Royal Grolsch

The improvement of Failure Mode, Effects and Criticality Analysis at Grolsch

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24-8-2017

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Document title	The improvement of Failure Mode, Effects and Criticality Analysis at Grolsch *Bachelor thesis for the bachelor Industrial Engineering and Management at the University of Twente*
Version	Non-Confidential *Confidentiality issues have been made black*
Pages	91
Date	24 August, 2017
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Preface

In front of you lies the bachelor thesis 'The implementation of FMECA'. This report contains a research to make the Failure Mode, Effects and Criticality Analysis more suitable for Grolsch. The research has been done as final project for the bachelor program Industrial Engineering and Management at the University of Twente. I was engaged in researching and writing the thesis from May until August 2017.

The project was executed at request of Grolsch. The research was difficult, since I was not familiar with the concept 'FMECA' before. Despite this unfamiliarity, I have been able to fulfil the research with the help of many people. I would like to thank some people in particular who have supported me in the past three months. First of all, many thanks to Rob Leurink who was my supervisor at Grolsch. He was my sparring partner and without his help I could not have come this far. I would also like to thank my colleagues at Grolsch, the people I talked to for research as well as the people at the Engineering Department who received me with open arms.

During my research I have been supported by my supervisors from the University: Ipek Topan and Engin Topan. With their feedback, I have learned a lot in doing and documenting research.

Finally, I would like to thank my friends, roommates and family, who supported me to continue despite everyone having holidays.

I hope you enjoy your reading.

Niek Wattel

Enschede, 24 August, 2017

Management summary

A lot of machines are necessary to brew, package and transport beer. At Grolsch, there are 1247 machines which all need to be maintained. This maintenance used to be a lot of reactive maintenance and Grolsch decided that they wanted to be more in control. At that point they introduced Failure Mode, Effects and Criticality Analysis (FMECA), which gives a better insight in risks and which risks are too high and therefore need to be prevented or reduced. After some FMECAs had been done, Grolsch was not as satisfied as they hoped to be. The results were conflicting with the employees' opinions and the executors of FMECAs encountered some vaguenesses which caused subjectivity in the analysis. These problems led to the main research question:

How does Grolsch need to use FMECA to make a valid and reliable estimation of the extent of acceptation of risks on component level?

In the first part of the research, the FMECA has been made more valid. The categories on which the criticality analysis is done, has been changed and better grounded by using company goals. Before, the FMECA was executed on component level. If a component breaks down, what effect will that have on Safety, Quality, Environment, Production Availability and Costs, and how critical is that for the system? The criticality analysis was scrutinised by looking at the different levels in the brewery. From the biggest to smallest level, the brewery consists of the next levels: Brewery, Department, Line, Machine, Component. In this research, it appeared that the criticality analysis could not be done on component level for every variable. Production Availability and Costs should be evaluated on department or machine level and Environment should be evaluated only on machine level, whereas Safety and Quality could be evaluated on component level.

In the second part of the research, the FMECA has been made more reliable. First, the vaguenesses in filling in the analysis were determined and clarified by either an explanation or a decision tree. Then the subjectivity in the decision making of the measures were objectified by means of a decision tree. The goal was to eliminate the vaguenesses and make the analysis more objective instead of subjective. This way it does not matter who executes the FMECA, the results will be practically the same.

Lastly, as requested by Grolsch, a list of practical recommendations to improve the template of the analysis was given. This list was based on frustrations which executors of FMECAs encountered, the practicality of the template and the additions which should be implemented in the template based on this research.

General recommendations for Grolsch are to record downtimes of machines in the Brewing, Warehouse and Utilities departments, like they already do in the Packaging department. Also, digging more into Quality is recommended. Other recommendations are about a broader use of the analysis. Environment could be broadened from violations of regulations to reduction of water, gas or electricity and the tool could even be used to predict what the impact will be of future company objectives.

Samenvatting

Het bereiden, verpakken en vervoeren van bier vereist een groot aantal machines. Grolsch heeft 1247 machines die allemaal onderhouden moeten worden. Dit onderhoud was voorheen veel reactief en Grolsch heeft besloten om meer de controle te willen hebben in het onderhoud. Om dat te bereiken hebben ze Failure Mode, Effects and Criticality Analysis (FMECA) geïntroduceerd. Dit is een analyse die de risico's inzichtelijk maakt en bepaalt of een risico te hoog is. Als dat zo is, moet het risico verkleind of volledig weggenomen worden. Nadat er een aantal FMECA's gedaan waren bij Grolsch, waren ze niet zo tevreden als ze gehoopt hadden. De uitkomsten van de analyses kwamen niet overeen met de meningen van de medewerkers en bij het uitvoeren van de FMECA's liepen ze regelmatig tegen onduidelijkheden aan die voor subjectiviteit zorgden. Deze problemen zorgden voor de volgende onderzoeksvraag:

Hoe moet Grolsch de FMECA gebruiken om een valide en betrouwbare schatting te maken van de mate van acceptatie van risico's op onderdeelniveau?

In het eerste gedeelte van het onderzoek is de FMECA meer valide gemaakt. De categorieën die de basis zijn voor de kritikaliteitsanalyse zijn veranderd en beter onderbouwd door bedrijfsdoelstellingen te gebruiken. Voorheen werd de analyse uitgevoerd op onderdeelniveau. Als een onderdeel kapot gaat, wat is dan het effect op Veiligheid, Kwaliteit, Milieu, Productiebetrouwbaarheid en Kosten en hoe kritisch is dat voor de brouwerij? De kritikaliteitsanalyse is onder de loep genomen door te kijken naar de verschillende niveaus in de brouwerij. Van groot naar klein bestaat de brouwerij uit de volgende niveaus: Brouwerij, Afdeling, Lijn, Machine, Onderdeel. Uit dit onderzoek bleek dat de kritikaliteit van elke variabele op een ander niveau getoetst moet worden. Productiebetrouwbaarheid en Kosten moeten getoetst worden op afdelings- of machineniveau en Milieu moet alleen getoetst worden op machineniveau, terwijl Veiligheid en Kwaliteit wel op onderdeelniveau getoetst moeten worden.

In het tweede gedeelte van het onderzoek is de FMECA betrouwbaarder gemaakt. Als eerste zijn de onduidelijkheden in het invullen van de analyse bepaald en verduidelijkt door een uitleg of een beslisboom. Daarna is de subjectiviteit in het bepalen van de tegenmaatregel objectiever gemaakt met een beslisboom. Het doel was om de onduidelijkheden weg te nemen en om de analyse objectiever te maken. Op die manier maakt het niet uit wie de FMECA uitvoert, de resultaten zullen vrijwel hetzelfde zijn.

Als laatste, op verzoek van Grolsch, is een lijst met praktische aanbevelingen gegeven om het template van de analyse te verbeteren. Deze lijst is gebaseerd op frustraties die uitvoerders van FMECA's kregen, de gebruikersvriendelijkheid van het template en de toevoegingen die in het template geïmplementeerd moeten worden naar aanleiding van dit onderzoek.

Algemene aanbevelingen waren om de stilstanden van machines in Brewing, Warehouse en Utilities te registeren, zoals ook al in Packaging gedaan wordt. Ook is aanbevolen om dieper in te gaan op Kwaliteit. Andere aanbevelingen gingen over een bredere inzetbaarheid van de analyse. Milieu kan uitgebreid worden van overtredingen van milieuvoorschriften naar water-, gas- en elektriciteitsverminderingen. De analyse zou zelfs gebruikt kunnen worden om te kijken wat de impact is van toekomstige bedrijfsdoelstellingen.

Table of contents

List of figures

List of tables

Definitions

Basic Failure rate:	Rate at which the item fails.
Bill of Materials (BoM):	A Bill of Materials is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture an end product. Usually a BoM also includes technical drawings.
Corrective Action:	A documented design, process, procedure, or materials change implemented and validated to correct the cause of failure or design deficiency.
Criticality:	A relative measure of the consequences of a failure mode and its frequency of occurrences.
Criticality analysis:	A procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence.
End effect:	The consequence(s) a failure mode has on the operation, function, or status of the highest indenture level.
Factory efficiency:	A measure of how effectively a line has performed relative to the time period available for production and / or maintenance work on the line.
Failure effect:	The consequence(s) a failure mode has on the operation, function, or status of an item. Failure effects are classified as local effect, next higher level, and end effect.
Failure effect probability:	The conditional probability that the failure effect will result in the criticality classification, given that the failure mode occurs.
Failure mode:	The manner by which a failure is observed. Generally describes the way the failure occurs and its impact on equipment operation.
Failure mode ratio:	The fraction of the basic failure rate related to the particular failure mode under consideration.
Functional failure:	A functional failure is defined as the inability of an asset to fulfil one or more intended function(s) to a standard of performance that is acceptable to the user of the asset.
Hazard Analysis of Critical Control Points (HACCP):	Hazard Analysis and Critical Control is a systematic preventive approach to food safety from biological, chemical, and physical hazards in production processes that can cause the finished product to be unsafe, and designs measurements to reduce these risks to a safe level.
Indenture level:	The item levels which identify or describe relative complexity of assembly or function. The levels progress from the more complex (system) to the simpler (part) divisions.

Local effect:	The consequence(s) a failure mode has on the operation, function or status of the specific item being analysed.
Machine efficiency (ME):	A measure of how effectively the line has performed relative to the time period available once adjustments for actual Maintenance & Cleaning time and actual allowed stops / service stops have been made.
Machine hours (MH):	The machine hours are the hours which are left when capacity loss, PFH adjustments, maintenance & cleaning, allowed stops and service stops are subtracted from the calendar hours.
Next higher level effect:	The consequence(s) a failure mode has on the operation, functions, or status of the items in the next higher level above the indenture level under consideration.
Operating time:	The operating time in hours or the number of operating cycles of the item.
Paid Factory Hours (PFH):	Paid Factory Hours are the hours which are left when capacity loss is subtracted from the calendar hours.
Pareto principle:	The Pareto principle (also known as the 80-20 rule or the law of the vital few) states that, for many events, roughly 80% of the effects come from 20% of the causes.
Potential failure:	The point in the deterioration process at which it is possible to detect whether a failure is occurring, or is about to occur
Process & Instrumentation Diagram (P&ID):	A process and instrumentation diagram is a detailed diagram in the process industry which shows the piping and vessels in the process flow, together with the instrumentation and control devices.
Risk Inventory & Evaluation (RI&E):	In the RI&E, all risks in the areas of safety, health and welfare are mapped out and documented. The 'evaluation' refers to the estimation of the level of each risk.
Severity:	The consequences of a failure mode. Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, or system damage that could ultimately occur.
Single failure point:	The failure of an item which would result in failure of the system and is not compensated for by redundancy or alternative operational procedure.

1 Introduction

Grolsch is a Dutch beer brand which is brewed in the Grolsche Bierbrouwerij in Enschede. The brewery was founded by Willem Neerfeldt on 11 May 1615 in Grol (Groenlo). The brewer Peter Kuijper, who is considered to be the founding father of the Grolsch beer, dies in 1684 and his family takes over the brewery. In the next decades, the brewery gets known as “De Klok”. In 1876 Grolsch cannot meet the demand with the small brewery. They decided to build a bigger brewery just outside Groenlo, which they also named “De Klok”. In the end of the 19th century, the textile industry is growing at a high speed during the Industrial Revolution and a lot of people are going to Twente. In many cities around Enschede new breweries are successfully founded and in 1895, some manufacturers, traders and bankers decided to set up a new brewery in Enschede, which they called “De Enschedesche Bierbrouwerij”. In 1897 Theo de Groen, a brewer from Utrecht, buys Grolsch with his three sons. Immediately he introduces the swingtop bottle, for which Grolsch is internationally known up to now. After World War I, De Enschedesche Bierbrouwerij is doing not so well. They merge with De Klok in 1922 and become “N.V. Bierbrouwerij 'De Klok' Enschede-Groenlo” located in Groenlo and Enschede. In 1954 the name of the brewery changes to “Grolsche Bierbrouwerij”. In 1959 the slogan “Vakmanschap is Meesterschap” (Craftmanship is Mastery) is introduced, which reflects the quality Grolsch delivers. Grolsch becomes Royal in 1995 thanks to its craftmanship and quality. In 1998 they decide that it would be way easier to have one brewery instead of two. This brewery is built and opened in 2004 as one of the most advanced, efficient and environmental-friendly breweries in the world. In 2008 Grolsch is taken over by SABMiller and in 2016 the Japanese Asahi takes over Grolsch from SABMiller. The Italian Peroni and the English Meantime are part of Asahi as well. With a market share of 13% and a production of 1,5 million hectolitres per year, Grolsch is in 2017 the second biggest brewery in the Netherlands, placed after Heineken. Andrei Haret is the CEO of Grolsch Nederland. In total, there are 764 people working at the Grolsch Brewery (see Figure 1).

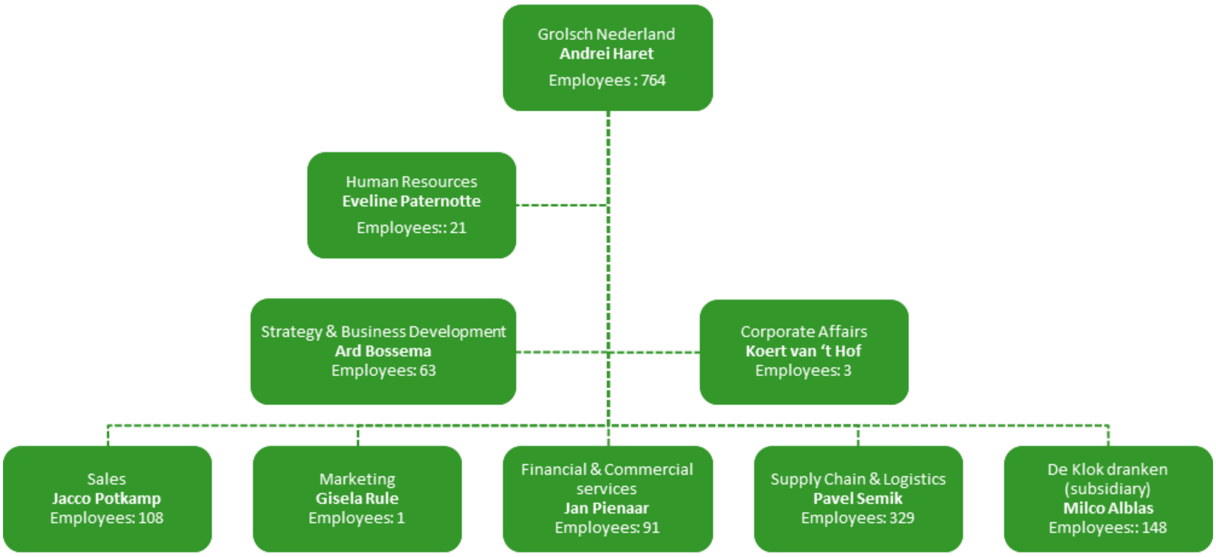

Figure 1: Organisation chart of Grolsch

The brewery is split up into four departments: Brewing, Packaging, Warehouse and Utilities (see Figure 2). In Brewing the raw materials arrive and that is where the beer is brewed. This can take up to a month. Then the beer is bottled in the Packaging department. This department has 9 packaging lines:

- Line 1: Keg line, pilsner as well as specialty beer
- Line 2: Specialty beer in regular brown bottles

- Line 3: Pilsner in regular green bottles
- Line 4: Pilsner in swingtop bottle
- Line 5: Magnum bottle (1.5L), pilsner as well as specialty beer
- Line 7: Export beer
- Line 8: Cans
- Line 20: Tanker beer
- Line 24: Swingtop assembly

After the beer is bottled it goes to the Warehouse department from where the beer is distributed.

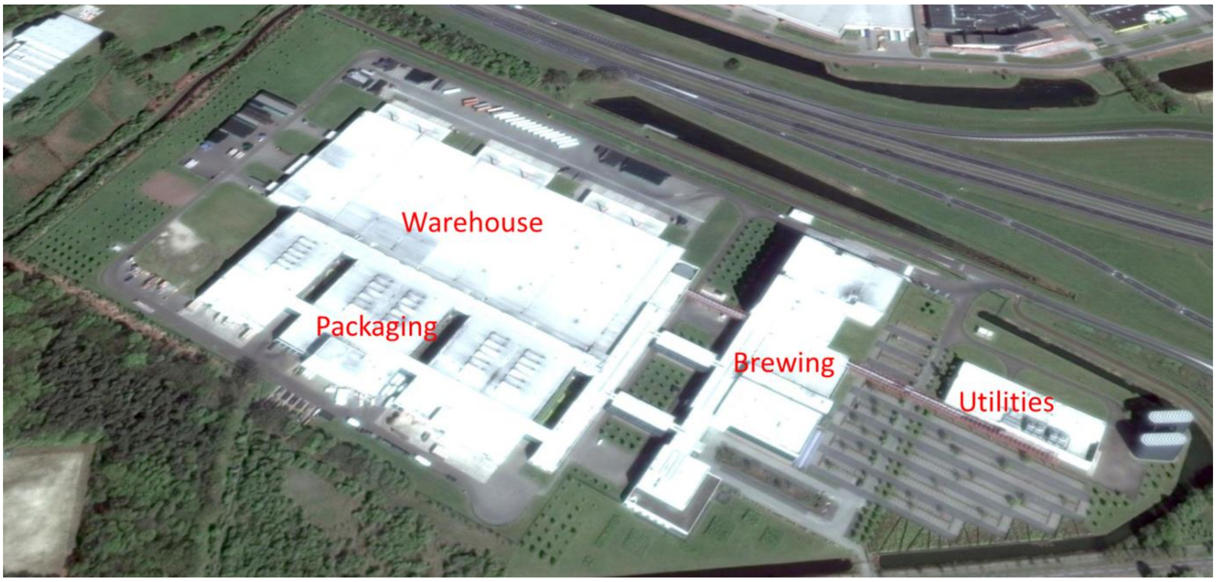

Figure 2: departments at Grolsch

A big company as Grolsch faces a lot of risks. A while ago, they encountered the problem of not having mapped the risks. This had three consequences: risks were estimated too high, risks were estimated too low or risks were not visible at all. To get a better view of the risks, Grolsch decided to use the Failure Mode, Effects and Criticality Analysis (FMECA). In chapter 2.3 I will further elaborate on the FMECA. Grolsch faces some troubles with the FMECA. In my bachelor assignment I will help Grolsch solve the troubles and make the FMECA suitable for Grolsch.

2 The problem

In this chapter I will further define the problem given by Grolsch. At the end the following things will be known: the problem, a brief explanation of how to solve the problem, the research questions and the variables.

2.1 Problem identification

At the moment, FMECAs at Grolsch are conducted on component level. The result of this analysis is that almost every risk on component level is 'acceptable', which means that no measures have to be taken to reduce the effect of the risk. But when looking at machine, line or brewery level, objectives are not always accomplished, which makes the risks 'unacceptable'. So all the acceptable risks on component level sum up to an unacceptable risk on line or brewery level. Figure 3 shows the problem cluster of Grolsch; due to a lack of knowledge in the use of FMECA, the analysis is filled in and interpreted incorrectly. The result is that Grolsch still hasn't mapped its risks well, which consequently causes unnecessary and unexpected costs. Also objectives with respect to safety, environment, quality and availability are jeopardised. Amongst other things, this combination has as result that company objectives are not accomplished.

