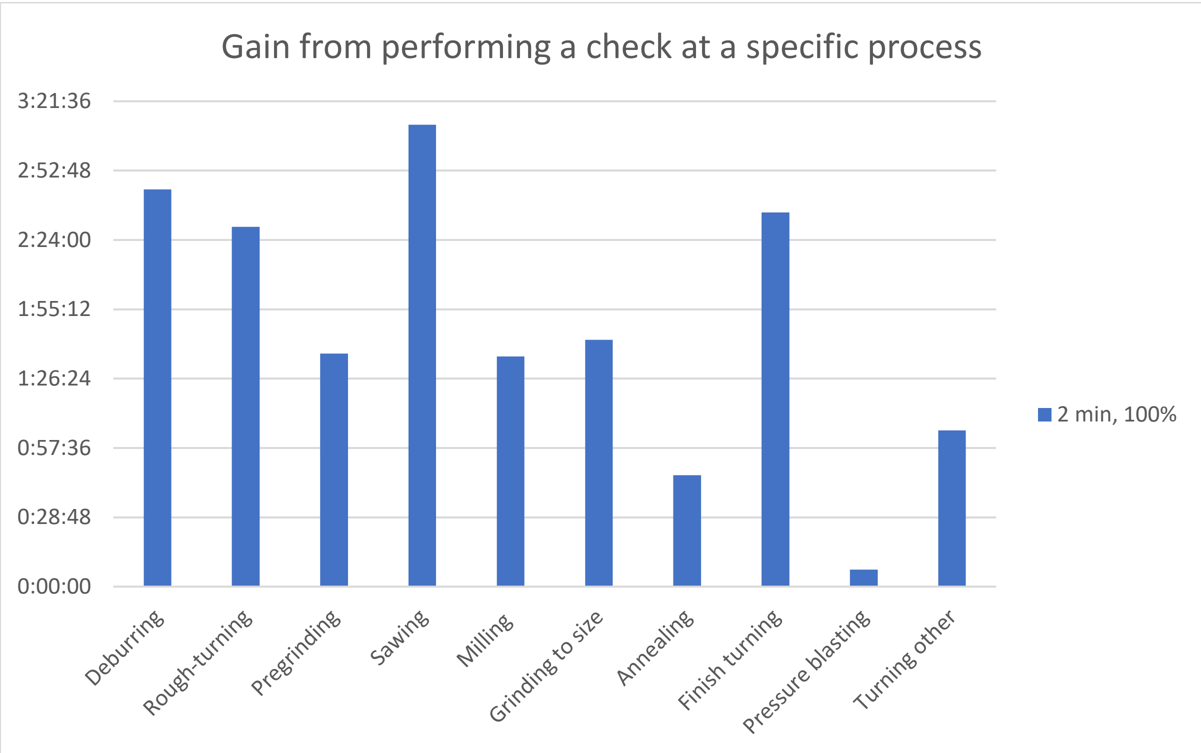

Figure 5.1 Gains from performing a quality check at a specific process using Approach 1

From Figure 5.1, it can be seen that a quality check at the 'sawing' process has the highest average gain of finding a failure. 'Sawing' occurs most often at the fifth or sixth position of a production, so usually around the middle. A complete overview of the assignment and the frequency of their position can be found in Appendix D. As all processes have an average positive gain, it would always be profitable to perform a quality check if the checking only takes 2 minutes per piston ring and with a 100% detection probability. The average throughput time of an order is 180 hours. The throughput time also includes the waiting time between processes.

5.2 Approach 2

Approach 2 uses the assumption that the failure occurred where it was found. The simulation has been run with a quality check at a specific process of the production line, with the assumption of a check time of 2 minutes, based on the production employee's input, and a 100% detection probability but now with the failure location probabilities as gathered from the failure registration form. As 'other' was the most often registered failure location, this has been assigned to all possible locations with equal distribution, since there is no way of finding out what the exact distribution was. Figure 5.2 shows the output of these configurations. 'Finish turning' has the highest average gain, and the second-best is 'sawing'. A quality check at a specific process would here also always be profitable, as all average gains are positive, though some are higher than others.