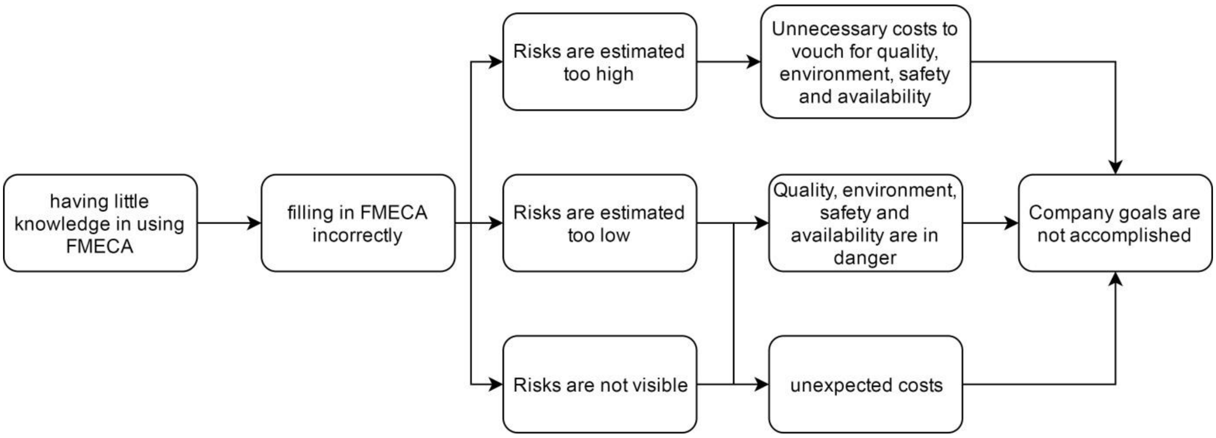

Figure 3: Problem cluster of Grolsch

The cause seems to be 'having little knowledge in using FMECA'. This problem does not have a cause and the problem can be influenced by doing research and creating the knowledge. Therefore, that is the problem I will investigate.

Grolsch has 1247 machines in total; 389 on the Packaging department, 73 on Warehousing, 510 on Brewery and 275 on the Utility department. At the moment, risks of only three machines have been mapped using FMECA, so risks have been mapped for just 0.24%. And it is even questionable if those results are reliable at all. The ultimate goal for Grolsch is to map the risks for the complete 100%.

2.2 Problem approach

Risks are present in every section of the company. Everybody therefore have to deal with risks. Mechanics have to show up when something breaks down due to a wrongly estimated risk, supervisors have to see, estimate and solve the risks, and managers see the risks back as negative results, something they have to take responsibility for. Since the managers are responsible at the end, they will be the starting point in my investigation.

On my first day at Grolsch, I have been introduced by Rob Leurink, supervisor at Grolsch, to a couple of people; managers, supervisors and people experienced in conducting an FMECA. Afterwards, Rob sent an email to those people and people we did not met during my first day to introduce me even more and to say that I will contact them for my research. I created a list from the people Rob mailed to and some additional people I heard later from. This list has been my basis for the interviews with subjects (see Table 2 in Chapter 4.2.2). In the research design, I will further elaborate on the different types of people.

The purpose of taking the interviews, is to find information inside the company which is already known. The way FMECA can be made suitable on brewery level is not information which is already known. I had to investigate that myself. There are a couple of things I needed to know to answer that question; I needed to know exactly how an FMECA works, how objectives on brewery level can be translated to objectives on component or machine level and how the objectives on component or machine level can be connected to the risks on those levels.

In order to get a broad insight in the FMECA, two things have been done: a literature study has been conducted with as subject 'FMECA', and I have watched people doing multiple FMECAs. In general, in the beginning the focus was on Packaging to get FMECA perfectly known.

2.3 Problem analysis

2.3.1 Problem description

As said in the problem identification, there is too little knowledge about how to use the FMECA. Therefore, risks cannot be determined good enough. This problem can be summarised in the next question:

How does Grolsch need to use FMECA to make a valid and reliable estimation of the extent of acceptation of risks on component level?

By solving this problem, I got more insight in the way Grolsch can use FMECA as a good tool to map their risks.

2.3.2 Research questions

To solve the problem, I split the problem into two things; making the FMECA valid and making the FMECA reliable. This resulted in the following two research questions:

1. How can Grolsch use company objectives to manage risks on component level? [validity]

   By answering this question, risks on component level are not just individual risks anymore, but they are part of the company objectives. The purpose of this, is to make a more valid estimation of the risks on component level.
   I split this question into several sub questions:

   a. What are the different company goals per effect and are they already split up in department and/or lines?
   b. How can we use the company goals to better ground the risk tables?
   c. How do we have to translate the different effects on component or machine level to compare them to company level?
   d. How can the components or machines be selected to execute FMECAs on?

2. What are the vaguenesses in making an FMECA and how can the vaguenesses be clarified? [reliability]

   When there are vaguenesses in the FMECA method, the analysis can be filled in and interpreted differently by executers of the FMECA. This results in different outcomes of the FMECA. This way the FMECA is not reliable. By eliminating and clarifying the vaguenesses, the tool will be an unambiguous, and therefore reliable way to estimate risks.
   I divided this question into three different sub questions:

   a. What are the vaguenesses in filling in the FMECA and how can they be clarified?
   b. How can we make the decision making for measures easier and more objective?

c. What are recommendations regarding the practical usage of the template?

2.3.3 Variables

The risks in the FMECA are determined by the following five variables, all reified by choosing between the corresponding effects on a risk:

1. Safety
    a. Lethal injury
    b. Serious accident with permanent injury
    c. Accident leading to sick leave
    d. Accident not leading to sick leave
    e. Near accident
    f. No effect
2. Production availability
    a. Stop entire department
    b. Production disruption critical line (consequences for the customer)
    c. Production decrease (with loss of product quality)
    d. Production decrease (without loss of product quality)
    e. Loss of redundancy without an effect on production
    f. No effect
3. Costs
    a. Costs more than 10.000 euro
    b. Costs between 5.000 and 10.000 euro
    c. Costs between 2.500 and 5.000 euro
    d. Costs between 0 and 2.500 euro
    e. No costs
4. Environment
    a. Violation of environmental regulations (waste substances, packaging, etc.) with major environmental impact
    b. Violation of environmental regulations (waste substances, packaging and so on) that leads to nuisance 'within the enclosure of the company site'
    c. Violation of environmental regulations (waste substances, packaging and so on) without any direct impact
    d. No effect
5. Quality
    a. Immediate public health hazard due to failure to comply with the legal quality requirements relating to food safety
    b. Rejection of product due to failure to comply with the legal quality requirements relating to food safety
    c. Rejection of product due to failure to comply with the in-house quality requirements
    d. Non-compliance with in-house quality requirements, not leading to rejection or reprocessing
    e. No effect

3 Theory

This chapter will be about theory. First a literature review to FMECA will be conducted and secondly the theoretical perspective for this research will be defined.

3.1 Literature review

In this literature review I will look into FMECA. First I determine which method(s) I will use when looking for literature. When this is known, I will begin the actual literature review. The first questions in the literature review will be what FMECA is and what it is used for, then I will look into the steps of conducting an FMECA. Thereafter I will address the different types of FMECA and at the end I will elaborate on some strengths and weaknesses of the FMECA.

3.1.1 Method

In this paragraph I will explain how I found the literature used in this literature review. This includes the search strings, inclusions and exclusion criteria, and also the which articles were useful for the which part(s) of the review.

Search strings

- FMECA
- Failure Mode, Effects, and Criticality Analysis
- FMECA in manufacturing industry
- Risk assessment methods
- FMECA method

Note: every time I used FMECA as search string, I did an additional search on FMEA.

Inclusion criteria

- *Articles in English or Dutch.*
  In English and Dutch I can (almost) completely understand scientific literature. When reading in German, French or Spanish, I will probably not understand the article.

Exclusion criteria

- *"FME(C)A" or "Failure Mode, Effects, (and Criticality) Analysis" not mentioned in the abstract or title.*
  If these criteria are not in the abstract or the title, I assumed that it is not treated as relevant in the paper.
- *Articles which are paid.*
  As a student I do not have the resources to pay for articles which might not be relevant.
- *Articles which require a different university login than the University of Twente.*
  These articles are simply not accessible for me.
- *Articles on a specific subject, unless the subject is something like manufacturing.*
  The literature review is quite broad. If I focus on very specific subjects which are not in my scope of research at Grolsch, then it will not be applicable on my research.
- *Articles before 1940.*
  The FMECA was developed in the 1940s, so articles before 1940 will not address this specific topic.

Concept matrix

In Table 1, the concept matrix is shown. This matrix visualizes which articles were used for which chapter in the literature review.

Table 1: Concept matrix

Article	What is FMECA/where is it used for?	How to conduct an FMECA	Types of FMECA	Strengths and weaknesses
Bahr, 2015		X		X
Department of Defense, 1980	X	X		X
Jun, 2012	X			
Schneider, 1996	X		X	
Carlson, 2014		X	X	X
Price, 2006		X		
Tixier, 2002	X			
Apollo Reliability and Quality Assurance Office, 1966	X			
Department of Defense, 1977		X		
Wang, 2007		X		

3.1.2 Introduction of the literature review

Companies use a lot of different methods to identify risks, such as FMEA, FMECA, HAZOP, PLSA, ETA and MOSAR (Tixier, Dusserre, Salvi, & Gaston, 2002). Failure Modes, Effects and Criticality Analysis (further called FMECA), was first introduced by the U.S. Military in 1940. In 1966, the NASA used FMECA for its Apollo program (Apollo Reliability and Quality Assurance Office, 1966) and nowadays it is also used in the automotive industry. FMECA is a bottom-up failure analysis method (Jun & Huibin, 2012), which gives a clear guideline to assess all possible failure modes, failure causes and failure effects of a system (Schneider, 1996; Department of Defense, 1980). The goal of identifying risks – in the case of Grolsch – is to prevent the occurrence of severe errors, reducing therefore the amount of disturbs in the production process and ultimately results in a higher safety, a higher production reliability and lower costs. In this literature review, the FMECA will be elaborated on. First, the way of conducting an FMECA will be found out. Then different kinds of FMECAs will be addressed. And finally the strengths and weaknesses of the FMECA will be discussed.

3.1.3 How to conduct an FMECA

Bahr (2015) explains FMECA as “an analysis tool that identifies all the ways a particular component can fail, what its effects would be at the subsystem level and ultimately on the system and what the criticality is.” In the first FMECA, conducted by the U.S. Military on missions, the effects were defined as mission success, personnel and system safety, system performance, maintainability, and maintenance requirements (Department of Defense, 1980). Each company needs to define its own effects, based on the company goals. The severity of the effects are ranked according to ranking levels. When creating the ranking levels, Carlson (2014) says to use the minimum number of ranking levels for each scale that adequately differentiates the risk criteria. The Department of Defense even differentiate effects on multiple system levels: local effect is defined as the consequence the failure mode has on the specific item being analysed. Next higher level effect is the consequence of the failure mode on the next higher indenture level above the indenture level under consideration. The end effect is the consequence of the failure mode on the highest indenture level. When FMEA is performed at the system level, the failure modes are component failures, and the effects are loss of system functionality or unexpected activation of functionality, due to the component failure(s) (Price, Snooke,

& Lewis, 2006).When the severity of the effects is determined, several things need to be taken into account, for example whether the component analysed is a single failure point or whether it is compensated by redundancy.

Next the occurrence of the failure needs to be determined. This can be done in either a qualitative or a quantitative way. For the qualitative assessment, frequency of occurrence levels are determined. For example, MIL-STD-882 uses five frequency levels: frequent, probable, occasional, remote and improbable. An FMECA-team can use known levels or produce its own. For the quantitative approach, a criticality number is calculated by multiplying the following parameters: basic failure rate *(λ_p)*, failure mode ratio *(α)*, conditional probability *(β)* and operating time *(t)* (Department of Defense, 1980). The qualitative probability level or the quantitative criticality number and severity are then compiled in a criticality matrix, and the analysis can rank the items based on which is the most critical failure to the system (Bahr, 2015). Carlson (2014) arguments that when criticality is used, high severity must be considered regardless of the criticality value. The FMECA-team must adequately address all high-severity as well as high-criticality issues. The FMECA team can set boundary levels for the criticality number in accordance with the company goals. If the calculated criticality number exceeds the pre-set boundary level, then the risk of the failure mode is too high and measures have to be taken to reduce the risk. When measures have to be taken, you should consider existing controls, relative importance (prioritization) of the issue, and the cost and effectiveness of the corrective action (Carlson, 2014). The kind of maintenance also needs to be chosen. Examples of maintenance strategies are corrective maintenance, time-based preventive maintenance, condition-based maintenance or predictive maintenance (Wang, Chu, & Wu, 2007).

3.1.4 Types of FMECA

FMECA is the Failure Mode and Effects Analysis (FMEA) with the added step of Criticality Analysis (CA). FMEA uses the following steps: for each potential failure identified, first an estimate of its chances of occurrence is made; second, a determination of the consequences (severity) of the failure is made; and third, the chances that the failure will be detected before it has severe consequences is assessed. Actions may then be taken depending on the combination of the three (Schneider, 1996). The main difference is that FMECA uses severity and occurrence risk rankings as input to the criticality risk, without the use of a detection risk ranking (Carlson, 2014). Carlson also recommends practitioners of the FMECA, to first understand the basics of FMEA, and then to learn the FMECA procedure.

The most common types of FME(C)A are system, design and process (Carlson, 2014). System FME(C)A is the highest-level analysis of an entire system, made up of various subsystems. In system FME(C)As, the focus is on functions and relationships that are unique to the system as a whole. Included are failure modes associated with interfaces and interactions and single-point failures.

Design FME(C)A focuses on product design, usually at the subsystem or component level. It aims to make design related deficiencies visible, resulting in the product operation being safe and reliable during the useful life of the equipment. Process FME(C)A focuses on the manufacturing or assembly process. It aims to improve the manufacturing process to ensure that a product is built to design requirements in a safe and efficient way. This FME(C)A can include manufacturing and assembly operations, shipping, incoming parts, tool maintenance and labelling.

3.1.5 Strengths and weaknesses

Bahr (2015) emphasises some strengths and weaknesses of the FMECA. The first one Bahr warns of is to not overuse FMECA, since it is very expensive to use it across the entire system. A solution he gives to this problem, is to identify significant hazards using for example HAZOP, and use FMECA to further drill down to all the causal factors of the component failure that could lead to that hazard. This is one of the strengths of FMECA: going to the piece-part level to determine root causes, which is important in understanding how to control a hazard. Bahr immediately comments on his own solution:

"A failure does not have to occurs for a hazard to be present in the system." In other words, identifying all the failures does not mean knowing all the hazard causes. Carlson (2014) acknowledges the expensiveness of conducting FMECAs. He gives a list of criteria on how to select FMECA projects:

- ✓ New technology
- ✓ New designs where risk is a concern
- ✓ New applications of existing technology
- ✓ Potential for safety issues
- ✓ History of significant field problems
- ✓ Potential for important regulation issues
- ✓ Mission Critical applications
- ✓ Supplier Capability

Another strength which is named by Bahr, is that FMECA is recognised as a legitimate safety analysis tool, by for example the Occupational Safety and Health Administration (OSHA). The Department of Defense also names the safety analysis together with some other purposes an FMECA provides information for, such as maintainability, survivability and vulnerability, logistics support analysis, maintenance plan analysis, and failure detection and isolation subsystem design.

3.1.6 Conclusion

Based on the literature review, there are some things which need to be taken into account as well as choices needs to be made in further chapters which are important for doing my research at Grolsch. First we need to determine if we want to take into account the effects on multiple system levels (local effect, next higher indenture effect, end effect). It is more time consuming to do, but it gives a better insight into the different effects. Next, there needs to be a distinction between single failure points and points which have redundancy. The chance a failure occur is much smaller when having redundancy. We also have to decide which kind of approach (qualitative or quantitative) we will use when determining criticality. At the moment this is done in the qualitative way, but this depends on the data available. Carlson arguments that when criticality is used, high severity must be considered regardless of the criticality value. This is something we need to discuss. The prevention strategy needs to be determined based on the type of risk. A high severity risk demands another prevention strategy than a high occurrence risk. Another thing which needs to be taken into account, is what type of FMECA we use. This can be multiple types, but it is good to make a conscious decision. The last one is not to overuse FMECA. We need to think how to use FMECA at Grolsch and reduce the time spent on FMECAs by implementing smartnesses and thinking logically.

3.2 Theoretical framework

I have mainly investigated a concept from scientific literature: the FMECA. FMECA is based on the meaning of risk with corresponding parameters. Risks can be determined by multiplying chance by impact. Since my research is mainly based on FMECA, this has been my biggest theoretical framework. But there are some other theoretical frameworks.

As said in chapter 3.1.6, we needed to make a distinction between single failure points and points with redundancy. A way to compare these two, is by pretending the points with redundancy fail based on the condition that the main point already has failed. This can be calculated with the conditional probability formula for independent events A and B: $P(A \cap B) = P(A|B) * P(B)$. In words: the chance that event A and event B happen at the same time is equal to the chance that event A happens given that event B happened multiplied by the chance event B happens. The exponential distribution will be used to calculate redundancy.

Another theoretical framework, is choosing the maintenance strategy. A concept which can help with the choice, is the bathtub curve. In the beginning of the product life cycle there are some infant mortalities. During this period the failure rate decreases. Then there is a certain time that the machine has a normal failure rate behaviour. At the end of the life cycle, the machines gets old, which goes hand-in-hand with an increasing failure rate. Looking at the failure rate, one can determine in which phase of the life cycle a machine is in, and depending on the phase, which maintenance strategy to choose or to exclude. The P-F curve is another useful tool to select the maintenance strategy. The P-F curve shows the time between the potential failure and the functional failure. Depending on this P-F interval, different maintenance strategies can be used.

Figure 4 shows a graphical overview of the theoretical frameworks I am planning to use in this thesis.

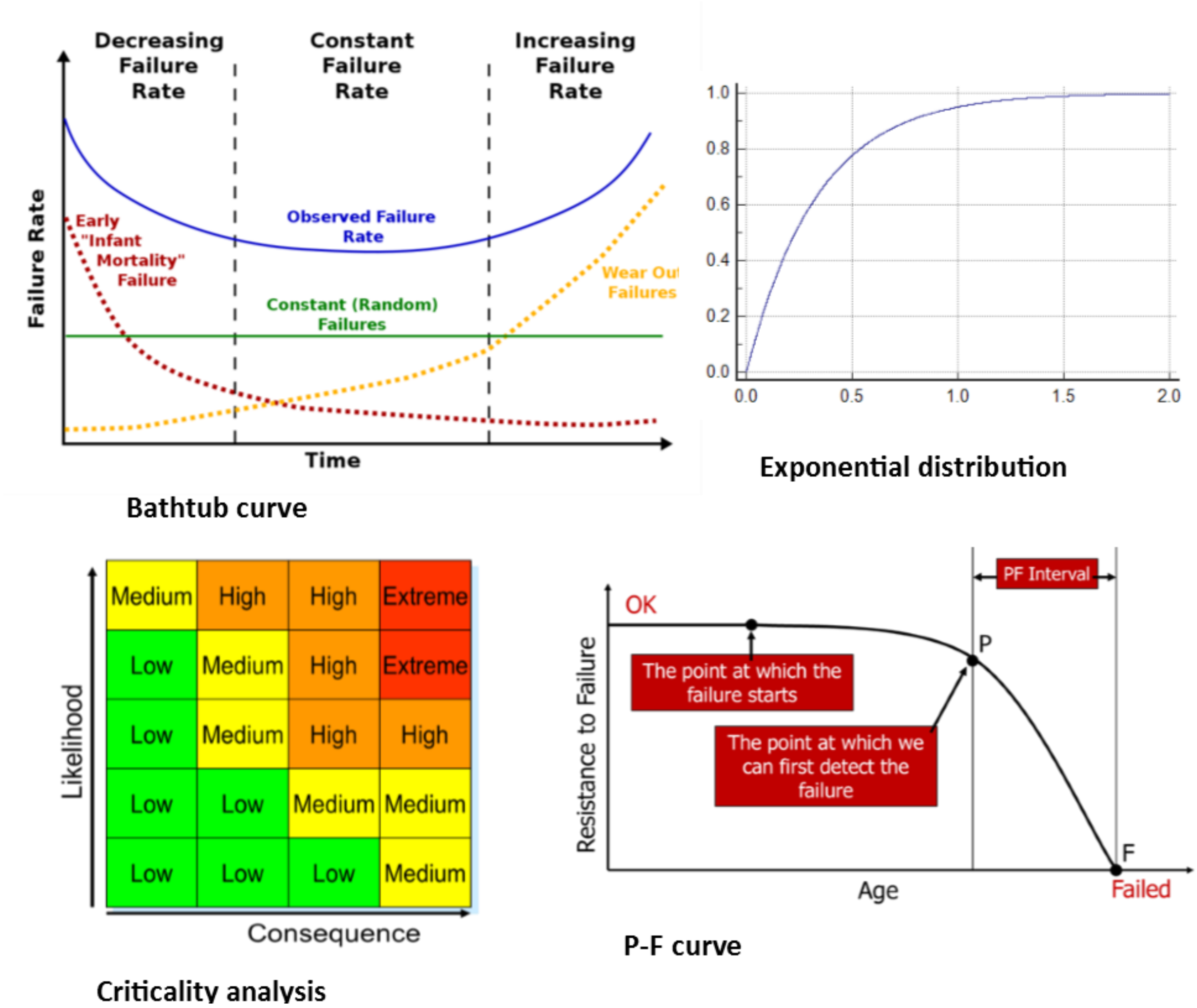

Figure 4: Overview of theoretical frameworks

4 Research design

In the previous sections, I described what my research is about. In this section, I explain how I have executed my research. Some choices have been made in this section.

4.1 Research strategy

Two research questions which both are a different type of research were set up. Research question 1 is an explanatory research, aiming to find the relation between risks on component level and company objectives. Research question 2 is a descriptive research, aiming to find the vaguenesses in making an FMECA.

Interviews with different people at Grolsch were conducted without using a stimulus. A stimulus has not been used, because this was not an experiment, but an interview, in which the knowledge of the interviewees needed to be gained without influencing them. The research took place in the field, not in a laboratory. I watched people doing an FMECA, not because I said them to do it, but because it is part of their work.

Research question 1 required a deep research approach. To translate the objectives on company level to risks on component level correctly, I needed to gain as much knowledge as possible, to prevent me from making a wrong translation.

Research question 2 required a broad research approach. I interviewed as much people who once conduct an FMECA as possible and combine all the vaguenesses they experienced in making an FMECA. The purpose is to find all the vaguenesses which are present.

In both research questions, I used a cross-sectional research. I did not measure changes over time. I wanted to know the vaguenesses in making an FMECA, which do not depend on time. This also applies for the relation between risks on component level and objectives on company level; this relation does not depend on time either.

4.2 Subjects

In this section I will define the categories of subjects at Grolsch and the specific people until now.

4.2.1 Subject categories

There are roughly four categories of people I have spoken to:

1. **Managers of the departments**
   I talked with the managers about the company objectives and how these objectives are used in their department for monitoring results. They also told me which results are hard to achieve. I also got to know which risks in the departments have big influence(s) on other departments. In the FMECA there are certain boundaries set for the acceptation of risks on the different variables (environment, quality, safety, costs and production availability). I got to know whether those boundaries are the same for every department and that we have to change them.

2. **Supervisors and mechanics**

   By talking to supervisors on the workplace, I found out what practical problems occur. They told me more specified where and what the risks are, the managers did this with a broader scope.
   Together with the supervisors and the mechanics, I looked at the outcomes of an FMECA to see how realistic the current FMECA is and to find points for improvement.

3. **Executers of FMECA**

Three FMECAs have been completed yet. Another FMECA once was started, but never finished. I talked to the people who conducted these FMECAs and found where the difficulties and vaguenesses were. I also was there when an FMECA was conducted.

4. **Experts in the area of safety, quality and environment**

   Safety, quality and environment are hard to quantify in the FMECA. The purpose of talking to those people, was to gain more knowledge in the areas. By using that knowledge, I acquired qualitative goals in the three areas.

4.2.2 Specific subjects

As said in chapter 2.2, a list of specific subjects to talk to was made. This research population can be find in Table 2. The interviews with these people can be found in Appendix G.

Table 2: Subjects at Grolsch

Department	Name	Function
Packaging	Domingo Jans	Packaging Specialist
	Marcel Hems	Manager Packaging
	Meije Lammers	Packaging Engineer
	Richard Stein	Shift team leader Packaging
Brewing	John Kalma	Brewing Utility engineer
	Harro de Vries	Manager Brewing
	Dennis Assink	Maintenance planner Brewing
	Paul Somers	Maintenance specialist
Utility	Martin Bosscher	Utility manager
Warehouse	Daan de Stigter	Manager Warehouse
Engineering	Susan Ladrak	Manager Engineering
	Ruud van Westen	Strategic maintenance planner
	Ilco Kuiper	Strategic maintenance planner
	Steven Groot Zevert	Maintenance planner
Quality	Garma Stubbe	Quality Assurance Specialist
	Wim Vermeulen	Manager quality and innovation
	Eino Staman	SHE (Safety, Health, Environment) specialist

4.3 Gathering information

Information was gathered in five different ways; a literature study, primary sources, secondary sources, observation and communication.

4.3.1 Literature study

To gain more knowledge of the FMECA, a literature study to FMECA was conducted (see chapter 3.1). In this study, it was examined what FMECA exactly is, how to conduct an FMECA, the different types of FMECA and the strengths and weaknesses. This gave a basis to start at Grolsch.

4.3.2 Primary sources

The primary sources have been yearly, quarterly and monthly scores on company objectives. This were scores on brewery level as well as scores on department level (Packaging, Warehouse, Utility and Brewing). Data of malfunctioning behaviour has also been used as a primary source.

4.3.3 Secondary sources

At the moment three FMECAs have been conducted. Those secondary sources of malfunctioning behaviour were input for my research. Also a lot of preventive maintenance is done. The plans for the preventive maintenance were also used for the research.

4.3.4 Observation

Every Tuesday people work for two hours on an FMECA. These sessions were visited as much as possible to do observations needed for the second research question.

4.3.5 Communication

The interviews conducted with the subjects of Grolsch are the communicative approach for gathering information. In these interviews, I wanted to get known how the current variables in the FMECA can be made quantitative to be able to make the connection between risks on component level and company objectives.

4.4 Data processing and analysing

The first research question was based on qualitative research. The thing needed to be discovered was *how* company objectives can be used to determine the risks on component level. This was verified with quantitative research, using the criticality analysis in the FMECA. When doing qualitative research, the criteria in the essay "Validation of qualitative research" were used to validate the research.

The second research question was primarily based on quantitative research using reliability statistics. The thing needed to be discovered was *what* the vaguenesses are in conducting an FMECA. But again, there was a qualitative research included; *how* we can clarify this vaguenesses.

4.5 Planning

4.5.1 Activity planning

There were a couple of concrete steps which had to be made which were mostly involved in gathering information. This were the following steps:

- Watch people do an FMECA to discover vaguenesses
- Identify company objectives on department level
- Identify risks which have a big influence on other departments
- Check if the boundary levels in the FMECA are the same for every department
- Making the variables in the FMECA quantitative
- Talk with supervisors on the workplace to discover practical problems
- Talk with supervisors and mechanics about already made FMECAs to verify the trueness of the analysis
- Talk to executers of FMECAs to discover the vaguenesses

4.5.2 Time planning

Figure 5 shows the time planning for the ten weeks research has been done. The bachelor assignment was divided into four different stages (the green bars): gathering data, analysing and processing data, create results and conclusion. It is notable that ‘gathering data’ is quite a long time. This was because I planned to do FMECAs until the 26th week. This is just 2 hours a week. That is why I started very early in the gathering data process with analysing and processing the data. In week 26 I started working on the recommendations for the template and the development of a method to aggregate company goals. Those activities are quite linked together, so I started them at the same moment. Then in week 27 I started working on the manual for FMECA. In week 27 I presented what I had so far to my colleagues at Grolsch. After that presentation, I adapted my report using their feedback. Week 29 was the last week of my contract at Grolsch. In week 30 and 31 I finalised my report and prepare for the defence in week 34.

I met every Friday afternoon with my supervisor at Grolsch, Rob Leurink. In the beginning of week 22 I had an appointment with my supervisors from the University, Ipek Topan and Engin Topan. Furthermore, I talked to a lot of people at Grolsch (see Table 2), mostly conversations of about one hour, sometimes just a brief discussing or sessions of 2 hours.

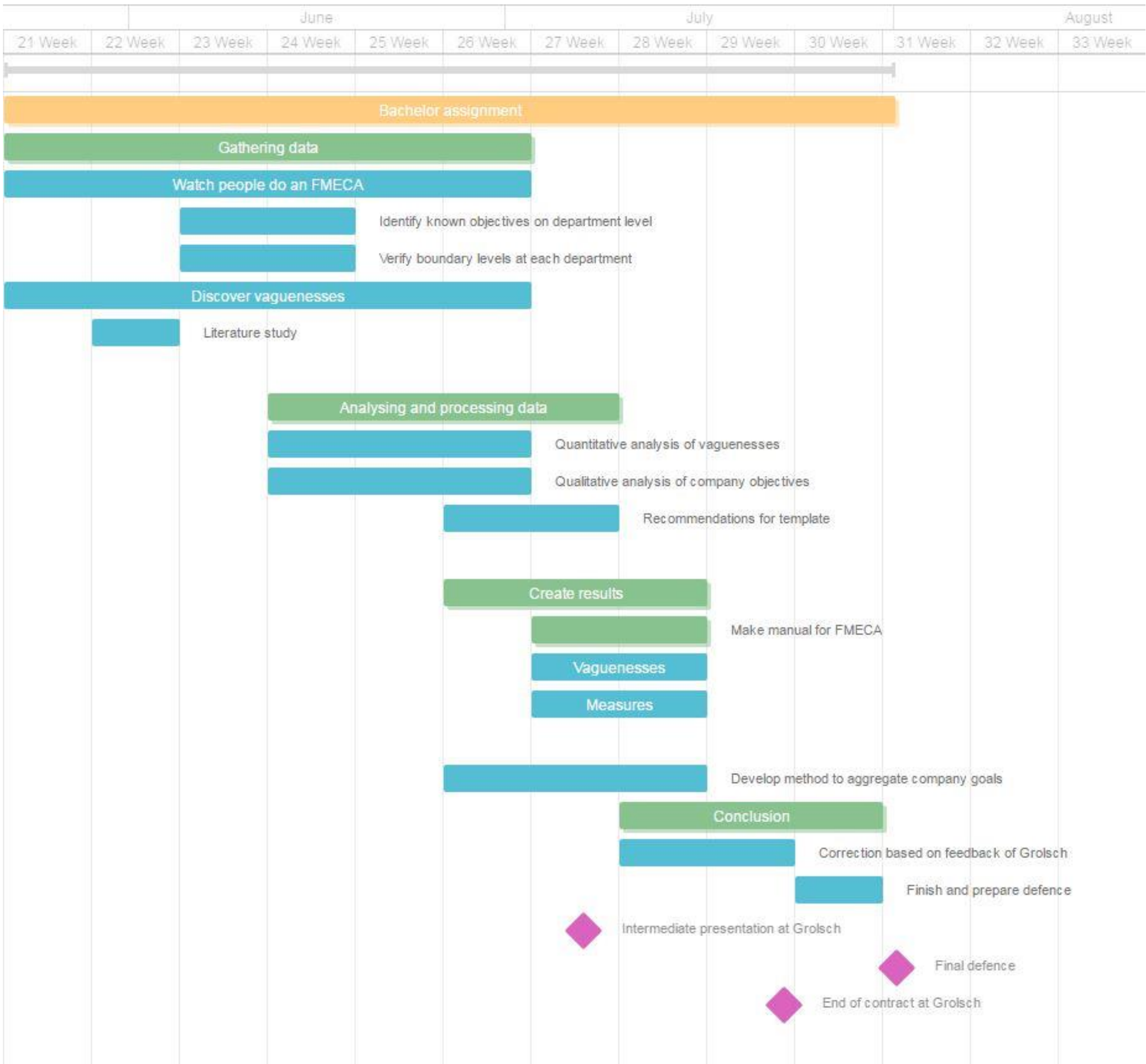

Figure 5: Time planning in Gantt chart

4.6 Deliverables

As first deliverable, a method to aggregate company goals better in the FMECA was developed as well as a method on which level to execute the criticality analysis.

As second deliverable a manual for FMECA was made. In this manual it is addressed how to fill in the FMECA and what to do when facing certain vaguenesses.

The last deliverable is a list of recommendations to practically improve the FMECA template.

4.7 Limitations and constraints

The only limitation (set by myself) was time. Ten weeks was given for the bachelor assignment and I therefore could not make my research too big. This means choices had to be made. For example, I made the decision to start at Packaging and find out what the answer is on my research questions for this department. Also Quality could not be digged in properly.

There are almost no constraints set by Grolsch. In this internship agreement, a couple of conditions have been set concerning secrecy and intellectual property. Those two Dutch articles of the internship agreement can be found in Appendix A.

Another constraint is that there might not have been enough knowledge inside the company. Therefore everything I did not know for sure had to be verified. That way I prevent doing research based on falsehoods.

The last constraint is about confidentiality. In the public report I had to exclude company goals.

5 Analysis

In this chapter the first research question will be answered: “How can Grolsch use company objectives by using FMECA to manage risks on component level?” This question will be answered by using four steps. The first step is to analyse what company goals there are for the five variables in the FMECA: Safety, Environment, Quality, Production Availability and Costs. Next, I will take a critical look to the current risk tables in the FMECA. Then a method to make the translation from component level to company level will be developed and lastly a way on how to select machines on which a FMECA should be done will be described. The FMECA template as used by Grolsch before can be found in Appendix B with an explanation.

5.1 Company goals per variable

In this chapter the first sub question of the first research question will be answered: “What are the different company goals per effect and are they already split up in departments and/or lines?” By knowing the company goals, the values and categories in the risk tables can be better grounded.

5.1.1 Safety

There is one main goal on safety at Grolsch: less injuries than the previous year. For 2017 we can use the amount of injuries of 2016 as a target. Table 3 shows the targets for 2017 which are the results of 2016 in the second column. In the first column the different categories Grolsch uses can be seen. Since FMECA only considers mechanical failures, it is not reasonable to take this targets as input for the FMECA. In a conversation with Eino Staman, SHE specialist, he estimated that about 95% of the injuries are caused by human failures. Just 5% is due to mechanical failures. The targets on safety adjusted for mechanical causes are put in the third column of Table 3.

Table 3: Company goals on safety

Injury	2017 Target	2017 Target for mechanical failures
Minor injuries	[redacted]	[redacted]
Disabling injuries	[redacted]	[redacted]
Near Misses	[redacted]	[redacted]
Dangerous Situations	[redacted]	[redacted]
Lethal injuries	[redacted]	[redacted]

5.1.2 Quality

Table 4 shows some of the company goals on quality. There are a lot of goals on quality, since beer is a consuming good and Grolsch wants to be distinctive from its competitors through quality and craftsmanship. Therefore the quality needs to be excellent.

Table 4: Company goals on quality

Quality targets	Department	Weekly target
Blockades per line	Packaging	[redacted]
Total Blockades closed (colli)	Packaging	[redacted]
Total Blockades destroyed (colli)	Packaging	[redacted]
Total Blockades reworked (colli)	Packaging	[redacted]
Total Blockades released (colli)	Packaging	[redacted]
Quality complaints keg	All departments	[redacted]
Quality complaints bottles/cans	All departments	[redacted]
Packaged Product Quality Assessment (PPQA)	Packaging	[redacted]
Integrated Quality Management System (IQMS)	Brewing/Packaging	[redacted]
Consumer Index	Brewing/Packaging	[redacted]
Beer loss (%)	Packaging	[redacted]
Beer extract loss (%)	Brewing	[redacted]

5.1.3 Production availability

When talking about production availability, automatically efficiency at Packaging comes up. This is a target which is vital for Packaging. Efficiency has been divided into Machine Efficiency (ME) and Factory Efficiency (FE). Factory Efficiency is the efficiency of the line relative to the time period available for production. Machine Efficiency (ME) is the efficiency of the line relative to the time period available for production once adjustments for maintenance, cleaning, service stops and allowed stops has been made. Table 5 shows the ME of the packaging hall and of the individual lines in the packaging hall. Each machine in Packaging can affect the efficiency directly, because the machines are connected in series. Utilities, Brewing and Warehouse are different from Packaging. Packaging is very mechanical and connected in series, whereas Utilities, Brewing and Warehouse are more process-oriented and have a lot more redundancy. Therefore there is no target on efficiency at Utilities or Brewing. Warehouse does have a target on efficiency: moved pallets per man-hour, but that is subjected to the quality of the people working in Warehouse. In other words, it is not due to mechanical failures and can therefore not be used in the FMECA. But Utilities, Brewing and Warehouse certainly affect the efficiency of Packaging, for example by delivering beer or other supplies too late. Goals have been set for the percentage of service stops at packaging, which can be found in Table 6. This table shows the maximum percentage of the Paid Factory Hours on service stops caused by other departments. Paid Factory Hours (PFH) are the hours a line has been planned to run.

Table 5: Target for efficiency per line

Machine efficiency	Target (%)
ME Packaging [%]	[redacted]
ME Line 1 [%]	[redacted]
ME Line 2 [%]	[redacted]
ME Line 3 [%]	[redacted]
ME Line 4 [%]	[redacted]
ME Line 7 [%]	[redacted]
ME Line 8 [%]	[redacted]

Table 6: Other departments causing service stops at Packaging as PFH percentage

Service stops Packaging	Target (%)
Stops Brewing [%]	[redacted]
Stops Warehouse [%]	[redacted]
Stops Utilities [%]	[redacted]

5.1.4 Costs

When looking at costs, maintenance budgets should be the starting points. In chapter 6.1 I will address what kind of costs should be included in the FMECA and why therefore maintenance budgets are suitable to be a target in the FMECA. For now, I will use maintenance budgets as targets for costs in the FMECA.

Table 7: Maintenance budgets F16

Department/Line	Maintenance budget (€)
Packaging	[redacted]
Line 1	[redacted]
Line 2	[redacted]
Line 3	[redacted]
Line 4	[redacted]
Line 5	[redacted]
Line 7	[redacted]
Line 8	[redacted]
Line 24	[redacted]
General	[redacted]
Brewing	[redacted]
Warehouse	[redacted]
Utilities	[redacted]

Table 7 shows the maintenance budgets for the financial year 2016 (F16). The division in Packaging between the lines is made based on history and is not a budget placed by the management.

5.1.5 Environment

There are several company objectives on environment. Those objectives are mainly on reducing energy and water. Environment used as variable in the FMECA is more about violation of regulations and not about optimisation. Regulations regarding emission and pollution set by the (local) government are input for the FMECA.

5.1.6 Conclusion

In this chapter I answered the question "What are the different company goals per effect and are they already split up in departments and/or lines?" Every variable has certain company objectives. Most of these objectives are defined on company level and department level, only availability is further split into line level. The maintenance budget for Packaging is given by the management, but the division between the lines is a division made by Packaging themselves. Table 8 shows a summary of the company goals per variable in the FMECA.