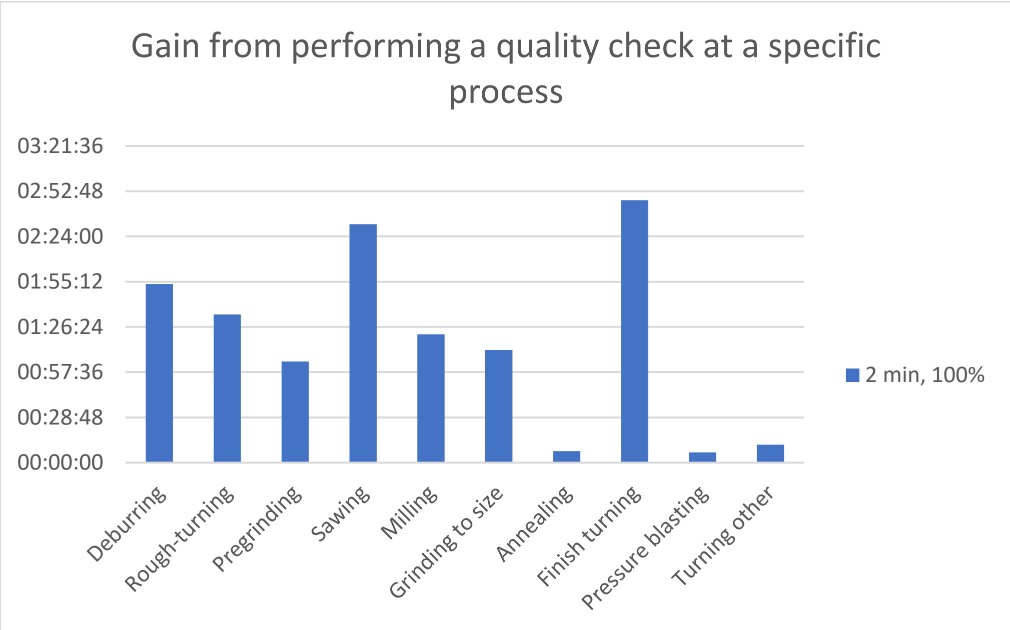

Figure 5.2 Quality check at a specific process using Approach 2

5.3 Difference between approaches

Figure 5.3 shows the average gain per process averaged over the approaches from Section 5.1 and Section 5.2. 'Sawing' and 'finish turning' have the highest average gain, as they had the highest gains in both approaches. Since production employees often do fill in the correct process, but not always, the reality likely lies between the two approaches and therefore the average is taken. 'Sawing' and 'finish turning' are the best locations for use as a quality check.

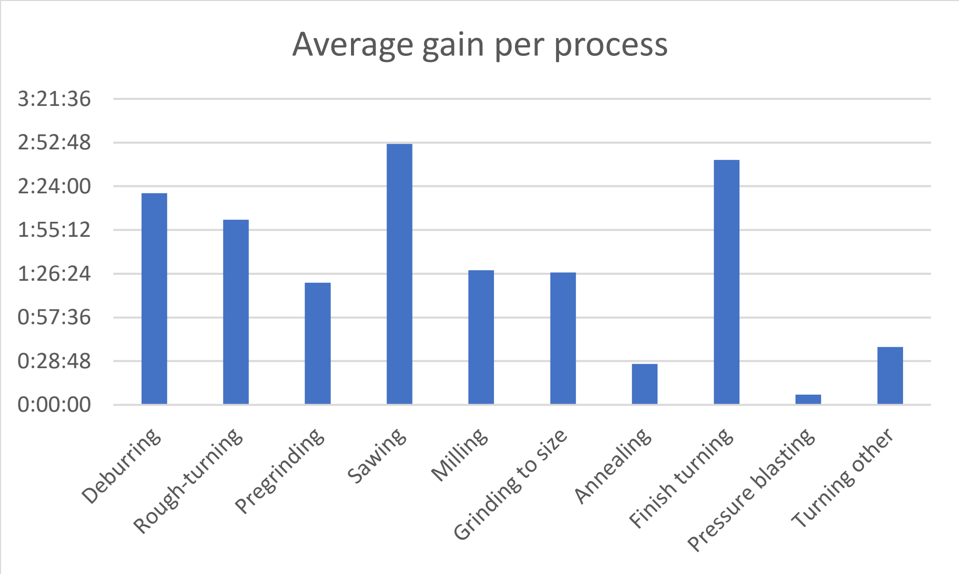

Figure 5.3 Gain per process averaged over both simulation configurations

5.4 Using an alternative check station

Even though 'sawing' is in most production sequences, there are some sequences without it. That means in those cases, there is no quality check. To ensure that a quality check always takes place, the simulation can also make use of an alternative check station. This means that the simulation performs the quality check at the preferred process, and if that process is not available then it uses the alternative. Table 5.1 shows the results from this, in which the first process is the preferred location, and the second is the alternative.