Table 8: Company objectives per variable

Variable	Company goal
Safety	Injuries
Environment	Several rules set by the (local) government
Quality	Several company goals
Production availability	Machine availability
Costs	Maintenance budget

5.2 Risk tables

In the previous chapter the first sub question of the first research question was answered. In this chapter, we will use the results of the previous chapter to answer the second sub question: "How can we use the company goals to better ground the risk tables?" A risk table is a table in which the categories of a certain variable are defined. Each category has assigned a weighting factor. Based on the multiplication of the weighting factor of the variable and the weighting factor of the frequency of occurrence, it is determined whether a risk is too high. This criticality analysis is shown in a risk matrix (see Appendix D and E). Each table has been checked and debated about with specialists in the specific areas. In this chapter I will address the changes I made in the different variables: MTTF, MTTR, Safety, Environment, Quality, Production availability and Costs. The original risk matrices can be found in Appendix D. The changes made after this chapter to the risk tables can be found in the adjusted risk matrices in Appendix E.

5.2.1 Mean Time To Failure (MTTF)

Table 9 shows the MTTF table as used by Grolsch. The first thing the executers of FMECA encountered was the limitation of the highest MTTF level: X > 1 Year. There is a significant difference in impact on production availability between an MTTF of 30 years and 2 years. Especially in high process environments, like Utilities, 30 years is quite common. In an interview with Sander Janssen (21 June, 2017), Senior Specialist at MaxGrip, he mentioned that usually the highest category for MTTF in the food and beverage industry is X > 10 Years, since the machines in a mechanical industry are likely to have a maximum lifetime of approximately 10 years. In an interview with Wilco Hekkert (15 June, 2017), Senior Account Manager Food and Beverage at MaxGrip, he advised to make as little different matrices as possible. This makes it easier to compare the departments. For that reason I decided to make the same table for every department, using a highest category of S > 30 years.

Table 9: Original Mean Time To Failure (MTTF) table

MTTF	Weighting factor
0 Hour < X ≤ 1 Day	243
1 Day < X ≤ 1 Week	81
1 Week < X ≤ 1 Month	27
1 Month < X ≤ 3 Months	9
3 Months < X ≤ 1 Year	3
X > 1 Year	1

Secondly, the ratios of the weighting factors are not completely coherent with the ratios of the MTTFs. The ratio between for example 3 Months < X ≤ 1 Year (on average 1.6 times per year) and 1 Month < X ≤ 3 Months (on average 6 times per year) is 6 / 1.6 = 3.75, which is not the same as 9 / 3 = 3 (see the weighting factors of Table 9). To be able to make mathematical calculations, the ratios of the weighting factors needs to be the same as the ratios of the MTTFs itself. Even better would be to estimate the MTTF exactly, instead of putting it into an interval. I will elaborate on this in chapter 6.3.

Table 10 shows the adjusted MTTF categories and weighting factors. For determining the occurrence per year (second column), an average of the interval is used. Furthermore, a month is assumed to be equal to 30.5 days on average. The weighting factors (fourth column) are based on the occurrence per year, by changing the lowest factor to 1.

Table 10: Adjusted Mean Time To Failure (MTTF) table

MTTF	Occurrence per year	Formula for occurrence per year	Weighting factor
0 hour < X ≤ 1 day	730.00	365 / ((0 + 1) / 2)	21900
1 day < X ≤ 1 week	91.25	365 / ((1 + 7) / 2)	2738
1 week < X ≤ 1 month	19.47	365 / ((7 + 30.5) / 2)	584
1 month < X ≤ 3 months	6.00	12 / ((1 + 3) / 2)	180
3 months < X ≤ 1 year	1.60	12 / ((3 + 12) / 2)	48
1 year < X ≤ 10 years	0.18	1 / ((1 + 10) / 2)	5
10 years < X ≤ 30 years	0.05	1 / ((10 + 30) / 2)	2
X > 30 years	0.03	1 / 30	1

5.2.2 Mean Time To Repair (MTTR)

Table 11 shows the MTTR table as used by Grolsch. The adjustments are quite similar to the MTTF table. The upper category was too small, it can happen that the time to repair is more than a week. In that case there is again a significant difference between for example 7 days and 25 hours. Therefore an extra category has been added: R > 1 week.

Table 11: Original Grolsch Mean Time To Repair (MTTR) table

MTTR	Weighting factor
R > 24 hours	16
8 hours < R ≤ 24 hours	8
4 hours < R ≤ 8 hours	4
1 hours < R ≤ 4 hours	2
R ≤ 1 hours	1

In a packaging line there is a core machine which is the bottleneck of the line. The machines on either side of the core machine have extra capacity to restore the accumulation after a failure has occurred. And this overcapacity increases for each machine going upstream or downstream from the core machine. The graph of the machine capacities has a 'V' -shape with the core machine at the base (Härte, 1997). In Figure 6 the V-shape of an imaginary packaging line is shown. The filler is the most critical machine looking at production availability. Due to the difference in machine capacity, there is some buffer time. If a failure occurs in the crate depalletiser, it takes a while before this failure affects the filler. If a failure occurs in the pallet strapper, the filler can continue working some minutes and the pallet strapper will catch up with the production thanks to the higher machine capacity. This way, the line speed is not affected by small stoppages in every machine except for the filler. This buffer time should be taken into account in the FMECA. It can be done very precisely by giving each machine its own buffer time in the FMECA, but then it would be a complex process, where FMECA should be quite easy for everyone to use. Using the law of the large numbers, an average of the buffer time would approximately yield the same result as calculating each buffer time separately. At Grolsch, micro stops are stops which are shorter than 3 minutes. On average, this would not affect the filler. Therefore, an extra category has been added to the MTTR: R ≤ 3 minutes.

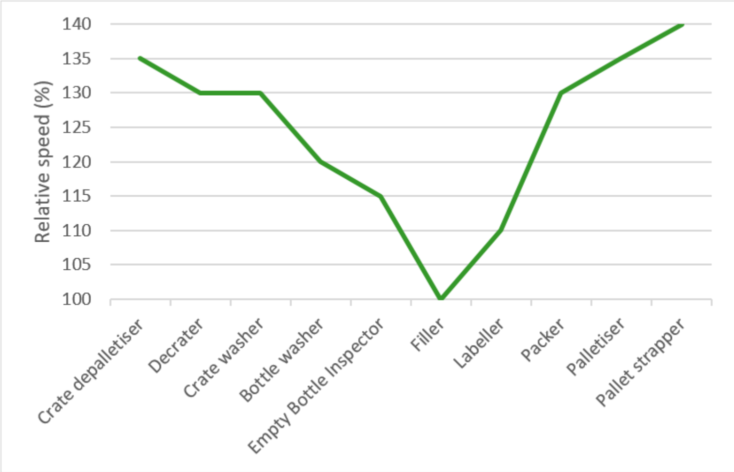

Figure 6: V-shape of an imaginary line

Lastly, the weighting factors has been corrected for the ratios in the MTTR. For determining the hours of repair (second column), an average of the interval is used. The weighting factors (fourth column) are based on the hours of reparation, by changing the lowest factor (R ≤ 3 minutes) to 1. After the factors were determined, the factor of R ≤ 3 minutes was set back to zero, since this category represents the stops which have no influence on the efficiency of the line. For MTTR applies the same as for MTTF: exactly estimate the value of MTTR. I will elaborate on this in chapter 6.3.

Table 12: Adjusted Mean Time To Repair (MTTR) table

MTTR	Hours of reparation	Formula for hours of reparation	Weighting factor
R > 1 week	168.000	7 * 24	3360
24 hours < R ≤ 1 week	96.000	(24 + 7 * 24) / 2	1920
8 hours < R ≤ 24 hours	16.000	(8 + 24) / 2	320
4 hours < R ≤ 8 hours	6.000	(4 + 8) / 2	120
1 hour < R ≤ 4 hours	2.500	(1 + 4) / 2	50
3 minutes < R ≤ 1 hour	0.525	(3 + 60) / 60 / 2	11
R ≤ 3 minutes	0.050	3 / 60	0

5.2.3 Safety

Table 13 shows the original safety table of Grolsch. There were no comments on the categories, neither from the executers of FMECA nor from the specialists in safety. Grolsch uses almost the same categories as the FMECA (see Table 3 in chapter 5.1.1). The only differences are that Grolsch uses *disabling injury* for category two and three in the FMECA (*serious accident with permanent injury* and *accident leading to sick leave*) and Grolsch makes a distinction between near accident and dangerous situation, whereas the FMECA put in into one category.

Table 13: Original safety table

Effect on safety	Weighting factor
1. Lethal injury	2430
2. Serious accident with permanent injury	810
3. Accident leading to sick leave	270
4. Accident not leading to sick leave	90
5. Near accident	30
6. No effect	1

The only thing that has been changed are the weighting factors. This factor was changed according to the targets per category. Two things are changed to correctly determine the weighting factors. The first one is the division of *disabling injury*. That category had to be split up into permanent injury and sick leave. We split this up in a ratio of 1:3, although there was no direct input for. The second one concerns the lethal injuries. The target is zero, so technically the weighting factor should be infinite. To make this more tangible, the industries' average of lethal injuries was used. In 2015 there were approximately 6,500 people working in the Beverage Industry in the Netherlands (CBS, 2017). According to the RIVM (National Institute for Public Health and the Environment, 2012), there are 6 major accidents per year in the Beverage Industry. 2% of those accidents are lethal. This means that on average an employee in the Beverage Industry has a dying chance of 6 / 6500 * 2% = 0.0018% every year. Currently there are 764 people working at Grolsch. So that means that the chance someone dies at Grolsch is equal to 0.0018 * 764 = 1.38% per year. The mathematical expectation would be once in the 73 years. But this includes every lethal injury caused by any reason. As said in chapter 5.1.1, just 5% of the safety issues are caused by mechanical failures. This would mean that at Grolsch a lethal injury caused by a mechanical failure would be normal if it happens once in the 1454 years. Also for safety, *no effect* has been valued with a weighting factor of zero.

Table 14: Adjusted safety table

Effect on safety	2017 Target	Frequency (years)	Weighting factor
1. Lethal injury	[redacted]	[redacted]	15267
2. Serious accident with permanent injury	[redacted]	[redacted]	420
3. Accident leading to sick leave	[redacted]	[redacted]	140
4. Accident not leading to sick leave	[redacted]	[redacted]	8
5. Near accident	[redacted]	[redacted]	1
6. No effect	[redacted]	[redacted]	0

5.2.4 Environment

Table 15 shows the environment categories and scores as used by Grolsch. In an interview with Eino Staman, SHE specialist, and Martin Bosscher, Utilities Manager, (12 June, 2017) it became clear that two things were missing. The first one is the distinction between long term violation and short term violation. Only if it has major impact on the (direct) neighbourhood, short term or long term does not matter; neither of them is acceptable. The second one is an additional category for violation outside the enclosure of the company site. The only one Grolsch uses for violation outside the company site was the upper category. But there are some ways of violation with minor impact going outside the company site, such as smell. This kind of violations did not belong to any category, so a category was added: "Violation of environmental regulations leading to nuisance outside the enclosure of the company site".

Table 15: Original environment table

Effect on environment	Weighting factor
1. Violation of environmental regulations with major environmental impact	1801
2. Violation of environmental regulations that leads to nuisance 'within the enclosure of the company site'	600
3. Violation of environmental regulations without any direct impact	200
4. No effect	1

The second thing that has been changed are the weighting factors. Eino and Martin declared that a violation of environmental regulations with impact outside the company site (category 2 and 3 in

Table 16) is considered acceptable if it happens once every three years. Therefore we assigned an acceptability level of 3 years to category 3 and 6 years (36 and 72 months) to category 2. The upper category is never accepted, so we just had to assign a high number to it (see chapter 5.3.2 for the calculation of this number). The weighting factor of category 4-7 was determined based on the original environment matrix. In the original matrix (see Appendix D), violations causing nuisance within the company site were acceptable once per 8 months and violations with impact within the company site without a direct consequence was acceptable once per 2 months. Because there was no distinction made between long and short term in the original matrix, the weighting factors should be a bit changed. Therefore, the months of interval for categories 4-7 have been determined to be respectively 10, 6, 3 and 1 month, with 8 and 2 months of the original matrix as averages. Lastly, *no effect* was initially equal to 1, but in our view *no effect* should be weighted with zero. Otherwise there would be a score on environment even if there is no effect on environment. Giving a weighting factor of zero, makes sure that environment does not get a score when there is no effect on environment. Table 16 shows the adjusted environment table. The weighting factors are directly connected to the acceptability on a monthly basis.

Table 16: Adjusted environment table

Effect on environment	Weighting factor
1. Violation of environmental regulations with major environmental impact	361
2. Long term violation of environmental regulations leading to nuisance outside the enclosure of the company site	72
3. Short term violation of environmental regulations leading to nuisance outside the enclosure of the company site	36
4. Long term violation of environmental regulations leading to nuisance within the enclosure of the company site	10
5. Short term violation of environmental regulations leading to nuisance within the enclosure of the company site	6
6. Long term violation of environmental regulations within the enclosure of the company site without any direct impact	3
7. Short term violation of environmental regulations within the enclosure of the company site without any direct impact	1
8. No effect	0

5.2.5 Quality

On quality almost nothing has changed compared to the original matrix. The only thing that has changed are the names of the categories to make it clearer for the executor of FMECA. In an interview with Garma Stubbe (22 May, 2017), Quality Assurance Specialist, she mentioned that Grolsch does not care about the reason of rejection, as long as it does not reach the client. In other words, Grolsch does not make a distinction between rejection due to in-house quality requirements and legal quality requirements. She also made clear that there is a distinction between releasing the product despite non-compliance with in-house quality requirements and reprocessing the product. The latter simply costs more than the first. Based on this conversation and the categories in 'Blocked products per line' (Table 4) I split up the original category 4 (see Table 17) into category 3 and 4 (see Table 18) and the original categories 2 and 3 were combined to category 2. And lastly, also for quality, a weighting score of zero has been assigned to *no effect*.

Table 17: Original quality table

Effect on quality	Weighting factor
1. Immediate public health hazard due to failure to comply with the legal quality requirements relating to food safety	1700
2. Rejection of product due to failure to comply with the legal quality requirements relating to food safety	180
3. Rejection of product due to failure to comply with the in-house quality requirements	60
4. Non-compliance with in-house quality requirements, not leading to rejection or reprocessing	20
5. No effect	1

Table 18: Adjusted quality table

Effect on quality	Weighting score
1. Immediate public health hazard due to failure to comply with the legal quality requirements relating to food safety	1700
2. Rejection of product due to failure to comply with the quality requirements	180
3. Reprocessing of product due to failure to comply with the in-house quality requirements	60
4. Non-compliance with in-house quality requirements, not leading to rejection	20
5. No effect	0

5.2.6 Production availability

As said in chapter 5.1.4 there only is a production availability target at Packaging. Although there is no efficiency target in Warehouse, Utilities or Brewing, we want to say something about efficiency in these departments. This can be realised by connecting all efficiency issues to Packaging. So for example: if a machine fails at brewing, what kind of production availability effect will it have on Packaging? Almost every machine in Utilities and Brewing can be directly linked to Packaging regarding efficiency. In Warehouse it is a bit different. Warehouse is roughly divided into two parts: one part serving Packaging (delivering empty goods and picking up filled goods) and one part serving logistics (collecting empty goods from the trucks and delivering filled goods to the trucks). For the first part, we can use the same approach and the same risk matrix as we can use for Brewing and Utilities. The second part of Warehouse should be looked over separately. Different matrices have to be made, since they do not have a direct influence on Packaging. Table 19 shows the original table as used by Grolsch. The categories have slightly been changed to make it more quantitative and measurable. The same has been done with the weighting factors. Table 21 shows the adjusted availability table. The first two categories will be used in conducting an FMECA in Brewing, Utilities or Warehouse, since they can affect the complete Packaging department. The other categories will be used in Packaging. The weighting factors are based on the percentage of availability impact. In the Packaging department there are six important lines. Therefore a weighting factor of 100 / 6 ≈ 17 is used.

Table 19: Original production availability table

Effect on production availability	Weighting factor
1. Stop entire department	567
2. Production disruption critical line (consequences for the customer)	81
3. Production decrease (with loss of product quality)	27
4. Production decrease (without loss of product quality)	9
5. Loss of redundancy without an effect on production	3
6. No effect	1

The weighting factor for loss of redundancy has also been changed using the exponential distribution. The exponential and the Weibull distribution are a common distributions used for failure times. The Weibull distribution has more variables which can make it more accurate than the exponential. Unfortunately there was no data available about failure times of redundancy machines. Since backup machines only work during the repair time of the main machine, I assume that the failure rates are constant instead of decreasing (infant period) or increasing (wear out period). Because of the lack of data, I decided to use the exponential distribution with fewer variables. The exponential distribution calculates the probability of survival given the probability of death and the lifetime. Redundancy means that when machine A fails, machine B can take over the tasks of machine A. Machine B functions as a backup for machine A. The chance that a loss of redundancy has effect on the system, looking at production availability, is equal to the chance that machine B fails during the repair time of machine A. As previously said, I have used the exponential distribution to calculate this chance, where the lifetime is equal to the repair time of machine A and the probability of death is equal to the rate of failure of machine B. This rate of failure is 1 / MTTF, expressed in hours. For example: the repair time of machine X is 6 hours and the MTTF is 2 weeks. The rate of failure per hour is then calculated as follows:

$$rate\ of\ failure\ per\ hour = \frac{1}{2 * 7 * 24} = 0.003$$

Using the exponential distribution, we calculate the chance that in 6 hours, no failures will happen, with a probability of failure of 0.003. The formula for the exponential distribution is:

$$P(\mathrm{X} > \mathrm{x}) = e^{-\lambda x}$$

λ = probability of failure

x = MTTR

Filling in the formula with the known variables yields the following:

$$P(\mathrm{X} > 6) = e^{-0.003*6} = 0.982$$

The probability of survival is 98.2%. Therefore the probability that machine B fails when machine A is repaired is equal to 1.8%.

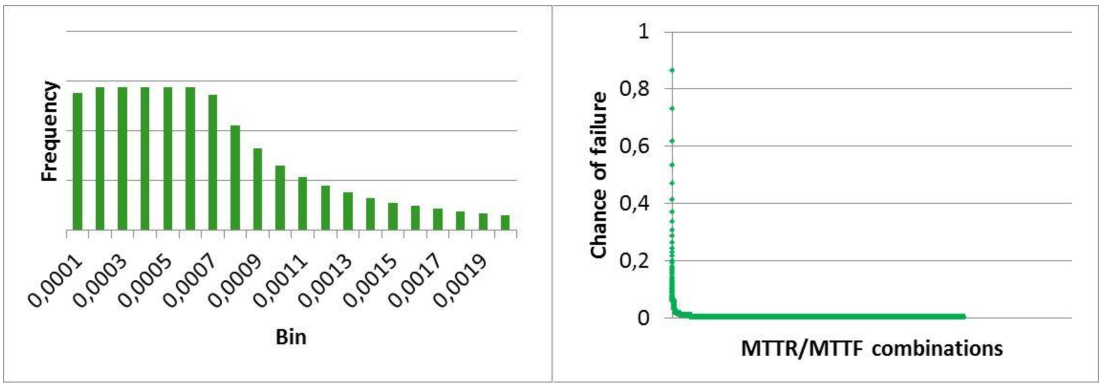

Figure 7: Outliers in redundancy data and frequencies histogram

Table 20: Histogram for redundancy data

Bin	Frequency	Cumulative %
0.0001	138,471	7.53%
0.0002	143,902	15.35%
0.0003	143,914	23.17%
0.0004	143,944	31.00%
0.0005	143,969	38.82%
0.0006	143,968	46.65%
0.0007	136,812	54.09%
0.0008	105,628	59.83%
0.0009	82,149	64.29%
0.0010	65,725	67.87%
0.0011	53,770	70.79%
0.0012	44,811	73.23%
0.0013	37,915	75.29%
0.0014	32,502	77.05%
0.0015	28,166	78.58%
0.0016	24,642	79.92%
0.0017	21,752	81.11%
0.0018	19,327	82.16%
0.0019	17,304	83.10%
0.0020	15,564	83.94%
1.0000	295,365	100.00%
More	0	100.00%

I did this calculation for every combination of MTTF and MTTR, where MTTF has values between 1 and 10950 days (1 day to 30 years) and the MTTR has values between 1 and 168 hours (1 hours to 1 week). For every combination I calculated the chance that a redundant machine would fail during the repair time of the first machine. I put this data in a histogram to determine the median of this data (see Table 20). The third column shows the cumulative percentage of data. As this column shows, the interval [0 – 0.0007] represents more than 50% of the data (54.09%), which means the median is somewhere between 0.0006 and 0.0007. Changing this probability to a percentage yields 0.07%, which is the new weighting factor for loss of redundancy. Looking at Figure 7, there are some outliers at the beginning and the distribution of frequencies is very skewed data. The mean is very susceptible to outliers and when having skewed data, the mean is very influenced by the skew data, where the median is not. So in both cases, the median will result in a better estimation of the typical value. That is why I used the median instead of the mean.

Table 21: Adjusted production availability table

Effect on production availability	Weighting factor
1. 100% production disruption Packaging	100
2. 50% production decrease Packaging	50
3. 100% production disruption line	17
4. 50% production decrease line	8
5. Loss of redundancy without an effect on production	0.07
6. No effect	0

5.2.7 Costs

In interviews with executors of FMECA, all approved the current categories of costs in the FMECA. I only changed the weighting factors, due to an incorrect ratio. For example: the ratio between category 2 and category 3 in Table 22 is 64 / 16 = 4, while the ratio between the averages of the costs of category 2 and category 3 is 7500 / 3750 = 2. Using the original weighting factors, would not yield a correct result when summing up the costs.

Table 22: Original costs table

Costs	Weighting factor
1. Costs > € 10,000	256
2. € 5,000 < Costs ≤ € 10,000	64
3. € 2,500 < Costs ≤ € 5,000	16
4. € 0 < Costs ≤ € 2,500	4
5. No effect	1

Table 23 shows the adjusted costs table, using averages of the cost interval as weighting factors. Even better would be to exactly estimate the costs. This would result in a better estimation of the total costs, as I will further explain in chapter 6.3.

Table 23: Adjusted costs table

Costs	Weighting factor
1. Costs > € 10,000	10000
2. € 5,000 < Costs ≤ € 10,000	7500
3. € 2,500 < Costs ≤ € 5,000	3750
4. € 0 < Costs ≤ € 2,500	1250
5. No effect	0

5.2.8. Conclusion

In this chapter we answered the second sub question of the first research question: "How can we use the company goals to better ground the risk tables?" We looked at the categories and their weighting factors. The categories of the MTTF and MTTR were changed to fit the MTTFs and MTTRs of the machines the best and the weighting factors were changed to make the weighting factors and categories coherent. The only change on Costs and Safety was the weighting factor. On Quality only the categories were slightly changed and the risk tables of Environment and Production Availability were completely changed.

5.3 Translation to company level for every effect

In the previous two chapters, the company goals per variable were defined and the risk tables were improved. This was a preparation to be able to answer the third sub question of the first research question: "How do we have to translate the risks on component level to a risk on company level?" In this chapter this question will be answered by developing a method per variable to make the translation to company level.

5.3.1 Safety

When looking at Table 14, category 3 (accident leading to sick leave) is acceptable once in the 13,33 years on company level, category 2 once in the 40 years and category 1 once in the 2680 years. Let's give a very simplified example: let there be ten machines at Grolsch which are completely responsible for all the safety issues due to mechanical failures. All other machines thus have no impact on safety. Given that all the ten machines are equally unsafe, each machine could fail once in the 133 years with an impact in category 3, once in the 400 years with an impact in category 2 and once in the 14540 years with an impact in category 1. According to Erumban (2008), machinery in the Dutch Food & Beverage industry has a maximum lifetime of 80 years. Although this example is very simplified, it shows that the upper three categories are actually never accepted. On top of that, if you know the safety issues of a machine which have major impact, why would you not prevent it? You could even say that it is unethical not to prevent a major safety issue once it is known. Concluding, it is easier, more realistic and more ethical to prevent the first three categories, no matter how often it happens. The fourth category is a bit of a grey area. This category includes dizziness because of falling, an electrocution, a cut due to a sharp object etc. Those are accidents which happen all the time. Probably this number (26 minor issues per year) is that low because almost no one will report a small cut in the finger if it has no consequences. Categories 1, 2 and 3 have to be registered due to insurances, so this number will be much more accurate than the number of minor issues. Since this is a grey area, I decided to always accept it in the FMECA. Grolsch already does safety evaluations. In its Risk Inventory and Evaluation (RI&E), Grolsch try to assess all risks using the Fine and Kinney model. This model uses the same way of thinking as FMECA does: every safety risk has a severity, a probability and an exposure. The product of these three variables is the risk. Depending in which risk interval the risk number falls, measures need to be taken (see Table 24). Heinrich (1941) explains: "When a situation exists that creates loss of life, injury and suffering; when it costs a king's ransom annually, when its cure has been demonstrated to be practical; and when all are agreed that something can and should be done about it, it is time to stop talking, roll up the sleeves and go to work." A minor injury is not a loss of life or suffering, it is just a small injury. This small injury will practically never cost a lot. There might be a cure demonstrated to be practical. But the last one is very important: *when all are agreed that something can and should be done about it*. During an FMECA, a small group is conducting the analysis. In grey areas it might be better not to judge with a small group of people. Category 1, 2 and 3 are safety categories you want to prevent from happening, because of the big impact. Looking at category 4, it is not catastrophic if it happens sometimes. When it starts to be a regular recurring safety issue, then multiple people will experience this safety issue, therefore *all agree that something should be done about it* and, as stated in the Safety & Health RI&E of Grolsch[1], something will be done about it: ".. when accidents with sick leave or incidents [without sick leave] happen, the SHE-Specialist will evaluate and adapt the S&H RI&E when necessary."

Table 24: Risk model Fine & Kinney (Grolsch Safety & Health RI&E)

Risk number	Required actions
R > 400	Serious and imminent: Immediate suspension of the hazardous activity
200 < R ≤ 400	High: Immediate correction
70 < R ≤ 200	Notable: Correction needed urgently
20 < R ≤ 70	Moderate: It is not urgent, but is should be corrected
R ≤ 20	Acceptable: Corrections can be omitted

The fifth category is quite interesting too. In the operations reports, this category is split into *Near misses* and *Dangerous situations* (see Table 3). Near misses has a minimum, but dangerous situations has a maximum target. This does not mean that Grolsch wants as many dangerous situations as possible, but they do want as many reports of dangerous situations as possible. This is probably also why the difference between dangerous situations and near misses is huge.

Looking at the previous argumentations, I decided it is better to think in black-and-white terms. The first three categories are never accepted and the last three categories are always accepted. Given the weighting factors of Table 14, I set the boundary level at 140, to make sure the upper three categories are never accepted and the lower three are always accepted.

[1] Source derived from the intranet (not publically available) of Grolsch

5.3.2 Environment

In an interview with Eino Staman, SHE specialist, and Martin Bosscher, Utilities Manager (12 June, 2017) they said that the local authority looks at all machines as machines which fail independently. Thus, when a failure with environmental impact occurs in machine X and one day later a failure with environmental impact occurs in machine Y, it is not a sum of incidents which cross the boundary; all machines are considered separately. Knowing this, effects on the environment should be evaluated on machine level instead of on company level. It is important that the failure behaviour on a machine should not become a trend. The local government tolerate certain violations as long as it is resolved immediately and failure is prevented in the future. For the FMECA specifically it means that if different failures with environmental impact are likely to occur in a machine, the scores need to be summed up per category pair; the summation of category 2 and 3 (nuisance outside the company site) needs to be under a boundary level per machine, and the same applies for category 4 and 5 (nuisance within the company site) and category 6 and 7 (violation without nuisance within the company site).

To determine the boundary level, I use the fact that the weighting factor is equal to the acceptability on a monthly basis. The risk number is calculated by multiplying the weighting factor of environment by the MTTF score. The MTTF score is proportional with the occurrence per year. The MTTF score of once in the 30 years is equal to 1 (see Table 10), therefore the MTTF score of once per year is equal to 30. Let the weighting factor of the effect on environment be X. X is then equal to the time between failures, expressed in months. The occurrence per year is then equal to 12 / X. Then the MTTF score is calculated by taking the product of the MTTF score of once per year (30) by the MTTF score of occurrence per year (12 / X):

$$MTTF\ score = 30\ *\ \frac{12}{X} = \frac{360}{X}$$

Finally, to calculate the risk number, the MTTF score needs to be multiplied by the weighting factor:

$$Risk\ number = \frac{360}{X} * X\ =\ 360$$

This means that, no matter what the environment category is, the boundary level will always be 360.

Knowing that the boundary level is 360 and that category 1 should never be accepted, we can assign a weighting factor of 361 to the first category.

5.3.3 Quality

Quality is very hard to measure. There are a lot of different KPIs for different departments and it is hard or even impossible to estimate numbers of rejection due to mechanical failures. First I looked at Packaging and how I could measure and estimate whether quality requirements would be achieved. I looked at blocked products, which are all the products ejected from the line due to a certain quality problem. Category 3 and 4 of the adjusted quality table (Table 18) could be directly linked to blockades released and blockades (see Table 4). Category 2 could be directly linked to blockades destroyed and category 1 is never acceptable, so that is not a problem. The problem is that not every goal has a target. *Total blockades closed* has no target and Grolsch rather wants this KPI high to prevent products with a

Table 25: HACCP template

Process steps		Potential Danger		Risk analysis			Motivation	Measure
Nr.	Description	Description	Type	Probability	Severity	Risk class		

bad quality from going to the market. Blockades destroyed and blockades reworked do have a target and blockades released do not have a target. Every 30 minutes a batch of test bottles are put in every line. Every bottle has a certain defect and the machines should eject those bottles. If not, the machine apparently does not work properly and then the batch of the previous 30 minutes will be blocked. Knowing the speed of the line, which is usually expressed as bottles/cans/kegs per hour, you could theoretically calculate the amount of blocked products if you could estimate the amount of blockades due to the test bottles. But what you do not know, is the ratio between released products (released after being blocked), reworked products (reworked after being blocked) and destroyed products (destroyed after being blocked). When determining which products will be released, which products will be reworked and which products will be destroyed, there is a lot of subjectivity. Someone needs to check all the bottles/cans/kegs manually and he or she determines which of these three categories the beer falls in. Because we do not know that ratio, we cannot put a target on the different categories looking at blocked products. On top of this problem, the blockades are measured in colli, which is the customer's buying unit: this can be a 4 pack, a sixpack, a 12-pack, a crate, a keg (19,5L, 30L and 50L) etc. If just one unit would be made on every line, we could make a line division in the FMECA. But unfortunately that is not the case. Then we have to work with averages of colli and this will yield a result which is too inaccurate. I also looked at Beer loss (see Table 4) which is a target on Packaging as well as on Brewing. This KPI again has the same problem as the KPI Blocked products; it is impossible to estimate the amount of beer loss because of a mechanical failure. Another problem with beer loss, is that it only represents category 2 (Table 18). Category 4 will not results in beer loss, category 3 will be perhaps a bit of beer loss, but mostly time and costs. Category 1 is beer which is already at the customer. This category will not be in the KPI beer loss, but in the KPI Quality Complaints. There is also already done a lot of preventive control on quality. Hazard Analysis of Critical Control Points (HACCP) is a tool which has the same reasoning as FMECA, but then completely focused on quality (see Table 25). In this analysis, the danger is described. The combination of chance of occurrence and severity puts the danger into a risk category. Depending on the risk category level, a measure needs to be taken to prevent the danger. The type of measure is a Critical Control Point (CCP) or a General Control Measure (ABM, Algemene Beheersmaatregel in Dutch), this type is determined using the HACCP decision tree (see Appendix C). Besides HACCP, Grolsch also claims that its quality system will be equivalent to Good Manufacturing Process (GMP) regarding to by-products. Lastly, due to the time limit of 10 weeks for the bachelor assignment, it was not possible to dive completely in Quality to make a better adjusted risk table.

Combining the difficulty of targeting quality requirement, the subjectivity of quality, the preventive controls already used at Grolsch and the time limit of the assignment, we decided not to translate quality from component to company level. We will use quality with the original matrix on component level. Just two things have been changed. The first is adjusting the boundary level, since new MTTF levels are compared to the past. The second level is adjusting the weighting factor of category 1. Category one is never accepted, but category 2, 3 and 4 are accepted. As can be seen in Appendix D, category 4 was accepted in MTTF levels of 1 week < X ≤ 1 month and higher, category 3 was accepted in MTTF levels of 1 month < X ≤ 3 months and higher, category 4 two was accepted in MTTF levels of 3 months < X ≤ 1 year and higher. In the adjusted risk matrix (see Appendix E), the levels of acceptance for category 2, 3 and 4 are respectively 8640, 10800 and 11680. The highest is 11680 and therefore 11681 will be the boundary level for the risk matrix. Subsequently, the weighting factor for category 1 has been changed to 11681, since this category never should be accepted.

5.3.4 Production availability

As said in chapter 5.2.6, production availability will completely be redirected to Packaging. When doing an FMECA inside Packaging, the Machine Efficiency can be used (see Table 5). When doing an

FMECA in Warehouse, Brewing or Utilities, the stops relative to the Paid Factory Hours will be used (see Table 6). First I will look at the calculation of production availability inside Packaging.

Grolsch has an Excel file in which they keep track of all stops inside Packaging. This file only registers stops of the filler. The filler is the weakest equipment of a line and it is assumed that only if the filler stops working, the line stops working. So only the stops on the filler are considered to have effect on the machine efficiency. In the Excel file can be found what the reason was for the stop: cleaning, maintenance, service stops, downtime etc. The downtime is further split into Production stoppages, Quality losses, Breakdowns and Uncategorised. For us Breakdown is the relevant category, since this is due to mechanical failures. Breakdown is further split into all the machines on a line which were responsible for stops on the filler. Figure 8 is an example of the downtime of Line 8 in 2016. In this case, the Palletiser of Line 8 (green arrow) was in 2016 responsible for 2,294 minutes downtime on the Filler on Line 8 and the total downtime in 2016 on Line 8 (red arrow) was 51,125 minutes. This gives us something to work with.

Year - Week - Day	2016
Downtime	51124,9123
Filler_LC8	51124,9123
Production stoppages	2772,016531
Quality Losses	258,033332
Breakdown	45914,66246
	83,149996
Filler	8072,232907
Palletiser	2294,433263
Micro Stoppages	4047,165431
Seamer	2798,499898
Lid feeder	3776,116052
Rinser	192,7333

Figure 8: Filler downtime of Line 8, categorised per machine

Currently, FMECAs are done on a machine, spitting the machine up to component level. On every line, there is a Machine Efficiency (ME) target. But there is no ME target on machine level. Using the downtime data, I have made a theoretical ME per machine. In Appendix F, the theoretical MEs of the lines can be found. The theoretical ME is determined with the following calculation. As Figure 8 shows, the Palletiser is responsible for 2,294 / 51,125 ≈ 4.49% of the downtime (red part in Figure 9). Line 8 wants to achieve a ME of 85% (green part in Figure 9), which means they can be down for 15% of the time. 4.49% of this 15% can be caused by the Palletiser, which is 0,673% of the total running time (red part in Figure 9). This corresponds with a ME of 100 – 0.673 = 99.327% (green and grey part together in Figure 9).

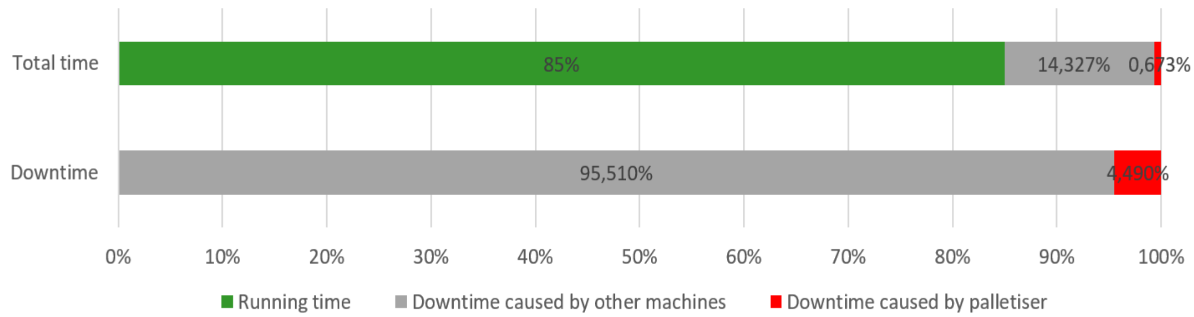

Figure 9: downtime palletiser

I did this calculation for every machine on every line. Using this calculation, it is also possible to change the ME of the line and see what the influence will be on the ME of the machines. Knowing what ME an individual machine should achieve, we can sum up the production availability scores per machine. Next, the maximum production availability score needs to be determined per machine. This depends on the following two variables: the theoretical ME of the machine and the machine hours per year of the line. The allowed downtime per year for that machine can be determined as follows:

$$Allowed\ downtime\ =\ (\ 1 - Theoretical\ ME\ of\ the\ machine\ )\ *\ machine\ hours\ per\ year$$

As Table 10 and Table 12 show, the ratio between the weighting score of MTTR and MTTF and the actual MTTR and MTTF is respectively 20 and 30. In other words: you would have to multiply the exact MTTR by 20 to get the weighting score of that exact MTTR and multiply the exact MTTF by 30 to get the weighting score of that exact MTTF. Lastly, the weighting score for production availability when a complete line is down, is 17 (see Table 21). To determine the boundary level for production availability on machine level in Packaging, the following formula has to be used:

$$Boundary\ level\ =\ allowed\ downtime\ per\ year\ *\ 30\ *\ 20\ *\ 17$$

If the sum of the availability scores on a machine is lower than the boundary level, then the machine is acceptable looking at production availability.

The calculation of the theoretical MEs is based on data from 2016. During the year 2015 the downtime Excel was introduced and it took a while before it was completely used. Therefore I considered data from 2015 as non-valid. The data of 2017 is not complete, since the year has not ended yet. Due to possible differences in seasons I also did not include data of 2017. Based on this, data of 2016 seemed the most valid to me.

Next, I will look at the production availability of Packaging when another department is responsible. As Table 6 shows, there are targets set for the maximum downtime caused by Brewing, Utilities and Warehouse relative to the Paid Factory Hours of Packaging. The calculation of this boundary level has the same reasoning as the calculation for the boundary level of the ME inside Packaging. Knowing the PFH and the downtime percentage of the PFH, the maximum allowed downtime of Packaging caused by the other departments can be calculated. The ratio between the weighting score of MTTR and MTTF and the actual MTTR and MTTF is again respectively 20 and 30. The weighting score for production availability when the complete Packaging department is down, is 100 (see Table 21). The boundary level is again determined by the following formula:

$$Boundary\ level\ =\ allowed\ downtime\ per\ year\ *\ 30\ *\ 20\ *\ 100$$

Unfortunately, this boundary level is a level what applies to the complete department (Utilities, Warehouse or Brewing). It is not the same as for Packaging, where I could divide it between all the machines based on historical data. This means that Grolsch can decide to choose between two things:

1. they can do an FMECA on every machine in Brewing, Warehouse and Utilities with impact on Packaging, sum up the availability scores and check if they cross the boundary level per department. This will give an accurate result, but it will take a lot of time.
2. Another approach would be to use the Pareto principle and select the machines in Brewing, Warehouse and Utilities which have the most impact on downtime in Packaging. The hardest thing to estimate is how much of the total downtime the selected machines are responsible for.