Table 5.1 Gain from having an alternative check station for both approaches and the average

Check/Alternative	Approach 1	Approach 2	Average
Sawing/Finish turning	03:35:19	01:51:43	02:43:31
Pregrinding/Grinding to size	03:36:17	02:21:45	02:59:01
Sawing/Deburring	03:35:07	02:37:36	03:06:22
Sawing/Milling	03:39:05	02:23:57	03:01:31

Table 5.1 shows the results of 'sawing' with several other processes that had a high gain, to see if the processes together also have a high gain. It also shows the combination of pregrinding/grinding to size. As could also be seen in Table 2.3, both processes are often in 2nd or 3rd position, one or the other, meaning if there is no 'pregrinding' at that point, then there is usually 'grinding to size'. That is why the gain with an alternative check station is this high. The averages of these policies are comparable to the averages from a fixed process quality check. The small differences between the highest three averages in Table 5.1 are negligible and can be explained by the variability in the production and the simulation. The advantage of using the pregrinding/grinding to size approach is that these two assignments are performed by the same two production employees who perform all 'grinding' assignments and that this would be easier to implement.

5.5 Higher inspection time, higher detection probability

The inspection time relates positively to the effectiveness of the quality check, as mentioned in Chapter 3. The simulation also considers this relation to research when implementing a quality check policy is most effective.

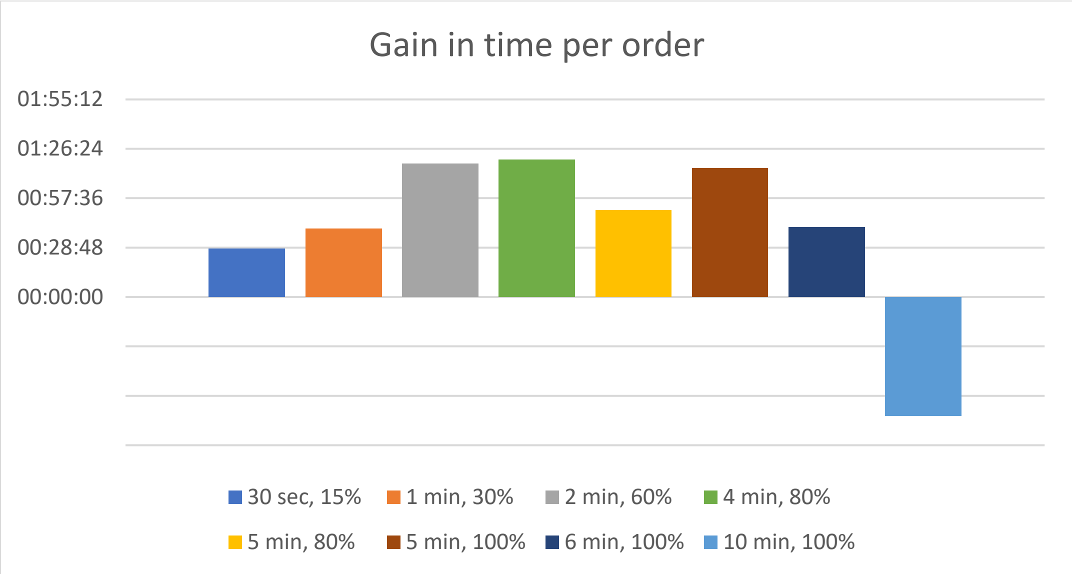

Figure 5.4 Gain in time per order based on different assumptions for the quality check

Figure 5.4 shows the results of these different assumptions. The research also investigates the threshold of effectiveness, as the 2-minute duration of the quality check is an assumption, and the detection probability is also uncertain. This showed that the duration of the inspection is of greater influence than the quality. A 2-minute inspection time per ring, with a 60% detection probability has a higher gain than a 5-minute inspection time per ring with a 100% detection probability. An inspection that takes 10 minutes per ring, but has a 100% detection probability has a negative gain, as the long duration does not outweigh the time saved in locating a failure. Also, a 5-minute inspection per ring, with a 100% detection probability has a higher gain than a 6-minute inspection per ring with a 100% detection probability.