This is a decision for Grolsch to make. This assignment is about improving FMECA. Decisions after the implementation are not in the scope of this assignment.

5.3.5 Costs

First of all, two things can be done with costs in the FMECA. The first one is that the costs are used to achieve the maintenance budget. In this case a maximum will be set to the total costs per line or department and everything higher than that maximum is not acceptable and should be reduced. Another argument is that to achieve a certain level of production availability, safety, environment and quality, a certain maintenance budget is needed. In general it is impossible, using the current resources, to lower the budget and increase production availability, safety, environment or quality. So the FMECA can be used to ground the maintenance budget. In the first case, a boundary level needs to be calculated. In the second case, there is no boundary level needed. I will give a calculation to determine the boundary level.

The total costs per component can be calculated by multiplying the occurrence per year by the costs per occurrence. The costs score in the FMECA is determined by multiplying the weighting factor of costs by the weighting factor of the MTTF. As said in chapter 5.3.4, the ratio between the MTTF weighting factor and the actual MTTF is 30. So the total costs per component per year can be calculated by dividing the costs score by 30. Likewise, the total costs on machine level per year can be calculated by dividing the sum of cost scores by 30. For costs arises the same problem as for production availability: to calculate the total costs precisely, all machines need to be evaluated. Something less precisely, but still a good estimation, is using the Pareto principle. Find the machines which causes the most costs in every department or line. Let's say that 80% of the costs are caused by 20% of the machines. Then just 20% of all machines has to be evaluated. In that case, the total costs per year of those 20% machines, should be lower than 80% of the maintenance budget in that department. The formula to determine the boundary level should therefore be:

$$\begin{aligned} &\mathit{Boundary\ level} \\ &= \mathit{maintenance\ budget\ for\ a\ certain\ line\ or\ department} \\ &* \mathit{percentage\ of\ the\ costs\ caused\ by\ the\ selected\ machines} * 30 \end{aligned}$$

And again, this is a decision for Grolsch to make after the implementation. Thus, the decision is not in the scope of this assignment.

5.3.6 Conclusion

In this chapter a method per variable was developed to translate risks from component level to company level. It became clear that every variable needs a different approach. Some variables can be judged on component level, some variables on machines and others have to be judged on department level. Depending on the level of judgment, a boundary level has been set. This boundary level is based on the company objectives, as described in chapter 5.1. Table 26 shows the different approaches per variable.

Table 26: Level of criticality analysis

Variable	Level of criticality analysis
Safety	Component
Environment	Machine
Quality	Component
Production availability	Department / machine
Costs	Department

5.4 Selection of components or machines

As said in chapter 3.1, the FMECA is very time intensively and therefore expensive. The trick is to conduct as little FMECAs as possible with the highest coverage level. In this chapter the last sub question of the first research question will be answered: “How can components or machine be selected to execute FMECAs on?” As said previously, the Pareto principle will be enormously helpful for us. This principle, named after the Italian economist Vilfredo Pareto, is about “the vital few and the trivial many” (Juran, 1964). This principle is commonly known as the 80-20 rule, which means that roughly 80% of the effects come from 20% of the causes. If we can find the 20% of the machines, then we will have a coverage of 80% of the risks. Note that 80-20 is a rule of thumb. This explicitly does not mean that always 20% is accountable for 80% of the results. Any other ratio is possible.

5.4.1 Safety

In literature certain criteria can be found which can determine safety. Three sources will be checked and based on those three sources the safety criteria for Grolsch specifically will be determined.

Machinery and equipment safety 2007 *(Austria)* states that a machine’s safety can be determined using the following criteria:

- machinery and equipment with moving parts that can be reached by people;
- machinery and equipment that can eject objects (parts, components, products or waste items) that may strike a person with sufficient force to cause harm;
- machinery and equipment with moving parts that can reach people such as booms or mechanical appendages (arms);
- mobile machinery and equipment, such as forklifts, pallet jacks, earth moving equipment, operated in areas where people may gain access.

Machine safety 2009 *(Canada)* states the following criteria:

- moving elements (mechanical hazard);
- electrified components (electrical hazard);
- machine components that are too hot or too cold (thermal hazard);
- noise;
- vibration;
- visible (laser);
- invisible radiation (electromagnetic);
- hazardous materials;
- awkward postures (ergonomic).

“Hazard and Risk” (n.d.) adds the following criteria:

- Electricity;
- Pedestrian safety;
- Working at height.

Combing these criteria, the criteria for Grolsch will be:

- Moving parts which can reach people or can be reached by people (the only component excluded from this criterion, is the safety mechanism on fences
- Mobile machinery / pedestrian safety
- Electricity
- Thermal hazard
- Invisble radiation (röntgen)
- Visible (laser)
- Hazardous materials (fluids as well as gasses)

- Working at height
- Noise

Noise is not included, since everyone needs to wear earplugs at the machinery site. So the risks on this criteria are almost covered by Grolsch. Vibration is not included because it is not present on a high level. Awkward postures is also not included, because the FMECA only deals with mechanical failures.

5.4.2 Environment

After a discussion with Rob Leurink, Eino Staman and Martin Bosscher, there were just a couple of machines which have impact on the environment. The following machines at Grolsch were determined to be critical for the environment:

- Ammonia installation
- Waste water purification installation
- CO_2 installation
- Tanks in Brewery

5.4.3 Quality

As said in chapter 5.3.3, Grolsch uses Hazard Analysis of Critical Control Points (HACCP). By using HACCP, they have defined all the critical control points in the brewery. This CCPs will be the Pareto on quality.

5.4.4 Production availability

Looking at production availability, there is already an overview available of the machines in Packaging causing the most downtime. In this case there are 9 machines (Filler until Bulk Depalletiser) which cause 80% of the downtime (see Figure 10). On the line there are 40 machines, so 9 / 40 = 22.5%. This is very close to 80-20. As decided in chapter 5.1 and 5.2, there are no major production availability issues in Brewing, Utilities and Warehouse, but they all affect Packaging. The downtime in Packaging caused by other departments is recorded, but the very specific machine in the other department causing downtime in Packaging, is not recorded. This would be very helpful in determining the most critical machines in Brewing, Utilities and Warehouse looking at Production availability. Right now, this has to be determined using common sense and human knowledge of historical failures.

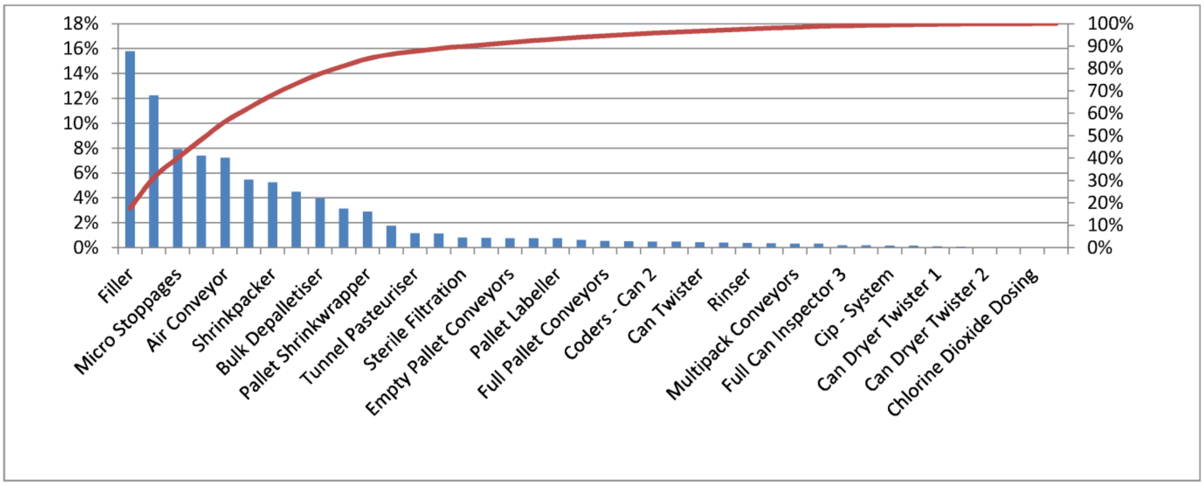

Figure 10: Pareto of downtime Packaging line 8

5.4.5 Costs

The last variable is costs. We can determine the costliest machines in at least two ways. The first one is looking up the most expensive machines. The machines which have in total the most expensive components, could be the most expensive in maintenance. This probably will not always be the case. Another way to approach this, is looking at the most expensive machines in history. The disadvantage of this approach, is that every machine has totally other maintenance costs every year. Machine X might have periodic maintenance every two years and machine Y might have periodic maintenance every ten years, but the maintenance costs of machine Y per revision might be 5 times as high as the maintenance costs of machine X. On average in ten years, both machines have equal maintenance costs. When we take the average of maintenance costs over one year, we can obtain a very unrealistic view. Therefore, determining the most expensive machines in maintenance should be done over a lot of years.

5.4.6 Conclusion

In this chapter methods have been defined to select machines to execute FMECAs on. This selection can be done in several ways. Either there is data available to make a Pareto, the machines are already known or the machines should be found using certain criteria.

5.5 Conclusion

In this chapter the first research question was answered by using four sub questions. The first research question was: "How to manage risks on component level?" I concluded that, before making the translation to company level, the risk tables should be grounded somehow. In chapter 5.1, company objectives per variable were defined. Safety, Production Availability and Costs had very clear objectives, respectively amount of injuries, machine efficiency and maintenance budget. Environment had company goals, but those were not applicable on the FMECA. Rules from the (local) government regarding emission were input for the FMECA. On Quality there were a lot of company objectives. In chapter 5.2 I improved the risk tables using the company goals. In the risk tables the categories were looked over and three variables were changed: Environment, Quality and Production Availability. Also the categories of MTTF and MTTR were changed. The risk tables were also improved by making the ratio of the weighting factors equal to the ratio of the categories of the variables. This way it would be possible to make a summation when translating the variable's risk from component to company level, if necessary. In chapter 5.3 the method for the translation to company level was defined. I concluded that every variable needed its own method for the level of criticality analysis. After that, in chapter 5.4, a method to select the machines to execute an FMECA on, was developed. In Table 27, a summary of all changes which were made are shown.

Table 27: Summary of changes made for the different variables

Variable	Changes
MTTF	The categories in the MTTF has been expanded to better cover the MTTFs of all machine at Grolsch. The weighting factors has been changed to be proportionally with the MTTF categories.
MTTR	The categories in the MTTR has been expanded to better cover the MTTRs of all machines at Grolsch. The weighting factors has been changed to be proportionally with the MTTR categories.
Safety	The weighting factors has been linked to the amount of injuries per year, which is a company goal. Next, it is decided to use a black-and-white approach on what to accept; the upper three categories are never accepted and the lower categories are always accepted. Safety has to be determined on component level.
Environment	The original categories of environment were used and expanded by making a distinction between long term and short term consequences. Environment has to be determined on machine level.
Quality	A clearer division has been made between rejection of a product, reprocessing of a product and a non-compliance not leading to rejection. Quality has to be determined on component level.
Production Availability	The categories have been made more quantitative by using percentages. This percentages are also directly linked to the weighting factors. Furthermore, the weighting factor of redundancy has been grounded using the exponential distribution and lastly, the boundary levels are linked to efficiency targets (machine efficiency and factory efficiency) by using a theoretical efficiency. Production Availability has to be determined on machine (Packaging) or department level (Brewing, Warehouse, Utilities)
Costs	The weighting factors are linked to costs in the categories and the boundary levels are linked to the maintenance budget. Costs has to be determined on department level.

6 Vaguenesses and clarification

When making an FMECA, there are some vaguenesses which cause subjectivity; person A fills in and interprets the analysis differently than person B. Grolsch does not want this subjectivity in the analysis, since FMECA should be an objective analysis. In this chapter I will answer the second research question: “What are the vaguenesses in making an FMECA and how can the vaguenesses be clarified?” First some vaguenesses in filling in the analysis and how to objectify those vaguenesses will be discussed. Then I will discuss the interpretation issues of the analysis and how to deal with those issues. And lastly I will present a list of practical recommendations for improvements on the Excel template.

After the vaguenesses were clarified, a manual for Grolsch was made for how to execute an FMECA and how to deal with the vaguenesses. A Dutch version was provided to Grolsch. The English version of the manual can be found in Appendix H.

6.1 Vaguenesses in filling in the FMECA

In this chapter the first sub question of the second research question will be answered: “What are the vaguenesses in filling in the FMECA and how can they be clarified?”
For now there are four major vaguenesses in filling in the FMECA which I will assess in this chapter. At the end of this chapter, it should be clear how to deal with these four vaguenesses.

6.1.1 Mean Time To Repair

There are different interpretations of the Mean Time To Repair (MTTR). In general there are five stages from the start of the failure until the machine works properly again after the failure. These five stages are shown in Figure 11. First the problem needs to be detected. When it is clear that a problem exists, an analysis of the problem has to be made, resulting in the problem approach. Then the maintenance tools (mechanics, spare parts etc.) needs to be collected, which is the delivery time. Then the actual repair starts and at the end the functioning of the machine needs to be tested and validated. Some people just see the MTTR as the actual repair time (phase 4 in Figure 11), others see the MTTR as the time when the problem is known until the machines works again (phase 3, 4 and 5). In the FMECA Grolsch uses, they refer to MTTR as ‘downtime’. In the method I developed for production availability (see chapter 5.3.4), I also made use of the MTTR as the total downtime. Furthermore in a conversation with Sander Janssen (21 June, 2017), Senior Specialist at MaxGrip, he advised to use the total downtime as the MTTR. Based on the previous, I decided to set the MTTR as the total downtime of the machine when a failure occurs. This is the time from the start of the failure until the machine works properly again after the failure. All five phases in Figure 11 are then included in the MTTR.

Figure 11: Five stages in repair time

6.1.2 Equal components

Executors of FMECAs at Grolsch mentioned that it was hard to determine how to fill in the analysis when there are multiple equal components. Take for example the empty bottle crate unpacker (see Figure 12). This machine unpacks crates with empty bottles. This is done by pistons, one piston takes one bottle using pneumatics. The machine can unpack six crates, a crate contains 24 bottles, so the machine has 144 pistons. How do we have to deal with those 144 pistons?

First of all, putting all the pistons separately in the FMECA, is a lot unnecessary work. Just considering this, it is the best to mention all the pistons at once and adding up the MTTFs of the individual pistons. For example, if one piston has an MTTF of 9 years, the MTTF of all the pistons together will be 9 / 144 = 0.63 year. When filling in the effects on the different categories, almost everything will be fine. Considering that the effect of one component needs to be filled in, Environment, Quality, Safety and Costs. Production Availability is harder unfortunately. This category is roughly split into three effects: production stop, production decrease and loss of redundancy. Production stop will be no problem. When using the MTTF of all equal components together and one component is responsible for a production stop, the analysis is filled in correctly. Loss of redundancy requires another approach. Only one machine or component is working and the redundant machine(s) or component(s) is/are idle. This means that the MTTFs of the redundant machine/components cannot be summed up, because only one machine at the time is working. So in the case of redundancy, only the MTTF of one machine should be filled in. The hardest part is in production decrease. In the previous case of the empty bottle crate unpacker (Figure 12), there is a decrease of production of 1/144 = 0.69% when 1 piston has broken. At the moment there is just one level of production decrease: 50% production decrease. So when this effect is selected, the production decrease is 72 times overestimated. This will bias the reality. We cannot change the MTTF, since the MTTF also affects the score on Environment, Quality, Costs and Safety. The only option is to change the effect from 50% production decrease to an individual determined production decrease. This can be done by filling in the amount of equal components. In the case of the empty bottle crate unpacker, the MTTF of all components should be filled in, and in the extra added column the number "144" should be filled in. If the effect on production availability is "production decrease", then the tool should automatically calculate the exact percentage of decrease, using the number of equal components.

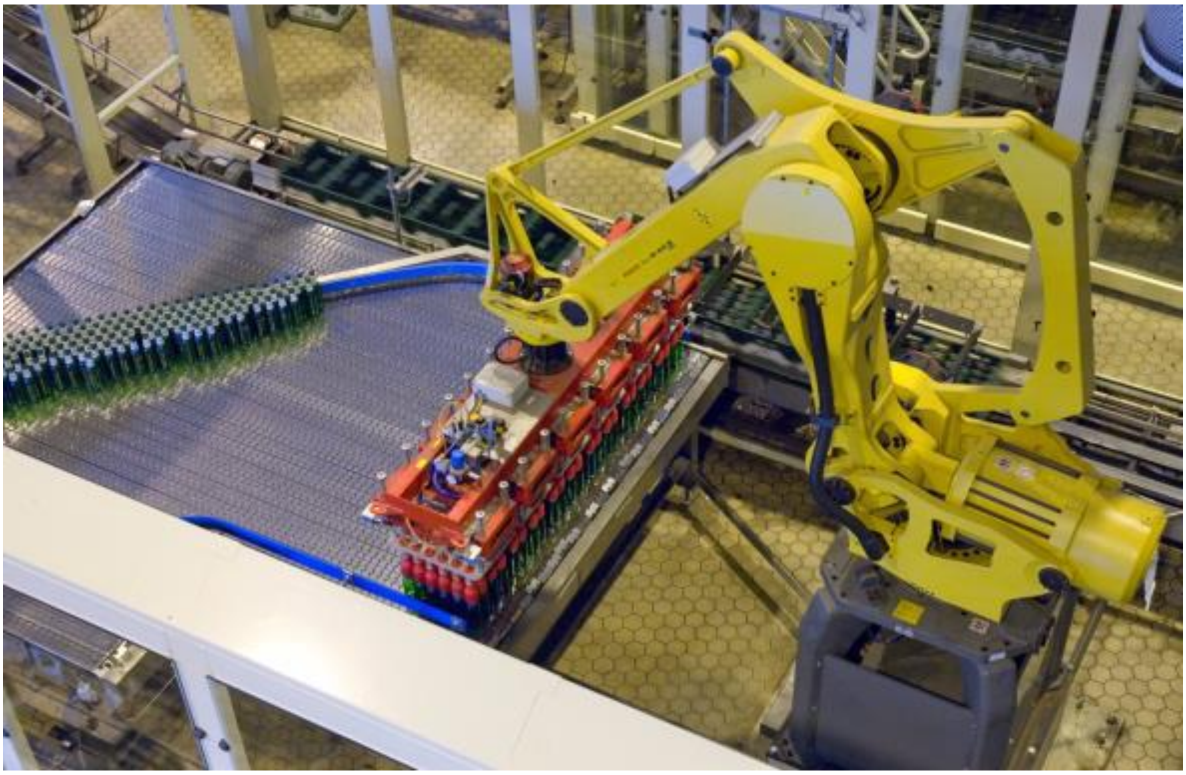

Figure 12: Empty bottle crate unpacker

Figure 13 shows the decision tree which helps with the question how to deal with multiple equal components. Note that the block in the right corner mentions "production decrease" instead of "50% production decrease". This is coherent with the text above: filling in the amount of equal components will give the exact production decrease.

Another note is that there is a V-shape in a line (see chapter 5.2.2). It seems like I did not include this V-shape in the production decrease calculation. However, we already included the V-shape in the weighting factor of an MTTR less than 3 minutes (see chapter 5.2.2).