5.6 Detection probability

Figure 5.5 shows that the probability of finding a failure does not increase for every further stage in the production process, as longer production sequences usually have ‘outsourcing’ at the end. Before ‘outsourcing’ an extra check is already performed, and after ‘outsourcing’ usually the ‘end control’ takes place. Therefore, it is assumed that the probability of a failure occurring at these stages is 0. Furthermore, since for these production sequences an extra check will be performed anyway, it would make more sense to plan a quality check not immediately before that, since that would be a waste. Figure 5.5 also shows a clear decrease in the probability of finding a failure when the detection probability decreases proportionally with a constant inspection time of 2 minutes.

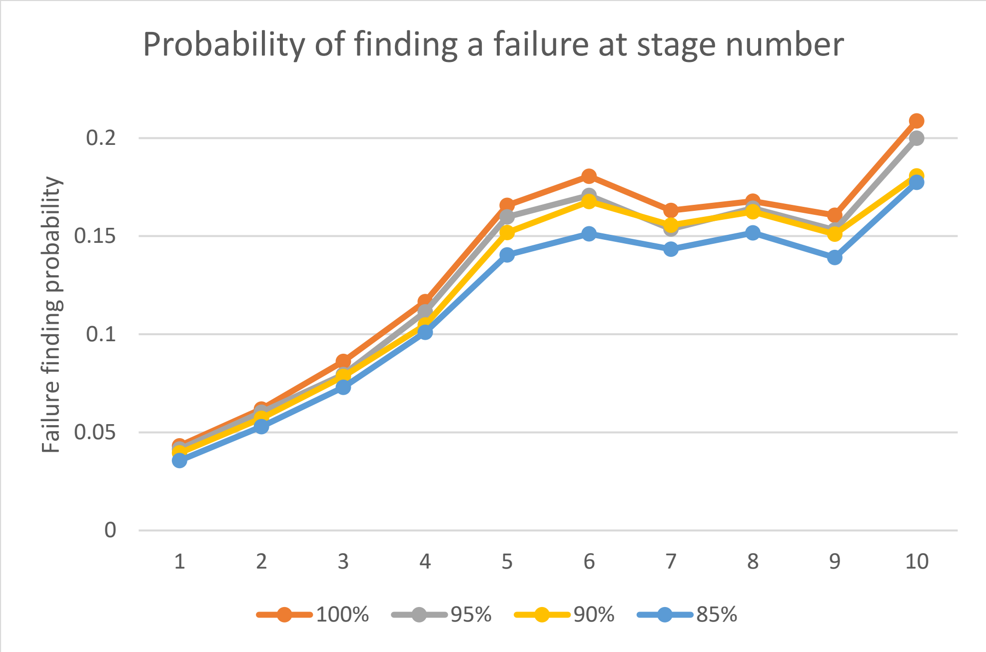

Figure 5.5 Probability of finding a failure at stage x with different detection probabilities

As Figure 5.5 shows, the probability of finding a failure increases further into the production process, it is better to find a failure earlier on, as this saves time spent on a product that has to be scrapped.

5.7 Random quality check

As it is likely that implementing a quality check will already reduce the number of failures, based on Section 3.2, a random quality check policy was also simulated. As not all orders have an equally long production sequence, a quality check is performed by randomly picking one of the first four stages, with a 2-minute check time, and a 100% detection probability. Table 5.2 shows this output.

Table 5.2 Gain of performing a random quality check at one of the first four stages

	Corrected	Registered	Average
Randomly pick 1,2,3, or 4	02:38:46	02:20:45	02:29:46

The average gain equals 02:29:46, which is lower than the best policies from Sections 5.3 and 5.4.

5.8 Conclusion

For implementing just one quality check in the production process, without an alternative quality check, the best process for that is ‘sawing’ based on the average of both assumptions. Even if the time to perform an inspection is higher than 2 minutes per ring, this has still the highest gain. When using an alternative check station, the best tactic is to use the pregrinding/grinding to size approach, as these are also really alternative production assignments, and can therefore be done at the same process. The gain from this policy is higher than implementing one quality check without an alternative. Also, a targeted policy provides a higher gain than a random check policy, even though a random check policy will also have a positive gain, as predicted in Section 3.4.

6. CONCLUSION, LIMITATIONS & RECOMMENDATIONS

This chapter provides a conclusion to the research on how to reduce the number of failures occurring during piston ring production at Rottink by way of more effectively finding and registering failure. Section 6.1 provides a summary and a conclusion to the research. Section 6.2 discusses the limitations of this research, and Section 6.3 discusses the recommendations for Rottink and opportunities for further research.

6.1 Conclusion

Rottink currently experiences too many failures within their production, and an underlying cause of this is that they also lack structure in handling them. There is no clear protocol on when production employees should perform a quality check or how they should perform these, with regards to calibrating the measuring devices. When a production employee does find a failure, they register it in the failure registration form. This information is currently not used to analyse the occurrences of failures, merely as a way of keeping track of failures. Furthermore, due to mistakes made with registering and the uncertainty of the effectiveness of quality checks, it can be questioned how accurate this is. This research aims to find a more effective way surrounding the failures at Rottink way, by researching different quality check policies. The analysis of the available failure registration data provides insight into the occurrences of failures, whether certain departments/processes are more prone to failure, and also whether certain piston ring characteristics are more prone to failure. The knowledge of production employees provides insight into the quality check and measuring procedures currently at Rottink. This information combined serves as input for the simulation, which tests the effectiveness of different quality check policies, to see what Rottink could save in time and material.

The analysis of the occurrence of failures based on the failure registration data showed that certain departments register more failures. Both the 'grinding' and the 'finish turning small' department show high failure numbers, but most failures are registered as 'Other', meaning it is unknown where the failures occurred. The question arises whether the failure occurred where it was found, or that it occurred before that. This leads to two approaches: Approach 1 assumes that a failure could have occurred at any of the stages before it was found, and approach 2 assumes that the failure occurred where it was found. As it saves time and material if a failure is found earlier, the focus of the research is to find a quality check policy that aims to maximise the time saved by preventing a failure from going through the rest of the production, while also maximising the chance that a failure is found.

Production employees provided information on how they register failures and perform quality checks. As there is no clear protocol surrounding the quality checks, this leads to differences between the production employees. If and when the production employees perform a quality check, this on average takes them two minutes per piston ring.

A literature study provides the research with guidelines on implementing quality checks within production. Most of these are not directly applicable to the situation at Rottink, as they need additional information and there is so much variability and uncertainty. Therefore, a simulation study is the best option. The research also shows that it is necessary to know where failures occur the most, to reduce the number of failures occurring. Furthermore, it is necessary to consider human skills in quality checks, as this reduces the effectiveness of implementing quality checks, and human error will always remain. However, small steps can mean a lot in this case.

A logistic regression analysis assigns coefficients to the different characteristics of a piston ring, based on historic failure registration data. These coefficients can then be used to calculate the failure probability *fp* of any piston ring based on its characteristics with the use of the following formula:

$$fp = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m)}}$$

The coefficients are the β variables.

As the production of the piston is highly specialised, there is no fixed production sequence. The production sequence refers to the sequence of the different processes. An analysis of historic orders provides the 20 most occurring production sequences. The simulation uses this to generate a production sequence for order.

With Approach 1, the highest gain comes from implementing a quality check at the 'sawing' process (3:11:40 per order). This approach also shows that it is always profitable to implement a quality check at a fixed process, as the average gain in time per order is positive. This even holds for processes that do not occur as often, such as 'pressure blasting'. Approach 2 shows the highest gain at 'finish turning' (2:47:07 per order). The average of these two approaches shows that 'sawing' would be best the best place to assign a quality check, saving 2:51:49 per order. As these approaches only perform a quality check at a specific process, and not all orders go through this process, another option is to use an alternative check station. This policy has a preferred process for the quality check, and if that process is not available the quality check moves to an alternative location. This way, every order would be checked within the production. The best options are pregrinding/grinding to size (02:59:01), sawing/deburring (03:06:22), and sawing/milling (03:01:31). A random quality check (at one of the first four processes) also has a positive average gain (02:29:46), as predicted from the literature search.

The research also investigates the threshold of effectiveness, as the 2-minute duration of the quality check is an assumption, and the detection probability is also uncertain. This showed that the duration of the inspection is of greater influence than the quality. An inspection that takes 10 minutes per ring, but has a 100% detection probability has a negative gain, as the long duration does not outweigh the time saved in locating a failure. Also, a 5-minute inspection per ring, with a 100% detection probability has a higher gain than a 6-minute inspection per ring with a 100% detection probability.

These results show that any policy would be an improvement, as there is a lot to improve. Small steps are easier to take, and a policy can never be 100% effective, due to the uncertainty, variability and room for human errors within the production. This could also be useful to other production companies that want to implement quality checks and currently have none. From a first step, it should then be further researched to take decrease the uncertainty and possibly improve more.