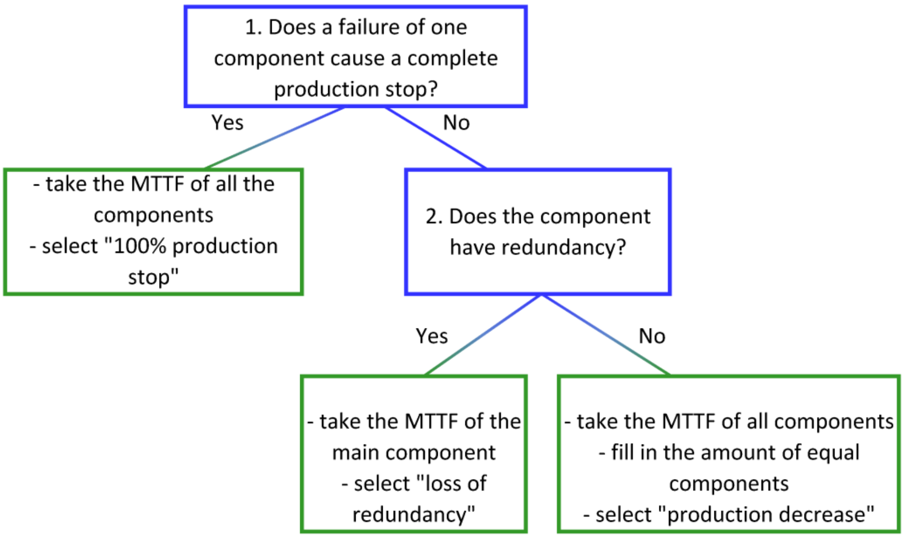

Figure 13: Decision tree equal components

6.1.3 Consequences

Another vagueness in making an FMECA is about consequences of failures. When a failure occurs, it can cause damage, costs, another failure etcetera. The question arisen is which consequences do we have to include in the FMECA. If it is a direct consequence, then it should be included, otherwise it should be excluded. This looks evident, but what is the definition of direct and indirect in the FMECA? A consequence certainly is direct when it happens immediately after the first failure. But where do we draw the line when the consequence does not happen immediately after the first failure? Here, we can use the time to detection since the failure occurred. If the time to detection is more than the time to the consequence, then it is a direct consequence, since it will happen. If the time to detection is less than the time to the consequence, then it is an indirect consequence, since the first failure will be detected before the next failure or damage can happen. Those three possibilities are graphically shown in Figure 14.

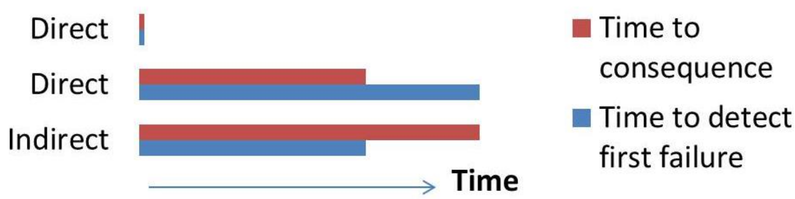

Figure 14: Direct and indirect consequences

Figure 15 shows the decision tree to determine whether a consequence is direct or indirect.

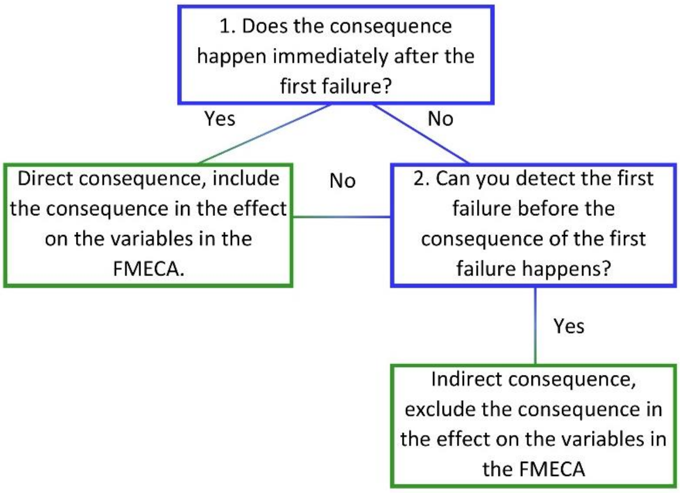

Figure 15: Decision tree direct and indirect consequences

6.1.4 Costs

Costs is one of the variables in the FMECA. Which costs to include in this variable is not very clear for every FMECA conductor. To eliminate the subjectivity from the FMECA, one standard should be given. A failure can cause a lot of different costs: material costs, costs of downtime, costs of mechanics, overtime bonus, reputational damage, external advice etcetera. Reputational damage, for example, is already covered in the highest category in Quality (see Table 18) and Environment (see Table 16) and maybe even in Safety (see Table 14), since a lethal injury would probably be local or national news. Also costs of downtime is included in Production Availability (see Table 21). Wilco Hekkert (15 June, 2017), Senior Account Manager Food and Beverage at MaxGrip, explained that all direct costs should be included in the costs part of the FMECA. But the costs already represented by the other variables in the FMECA (such as Quality and Environment), should be excluded. For an explanation of the distinction between direct and indirect, I refer to chapter 6.1.3. The standard as explained by Wilco Hekkert, will be the standard for Grolsch regarding costs.

6.2 Decision making for measures

When a risk is unacceptable, a measure needs to be taken to decrease the risk. There are several kinds of measures which can be taken. To prevent FMECAs from being subjective, Grolsch asked for a certain standard in choosing the measure. Person X can be a supporter of spare parts, while person Y is a supporter of inspection. Using a standard, I want to prevent that person X will always choose spare parts and person Y will always choose inspection. I decided to put this standard in a decision tree. By asking the FMECA conductor a couple of questions, a certain kind of measure would come out as being the best.

Firstly, I checked the information already available. Searching for a decision making process for measures in FMECA did not yield any result. In a kick-off presentation of FMECA at Grolsch, given by MaxGrip[2], three basic types of mitigating actions were defined: optimise maintenance strategy, apply stock management and revise / reengineer. Searching for decision making in maintenance strategies did yield results. I found some decisions trees which have been the basis for my decision tree. To determine what the questions would be in the decision tree, I searched for criteria when selecting the maintenance strategy. The first criteria important for selecting the best maintenance strategy was "detection" (U.S. Government (2005) and Smith & Mobley (2008)). This includes the detection of potential failure to functional failure and the detection of the functional failure. The P-F curve is an important visualisation of this criteria. As Figure 16 shows, there is a point at which the failure starts.

[2] Source derived from the intranet (not publically available) of Grolsch

Then there is a point when the failure is detectable – either with or without inspection – and at the end there is a point when the machine has failed. This can take a split second or much longer. Depending on the location of point P (and therefore the PF interval), different maintenance strategies will be applied.

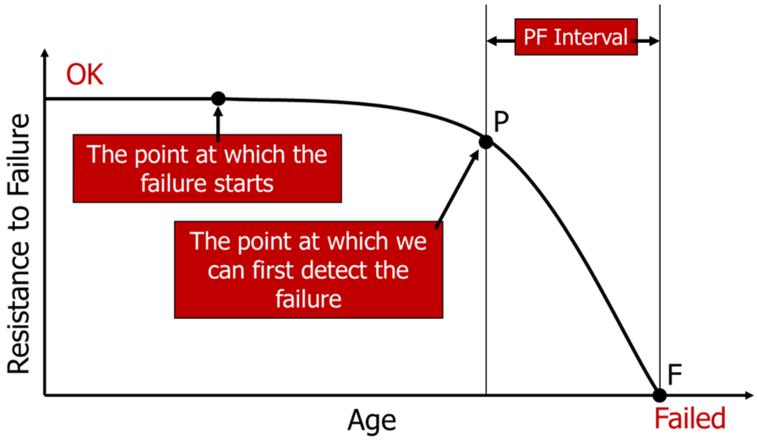

Figure 16: P-F curve (source: www.assetivity.com)

The second criteria was "predictability" (Kelly (1997) and International Atomic Energy Agency (2007)). Predictability is about how well the failure rate is distributed and therefore, how well the failures can be predicted. Figure 17 shows an example of predictability of a gearbox and an electric motor. The failure distribution of the gearbox has a good statistical predictability, which means planned preventive maintenance makes sense. On the other hand, the electric motor has a poor statistical predictability, which means planned preventive maintenance does not make sense, but condition-based maintenance might work.

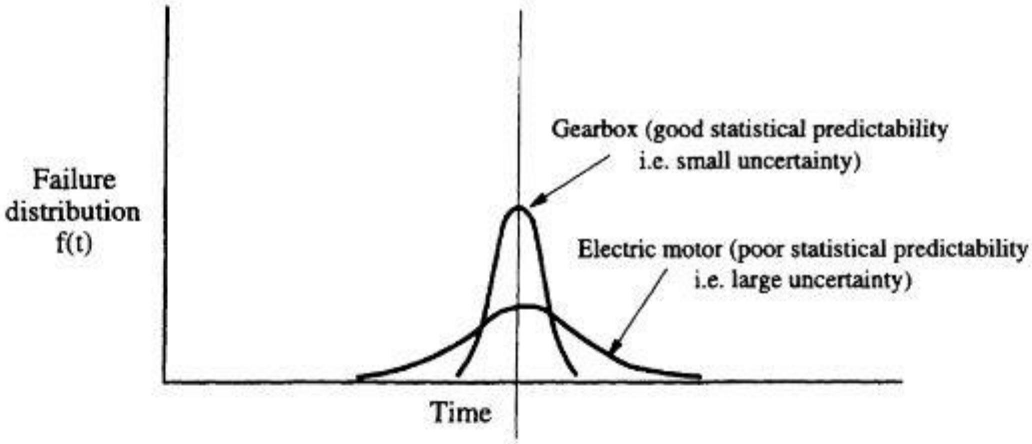

Figure 17: Predictability of failures (source: Kelly,1997)

The next criteria is "increasing failure rate" (Silva, 2015). This increasing failure rate refers to the wear out period in the Bathtub curve (see Figure 18). As Bazovsky (1961) mentions, only replacement makes sense when a component is in its wear out period. Note that a machine consists of many components which are replaced over time. So the machine itself will probably never reach the wearout period, since by then all the components have been replaced. Thus, the bathtub curve can be used on component level, but will not be an applicable theory on machine level or a higher level.

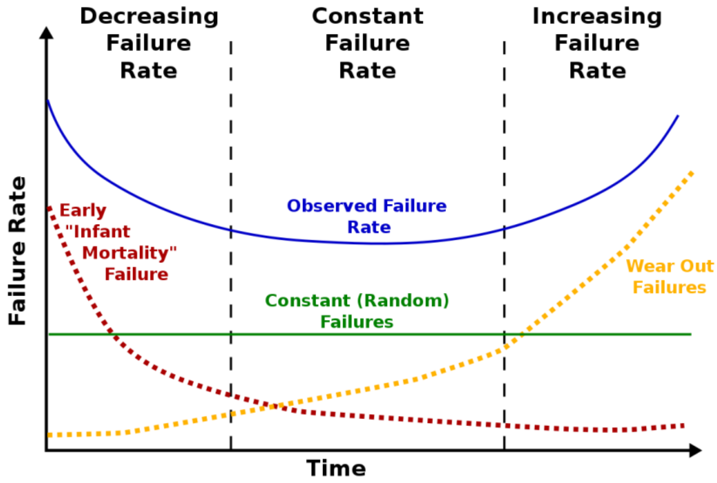

Figure 18: Bathtub curve (source: www.wikipedia.org)

The fourth criteria is "root cause known". This criteria came up in a brainstorm session with Rob Leurink. We argued that when the root cause is known, more specified / other maintenance policies might be used. The last criteria, which is not a maintenance criteria, is "delivery time". One of the mitigating actions given by MaxGrip was stock management. When a product has a long delivery time, it makes sense to have spare parts.

After determining this criteria, I created a table with the mitigating actions plotted against the criteria. For each combination I asked myself the following: "Would it make sense to do this mitigating action if this is the criteria?". Table 28 is the result of this table. For example, I asked myself: "Would inspection as mitigating action make sense when the detection of potential failure is bad?". The answer on that question was no. If the detection is bad, inspection will not give a result, since it is not visible. So only when detection of potential failures is good it makes sense to do an inspection. Another example is: "Would preventive replacement make sense when the root cause is known?" The answer is yes, but it also makes sense to do a preventive replacement when the root cause is not known. You could just replace the component which is the root cause or the whole machine. So the answer to that question is "both".

Table 28: Criteria for mitigating actions

Mitigating action	Detection potential failure	Detection functional failure	Predictability	Increasing failure rate	Root cause known	Delivery time
1 Inspection	Good	Good	Bad	Non Applicable	Both	Both
2 Functional test	Bad	Bad	Bad	Non Applicable	Both	Both
3 Spare parts	Both	Both	Bad	Non Applicable	Yes	Long
4 Preventive maintenance	Both	Both	Good	Non Applicable	Yes	Both
5 Revision	Both	Both	Good	Non Applicable	Both	Both
6 Preventive replacement	Bad	Both	Good	Applicable	Both	Both
7 Modification	Bad	Both	Bad	Applicable	Both	Both

After filling in the table, I determined what my first question in the decision tree (see Figure 19) would be. Two criteria have a clear distinction: increasing failure rate and predictability. It is either applicable or non-applicable and good or bad, contrary to the other criteria where "both" is mentioned everywhere. Based on a maintenance decision tree from the Hanzehogeschool (Hanzehogeschool Semester 6 chapter 2 *Onderhoudsvormen* ROC Twente) – where the question about increasing failure rate was the first question – I made this my first question. Then by filtering in the table I had to make a question which distinguishes preventive replacement and modification when there was an increasing failure rate. The only difference between those two was the criteria predictability. So that was my second question in the decision tree. When there is no increase in failure rate, the next question needs to be determined. The criteria without “both” in it, when excluding increased failure rates, is again predictability. So this was the third question. After the third question, I could easily remove spare parts – which has a lot of “both” in it – by asking the question whether the delivery time was the problem. Then it became a little more specific, so I asked specifically whether the potential failure could be detected by inspection or by a functional test. If both were not applicable, then a modification should be done, since this is a decision tree for measures when a functional failure is not acceptable. So if the potential failure is not detectable in any way, it will fail and that should be prevented. This resulted in the decision tree in Figure 19.

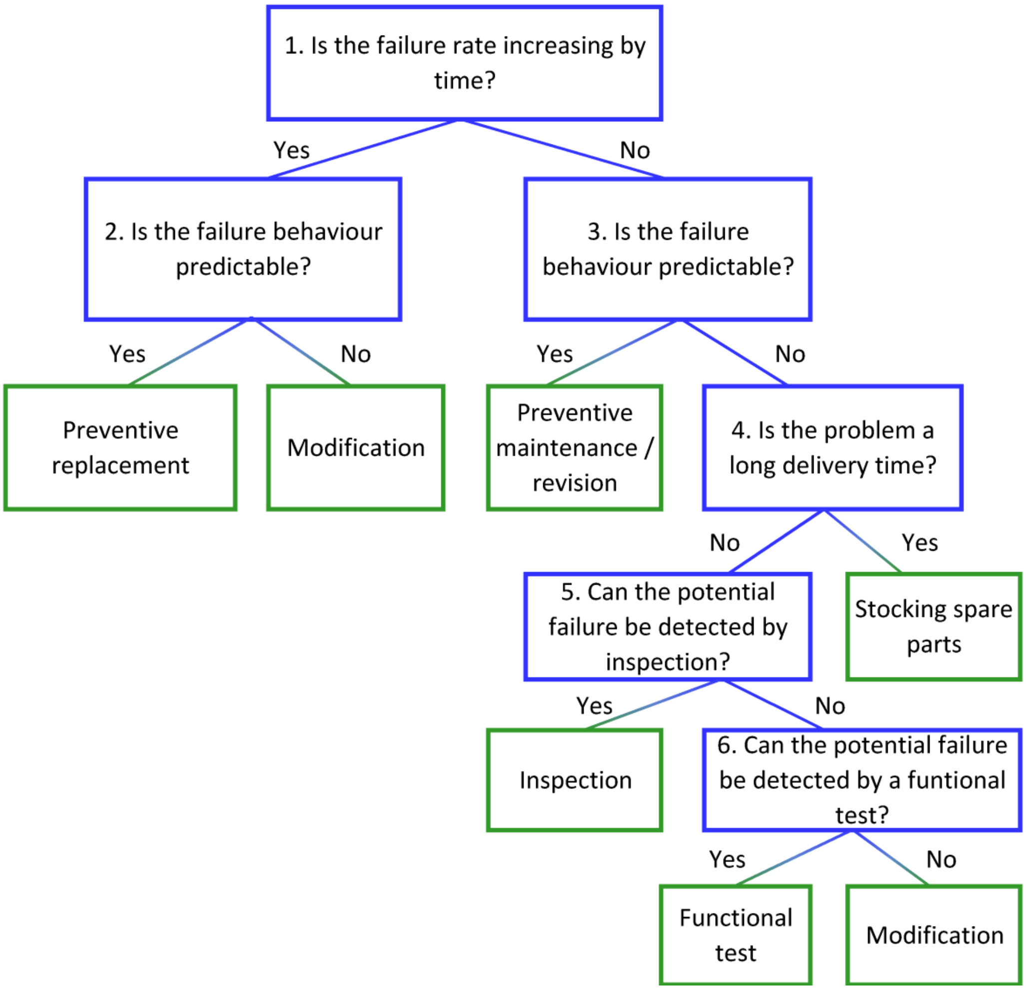

Figure 19: Decision tree measure

As can be seen, I did not use the criteria “root cause known” and “detection of functional failure”. As said previously, the decision tree has to be used when a risk of a failure is unacceptable. So whether the detection of the functional failure is good or bad, it does not matter since the machine or component is not allowed to fail. The root cause apparently had no influence in this decision tree. It can appear after “inspection” and it is a part of preventive maintenance. For example, out of the inspection it can appear that something has not been calibrated well. Then the root cause is known and the measure “adjust calibration” will be executed. The same applies for lubricating, cleaning etcetera. So this is actually a result or a part of a measure you initially take.

This decision tree objectifies which measure to take. The decision about the frequency of the measure is up to Grolsch. This was not in the scope of the assignment.

An example for the decision tree is the Empty Bottle Inspector (EBI). This machine tests if the bottle is empty and safe, based on several criteria. I will fill in the decision tree with one detection camera. If this camera fails, a bottle can go to the market which is a danger for the client. Let's say the failure rate does not increase by time. Then we go to question 3 of the decision tree. Is the failure behaviour predictable? No, a camera is an electric component, which cannot be predicted. The problem is also not a long delivery time. Can the potential failure be detected by inspection? No, because the P-F interval (see Figure 16) is a fraction of a second. Can the potential failure be detected by a functional test? Yes, by putting testing bottles through the machine which have defects based on the criteria the EBI tests its bottles. This is what Grolsch does at the EBI. Every 30 minutes, some testing bottles are put through the machine. If the machine rejects all the testing bottles, the cameras have not failed.

6.3 Recommendations for FMECA template

The last question from Grolsch was to give recommendations for making the FMECA template more user-friendly. I split this up in three parts: making the tool easier to use, taking away frustrations and implementing my additions.

6.3.1 Ease of use

The first recommendation is about ordering the parts. Every machine consists of main components, subcomponents and further/more levels. At the moment, the Excel template does not give a way to order the different levels properly. Some people make a distinction between levels using colours, others using different columns in Excel and other using the Group function in Excel (Data → Group). I am a supporter of the latter, since it gives you the opportunity to collapse and expand the different levels. This will look like Figure 20. The problem is that when you insert a new row, the groups are not moving with the new row. That would mean that every time you want to insert a new row, the groups need to be defined again. Perhaps a code could be written to prevent this from happening.