6.2 Limitations

This section lists the various limitations encountered in this research.

6.2.1 Variability

Due to the large variability in the production process at Rottink, and their specialised piston rings, many assumptions had to be made. As the production sequence can differ so much per order and is often adjusted along the way, it makes it difficult to accurately simulate this. The same goes for the difference in characteristics per order. Also, the time per process is taken as an average over all available historic orders, but it is not known what the influence is of the different characteristics on the time per process or the sequence of the production processes. As the research also assumes there is no relation between the type of piston ring and the production process, this could also be a point of improvement. This could lead to a more targeted quality check policy based on the type of piston ring. Another more targeted quality check policy could also result from using the failure probability of an order as a guideline for the quality check.

6.2.2 Data

The failure data is not extensive enough, as there are only a few processes that can be selected even though the failure could have occurred somewhere else. Therefore, the probabilities for where a failure occurs are based on assumptions, and therefore not accurate. Production employees sometimes make mistakes when filling in the failure registration form, which leads to partly polluted data. The data from the Planbord is also limited, as production workers often do not scan properly. This causes uncertainty in the duration of processes and the flow of a product since wrongly scanned actions remain in the data. Not only is the quality limited, but the data was also taken from a certain period (15-10-2019 until 6-09-2021) and does not contain the most recent data.

6.3 Recommendations

The following recommendations follow from the conclusion.

6.3.1 Implementing a quality check

The recommendation for reducing the number of failures is to use the pregrinding/grinding to size approach, with pregrinding as the preferred location and grinding to size as an alternative. This policy had the highest gain out of all the simulation configurations, 02:59:01 on average per order. The recommendation is to always perform a 100% quality check there, as it is not a given that all rings are conforming if the first one in a batch is conforming. Further research is then needed to see if these checks help and if more can be implemented, as there is still too much uncertainty if the extra quality checks are effective. As the inspection time is of great influence to the gain in time per order, another recommendation is to actively monitor how long these quality checks take, as the gain decreases with an increase in inspection time.

6.3.2 Measuring protocol

To help implement the quality check within production, clear guidelines are needed on how the production employees should measure and also calibrate. If there is a clear protocol for this, then this removes some of the uncertainty about the effectiveness of quality checks. This protocol should contain information on when and how to perform quality checks, and how often to calibrate the measuring tools. This could be combined with a training or a check of the production employees' performance. It will also be easier for the production leader to know if the measuring is then done correctly. The recommendation is to always check all rings from an order, as the measuring time is quite low, and piston ring quality can differ greatly within an order. Also, the production employees should calibrate their measuring tool when they start the quality check, as uncalibrated tools can lead to incorrectly registered failures and also influence the detection probability.

6.3.3 Scanning

Multiple factors contribute to the uncertainty of the simulation due to the uncertainty in the production process at Rottink. This starts with the scan data from the Planbord, as often the scanning is not done properly. To get a better model, that is based on more facts and fewer assumptions, this needs to be improved. If this data is better, this will provide more information about the overall production line, as it will be clearer how long different processes take, and how orders move through the facility. This starts with showing the relevance of the Planbord to the production employees, as this is not something they are always aware of. Reminders to the production employees to scan properly might also be helpful.

6.3.4 Communication

Another recommendation is to improve the communication between the office and the production, as this can lead to 'chaos' or unstructuredness in the production, which could also result in failures. A better production schedule leads to less rushed work and fewer failures, this could be improved by the fact that they will have a production leader starting from July on.

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APPENDIX A: OVERVIEW OF PISTON RING CHARACTERISTICS

Table A.1 Overview of piston ring characteristics

A	Type of material	01-04	Cast steel
		10-26	Bronze
		27-99	Steel
B	Type of ring	0..	Compression rings
		1..	Running-in rings
		2..	Scraper rings
		3..	Slotted oil scraper rings
		4..	Compression rings with inside tension
C	Type of cut	A	Straight
		B	Right-hand angle
		C	Left-hand angle
		D	Step cut
		E	Gastight cut
		F	Right-hand angle with rounded ends
		G	Left-hand angle with rounded ends
		H	Straight cut with rounded ends
		I	Lock step
		J	Tangential cut
		K	Lock step with gastight cut
		L	Gastight cut with rectangular recess
		M	Double gastight cut
		N	inseal
D	Outside diameter (mm)		
E	Serial number		

Appendix B: Overview of characteristics

Table B.1 Overview of characteristics and how often they occur as well as fail

Material	Total orders	Failed orders	% failed
Cast steel	1420	354	25
Bronze	198	79	40
Steel	1511	403	27
Type of ring			
001	2723	699	26
002	210	102	49
101	28	6	21
201	13	1	8
301	10	2	20
401	117	25	21
Type of lock			
A	1109	276	25
B	79	14	18
C	151	25	17
D	195	60	31
E	1155	353	31
I	301	106	35
J	2	0	0
K	116	13	11
L	21	1	5
Outer diameter			
0-50	243	112	46
50-100	438	153	35
100-150	525	171	33
150-200	456	115	25
200-250	335	77	23
250-300	263	69	26
300-350	227	45	19
350-400	157	29	18
400-450	117	16	14
450-500	93	13	14
500-550	71	9	13
550-600	57	12	21
600-650	36	10	28
650-700	25	5	20
700-750	20	8	40
750-800	8	1	13
800-850	17	3	18
850-900	7	1	14
900-950	1	0	0
>950	33	0	0

APPENDIX C: LOGIT REGRESSION INPUT

Table C.1 shows part of the logit regression input table. The second row presents a piston ring made from cast steel, of type 001 (compression ring), with lock type A (straight) and an outer diameter of 250 mm. This order did not fail. X_1=250, x_2=0, x_3=0, x_4=1, x_5=0, x_6=0, x_7=1, x_8=0, x_9=0, x_{10}=0.

Table C.1 Part of logit regression input table (total table contains 3129 rows)

Outer diameter	Cast steel	Bronze	001	002	401	A	D	E	I	Failure (yes-1/no-0)
250	1	0	1	0	0	1	0	0	0	0
210	1	0	1	0	0	0	0	0	1	0
300	1	0	1	0	0	1	0	0	0	0
75	1	0	1	0	0	0	0	0	0	0
190	1	0	1	0	0	0	0	1	0	0
260	1	0	1	0	0	0	0	1	0	0
93	1	0	0	0	1	0	1	0	0	0
445	0	0	1	0	0	1	0	0	0	0
445	0	0	1	0	0	1	0	0	0	0
445	0	0	1	0	0	1	0	0	0	0
445	0	0	1	0	0	1	0	0	0	0
80	0	1	1	0	0	0	1	0	0	0
90	0	0	1	0	0	1	0	0	0	0
90	1	0	1	0	0	0	0	1	0	0
320	1	0	1	0	0	1	0	0	0	0
480	1	0	1	0	0	1	0	0	0	0
184	0	0	0	0	1	0	0	1	0	0
168	0	0	1	0	0	1	0	0	0	0
350	0	0	1	0	0	0	0	1	0	0
300	1	0	1	0	0	0	0	0	0	0
500	1	0	1	0	0	0	0	0	0	0
450	1	0	1	0	0	0	0	1	0	0
250	1	0	1	0	0	0	0	0	1	0
244	1	0	1	0	0	1	0	0	0	0
260	1	0	1	0	0	1	0	0	0	0
244	1	0	1	0	0	1	0	0	0	0
260	1	0	1	0	0	1	0	0	0	0
28	1	0	0	0	0	1	0	0	0	0
22	1	0	0	1	0	1	0	0	0	0
513	0	0	1	0	0	0	0	0	0	0
154	0	0	1	0	0	0	0	0	0	0
380	0	0	1	0	0	1	0	0	0	0
450	1	0	1	0	0	0	0	1	0	0
120	1	0	1	0	0	0	0	1	0	0
200	1	0	1	0	0	0	0	1	0	0
1589	0	0	1	0	0	0	0	0	0	0
308	0	0	1	0	0	0	1	0	0	1

88	0	0	1	0	0	0	1	0	0	1
250	0	0	1	0	0	0	0	1	0	0
160	0	1	1	0	0	0	0	1	0	0
142	1	0	0	0	1	1	0	0	0	0
200	0	1	1	0	0	0	0	1	0	0
35	0	0	1	0	0	0	0	0	1	0
513	0	0	1	0	0	0	0	0	0	0
55	0	0	0	0	0	0	1	0	0	0
40	0	0	1	0	0	0	0	1	0	0
71	1	0	1	0	0	0	1	0	0	0
65	0	1	1	0	0	0	1	0	0	0
120	0	1	1	0	0	0	1	0	0	1
130	0	1	1	0	0	0	0	0	1	1
260	0	0	1	0	0	0	0	1	0	1
224	0	0	1	0	0	0	0	1	0	0
172	1	0	1	0	0	0	0	0	0	0
172	1	0	1	0	0	0	0	0	0	0
88	1	0	1	0	0	1	0	0	0	0
450	1	0	1	0	0	1	0	0	0	0
97	0	0	0	0	1	1	0	0	0	0
634	0	0	1	0	0	1	0	0	0	0
341	0	0	1	0	0	1	0	0	0	0
261	0	0	1	0	0	1	0	0	0	0
131	0	0	1	0	0	1	0	0	0	0
220	0	0	1	0	0	0	0	0	1	1
140	0	0	1	0	0	1	0	0	0	0
320	1	0	1	0	0	0	0	1	0	0
196	1	0	1	0	0	0	0	1	0	0
320	0	0	0	1	0	1	0	0	0	1
190	0	0	0	1	0	1	0	0	0	0
175	0	0	0	1	0	1	0	0	0	0
400	0	0	0	1	0	1	0	0	0	0
80	0	0	0	1	0	1	0	0	0	0
330	0	0	0	1	0	1	0	0	0	0
330	0	0	0	1	0	1	0	0	0	0
390	0	0	1	0	0	1	0	0	0	0
350	0	0	1	0	0	1	0	0	0	0
450	0	0	1	0	0	0	0	1	0	0
100	1	0	1	0	0	0	0	0	0	1
77	1	0	1	0	0	0	0	0	0	1
300	1	0	1	0	0	0	0	0	0	0
200	0	1	1	0	0	0	0	1	0	0
75	1	0	1	0	0	0	0	0	0	0
300	1	0	1	0	0	0	0	1	0	1
350	1	0	1	0	0	0	0	1	0	1
175	1	0	1	0	0	0	0	0	0	0

Appendix D: Frequency and position of assignment numbers during production of a piston ring

Table D.1 Assignment numbers and how often they occur at which stage in the production sequence

Assignment #	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th	18th	19th	20th	21st	22nd	
0	2014	0	0	1	0	1	0	2	0	0	1	2	0	1	0	0	0	0	0	0	0	0	2021
1	0	2014	0	24	69	25	14	11	8	7	6	6	3	5	2	1	2	0	0	0	0	0	2187
2	0	0	21	125	347	572	391	206	59	36	26	18	12	9	10	6	3	5	1	0	1	0	1813
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	332	75	45	19	17	12	5	3	1	1	1	4	0	0	2	0	1	0	0	0	511
6	0	0	5	70	417	341	159	57	94	38	25	10	9	6	8	8	1	1	1	0	0	0	1225
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	471	348	81	9	2	13	14	19	26	14	6	5	2	1	1	5	0	0	0	1	1003
12	0	0	693	163	118	51	70	148	188	146	159	80	52	27	35	24	8	6	6	1	7	1	1868
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	278	539	149	159	219	291	153	36	20	20	16	11	9	4	2	3	1	4	0	1	1880
15	0	0	0	2	3	4	5	15	4	3	2	3	0	1	0	1	0	0	0	0	0	0	41
16	0	0	0	2	2	10	23	56	81	66	87	44	18	12	9	10	4	4	3	1	1	1	389
17	0	0	1	1	2	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
18	0	0	14	466	557	316	227	99	37	19	13	10	3	6	1	2	0	0	0	1	0	0	1761
19	0	0	3	10	21	37	37	43	52	57	22	14	4	3	3	3	1	0	1	0	0	0	300
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	96	148	90	244	415	335	267	179	36	23	17	15	7	11	13	2	2	2	4	0	1850
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	75	21	62	63	60	39	40	10	10	5	3	1	0	1	1	0	2	1	0	0	388
24	0	0	0	10	28	57	219	314	292	296	263	256	161	104	72	29	58	18	8	12	5	10	1896
25	0	0	3	0	4	36	33	30	32	100	142	72	63	35	19	24	11	2	3	7	0	1	515
26	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	21	2	6	8	4	3	6	4	5	2	0	1	1	0	0	0	0	0	0	0	61
31	0	0	0	3	3	23	25	40	96	153	71	89	53	31	28	15	3	5	8	1	3	1	556
Total	2014	2014	2013	2010	2004	1976	1920	1716	1428	1172	915	669	421	277	206	140	110	51	37	30	21	16	21%