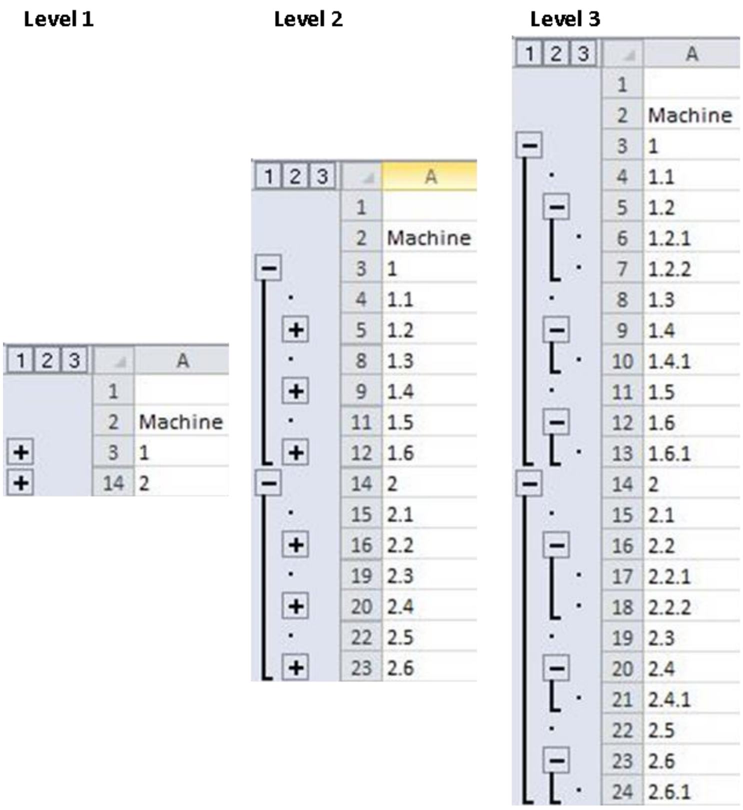

Figure 20: Ordering levels using the Group function in Excel

At the moment, the executors of FMECA have to write all the components down by head. An extension of the previous recommendation, is the possibility of importing the Bill of Materials (BoM) or the Process and Instrumentation Diagram (P&ID) into the Excel file. The hard thing is that every machine has another naming / description because of a different Original Equipment Manufacturer (OEM). Furthermore in a conversation with Ruud van Westen (Maintenance Planner), Jacquelien Aldenkamp Stokkingreef (Shift Teamleader Packaging) and Jos Loskamp (Line Operator Packaging) (23 May, 2017), they mentioned that the parts in the BoM usually are not in the same sequence as the machine is, the component levels go too deep and not everyone is familiar with the names used in the BoM (a lot of abbreviations, codes etcetera). Despite this drawbacks, Sander Janssen (21 June, 2017), Senior Specialist at MaxGrip, encouraged using a BoM or P&ID. He preferred using the P&ID rather than the BoM, since the P&ID is more function-oriented and the BoM is completely component-oriented. In the P&ID you can see easier what effect a failure would have on the system.

As said in chapter 3.1.6, conducting FMECAs is very time consuming. We need to implement smartnesses and think logically to reduce the time spent on FMECAs. In Chapter 5.4 I already showed a way to reduce the amount of FMECAs. Here I would like to introduce a way to make the FMECA a bit smaller. In the current FMECA every component needs to be judged on 7 variables: MTTF, MTTR, Safety, Environment, Quality, Production Availability and Costs. But for many machines some variables can be excluded; there is never an effect on. For example, conveyors will have no impact on quality and almost the complete Packaging department will have no effect on environment, except for a couple of machines. It would be perfect to simplify the FMECA upfront by deselecting the variables on which the machine has no influence. It is important to make this selection with a group of people who have a lot of different knowledge. Deselecting variables upfront saves the time of selecting "no effect" for every component and the time to think of whether the component has an influence on that variable.

6.3.2 Frustrations

For now there are two frustrations when using the FMECA template. The first frustration is when a row is added or deleted. Formulas are not pulled down automatically and formulas seems to change. This probably would be solved by making a table of the template, since in a table formulas are pulled down automatically.

Another frustration is that sometimes data validation suddenly resets. The pull-down menu is gone and the source needs to be specified again. It might help to name the arrays which are referred to and select the name in the data validation menu instead of the array itself.

6.3.3 Additions

In chapter 5 I changed a lot on the risk tables and the weighting numbers. Also the way of judging the acceptability has become different for the variables (see Table 26). As Table 26 shows, production availability can be judged on machine or department level, but not on component level. This will result in almost no red cells in the FMECA, but the total production availability might be unacceptable. Therefore, an extra worksheet showing the total score per machine of the different variables and its acceptability on machine level, would be a good – and necessary – addition. Only the total scores of Environment, Production Availability and Costs needs to be showed. Safety and Quality are assessed on component level, so there is no total score needed.

As mentioned in chapter 5.2, I want to introduce using exact data for the MTTF, the MTTR and Costs. Several people approved this, for example Rob Leurink (Supervisor, 22 May, 2017), Ilco Kuiper (Maintenance Planner, 1 June, 2017) and Sander Janssen (Senior Specialist at MaxGrip, 21 June, 2017). Ruud van Westen (Maintenance Planner, 22 May, 2017) was a bit sceptical because it is hard to estimate especially MTTFs. On the other hand, when you cannot estimate an MTTF exactly, you can always take an average. During the intermediate presentation at Grolsch, Stefan Fransen (Operations Reporting Specialist) asked why I took the mean as average for the intervals of all variables. In practice it could also be a skewed normal curve or a uniform distribution inside the interval. In that case the mean would not be an accurate picture of reality. By using exact data this would not be an issue. If for example the costs of a failure are €5,001, then they would fall into category 2 (€5,000 - €10,000), which is on average €7,500, using the mean as average. Costs are therefore estimated 7,500 / 5,001 ≈ 1.5 times too high. But the category which is the least accurate at the moment, is the upper category in MTTF (> 30 years), MTTR (> 1 week) and Costs (> €10,000). Costs of €10,001 as well as costs of €1,000,000 are put in the upper category. Filling in the exact data would prevent this situations.

The last recommendation for the template, is adding an extra column with the amount of same products, as mentioned in chapter 6.1.2. If there are multiple components all performing the same task in parallel, the exact production decrease can be calculated when one component breaks down using the number of components.

6.4 Conclusion

First the vaguenesses in filling in the FMECA were determined and clarified:

- MTTR includes all repair stages, that is, the complete downtime of the machine.
- If there are multiple equal components, then it is clear what to do depending on the function of the component in the system.
- Which consequences of a failure to include was clarified by defining direct from indirect in the context of FMECA.
- Which costs of a failure to include was also clarified: all the direct costs with exception of the costs already included in other variables.

Then the decision making when a measure needs to be taken was objectified by means of a decision tree. When using the decision tree in the decision process, each executor of FMECA should have similar measures in the same cases.

Lastly, recommendation regarding the FMECA template were given based on feedback of current FMECA executors and the research done in this thesis.

7 Conclusion

Failure Mode Effects and Criticality Analysis did not work properly at Grolsch. Employees of Grolsch did not agree with the results of the analysis. The analysis was done on component level but the acceptability of the risks was set on company level. Also when different people filled in the same analysis, the outcomes were different. This were the starting points for this thesis, which led to the main research question:

How does Grolsch need to use FMECA to make a valid and reliable estimation of the extent of acceptation of risks on component level?

Grolsch wanted to make the FMECA more valid to get results employees of Grolsch do agree on. Also the subjectivity of the analysis should be eliminated by making the tool more reliable. This has been approached by posing two research questions:

1. How to manage risks on component level?
2. What are the vaguenesses in making an FMECA and how can the vaguenesses be clarified?

The first problem that was encountered, was that the risk tables in the FMECA were barely grounded. Before translating risks from component level to company level, the risk tables were looked over. This was done using company goals on the different variables in the FMECA: Safety, Quality, Environment, Production Availability and Costs. After the risk tables were improved and better grounded, a method to translate the risks from component to company level was developed. It turned out that every variable had its own method. Lastly, an approach to select the machine to do an FMECA on was made. This were the results per variable:

- The risk table of Safety was changed using the number is injuries per year in different severity categories. An important decision was to only use the injuries which were caused by mechanical failures. The categories stayed the same, but the weighting factors were changed to make the ratios of the weighting factors of the categories equal to the ratios of the categories themselves. The three most severe categories are almost never allowed and the lower categories have such a low severity and are hard to prevent. Therefore I concluded that to make is easier, the upper three categories are never allowed to happen and the lower categories are always allowed to happen. Because of this decision, the risks can be evaluated on component level, no translation to company level had to be made. Finally, machine can be selected by certain safety criteria.
- The risk table of Quality was changed because of conversations with the Quality Assurance Specialist. The weighting factors stayed the same, but the categories slightly changed, because the reason of rejection did not matter, as long as the product with a bad quality did not reach the client. Due to the complexity of Quality, the existing preventive measures on quality and the time limit of this research, I concluded not to change anything but the categories. This variable can thus also be evaluated on component level. The machines to execute an FMECA on can be selected using the existing list of Critical Control Points.
- The risk table of Environment has been extended. The categories stayed the same, but duration was added to the categories: long and short term effects. The most important finding, was that environmental violations are judged per machine by the local government. Knowing this, the criticality analysis should be done on machine level. The selection of machines was very easy. Grolsch does not have a lot of machine which could lead to a violation of environmental regulations. It was determined that this can be narrowed down to four

installations: the ammonia installation, the waste water purification installation, the CO_2 installation and the tanks in Brewery.

- The risk table of Production Availability has completely changed. The categories were made more measurable by adding percentages of downtime and implementing the percentages in the weighting factors. Also the weighting factor for machines with redundancy has been grounded using statistics. Based on historical downtimes and the company goal for machine efficiency, the boundary level for the criticality analysis has been changed to be adaptable for every machine in Packaging. The most important decision was to link downtime in every department to downtime in the Packaging department, since Packaging suffers the most from downtime. In Packaging the criticality analysis can be done on machine level using the downtime history to make theoretical machine efficiencies. In Brewing, Utilities and Warehouse this has to be done on department level, since there is no downtime history per machine available. The selection of machines in those departments therefore has to be done by memorising the machines which caused the most downtime in history. In Packaging, a Pareto analysis can be done using existing historical downtime data to find the least efficient machines.
- The risk table of Costs has been slightly changed by making the ratios of the weighting factors equal to the ratio of the categories. The criticality analysis is now based on the maintenance budget. This maintenance budget is available on department level, so the criticality analysis should be done on department level. The selection of machines can be done in two ways: make a Pareto analysis of the most expensive machines looking at components or the most expensive machines looking at maintenance in the past years. Another interesting point of view for Costs, is not putting a boundary level to it. A certain level of Safety, Quality, Environment and Production Availability requires certain costs. Using this point of view, Costs in the FMECA can be used to ground the maintenance budget instead of the maintenance budget being the boundary level for Costs.

After these adjustments, the FMECA analysis was made more valid. Then the analysis had to become more reliable. This was done by clarifying vaguenesses in filling in the FMECA and objectifying the choice of measures when a risk ended to be unacceptable. The following vaguenesses were clarified:

- MTTR includes all repair stages, that is, the complete downtime of the machine.
- If there are multiple equal components, then it is clear what to do depending on the function of the component in the system.
- Which consequences of a failure to include was clarified by defining direct from indirect in the context of FMECA.
- Which costs of a failure to include was also clarified: all the direct costs with exception of the costs already included in other variables.

Then the decision making when a measure needs to be taken was objectified by means of a decision tree. When using the decision tree in the decision process, each executor of FMECA should have similar measures in the same cases.
Lastly, recommendation regarding the FMECA template were given based on feedback of current FMECA executors and the research done in this thesis.

Although the results of this research have not been implemented yet, the reactions were positive. At Grolsch the people believed this would yield a better analysis of the risks the brewery faces.

8 Recommendations

In chapter 6.3 some recommendations were mentioned, as this was a question from Grolsch which I researched. Those recommendations were about ease of use of the template, frustrations when using the template and additions which should be made when implementing the findings of this research. In this chapter I will give some more recommendations which appeared during or after the research.

Downtime history

As said in chapter 5.3.4 and 5.4.4, there is historical downtime data available of machine in Packaging. However, machines in Brewing, Warehouse and Utilities does not have this data. I would recommend to start gathering that data from now on. This will have two advantages:

1. When executing an FMECA in Brewing, Warehouse or Utilities, machines have to be selected using common sense and memorising failures in the past. If there is downtime data available per machine in those departments, then a Pareto could be made like in Packaging. The selection of the machines will then be better motivated.
2. When eventually a machine is selected in Brewing, Warehouse or Utilities, the criticality analysis cannot be done on machine level, as a boundary level cannot be calculated. In Packaging an individual boundary level per machine can be calculated using historical downtime data (see chapter 5.3.4). Having such downtime data in the other departments too, will result in a better and easier FMECA looking at Production Availability.

Quality

On Quality the least has changed. As said in chapter 5.3.5, Quality is very complex and there was a time limit of 10 weeks for this thesis. I would recommend to dig more in Quality when there is time available. Perhaps HACCP could be combined with FMECA eventually.

Environment

As said in chapter 5.1.5, the current FMECA regarding environment is completely about violation of environmental regulations. This could be broadened to water, gas and electricity reductions. In that case the categories should be changed and environmental company goals could be implemented in the FMECA.

Broader use

In 5.3.5 a broader use of FMECA was mentioned: using Costs as explanation for the maintenance budget to achieve a certain level of Safety, Quality, Environment and Production Availability. FMECA is a tool to analyse the criticality of risks. FMECA might also be used as an optimisation tool. For example, in Production Availability the boundary level is based on the company objective on machine efficiency. If the management of Grolsch wants a higher machine efficiency, it can be easily implemented in the boundary level of Production Availability. Then the FMECA is not just a tool to estimate risks, but also a tool to show what is needed for the future company objectives. This can also be done with the other variables.

9 References

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Appendices

Appendix A – Internship Agreement (Dutch)

This appendix shows the internship agreement as described in chapter 4.7.

Artikel 5 - Geheimhouding

5.1 De stagiair(e) erkent dat door Grolsch stikte geheimhouding is opgelegd, zowel tijdens als na beëindiging van deze stageovereenkomst, ter zake van alle gegevens respectievelijk bijzonderheden betreffende of verband houdend met het bedrijf van Grolsch - of een met haar gelieerde onderneming waaronder begrepen haar moedermaatschappij. Deze plicht tot geheimhouding geldt tevens ten aanzien van de gegevens respectievelijk bijzonderheden betreffende personeel, relaties en opdrachtgevers van Grolsch of van een met haar gelieerde onderneming.

5.2 Voor zover de stagiair(e) software, documenten, correspondentie of kopieën daarvan, welke de stagiair(e) in verband met de stage onder zich heeft verkregen, in eigen bezit heeft, is de stagiair(e) gehouden op eerste verzoek van Grolsch, en bij gebreke van een dergelijk verzoek uiterlijk op de dag dat deze stageovereenkomst eindigt, onverwijld aan Grolsch ter beschikking te stellen.

5.3 De stagiair(e) zal zich onthouden van enige uitlating in spraak of geschrift omtrent Grolsch en/of opdrachtgevers of relaties van Grolsch die negatief is en/of enige schade in welke vorm dan ook toebrengt of toe kan brengen aan de goede naam en faam van Grolsch en/of haar opdrachtgevers of relaties.

Artikel 6 – Intellectuele eigendom

6.1 De stagiair(e) heeft voor alle publicaties, in welke vorm dan ook, waaronder mede een (stage)rapportage c.q. verslag aan het opleidingsinstituut begrepen, voorafgaande toestemming nodig van Grolsch. Een stageverslag of afstudeerscriptie zal alleen na goedkeuring door Grolsch aan het opleidingsinstituut of andere derden mogen worden verstrekt.

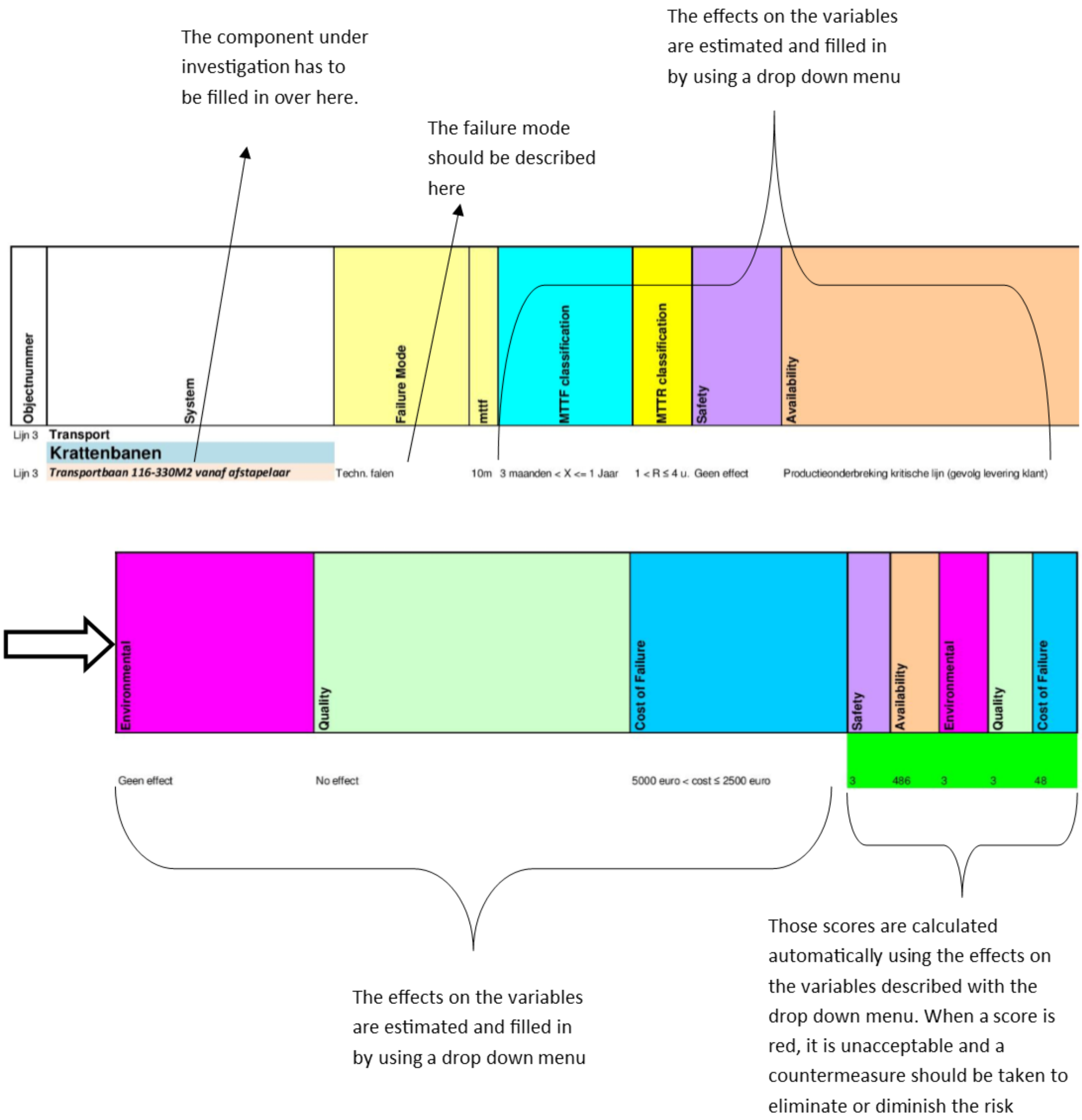
6.2 Alle rechten met betrekkingen tot werken, uitvindingen, nieuwe werkwijzen, ideeën, knowhow, slogans, merken, handelsnamen, en dergelijke, die de stagiair(e), al dan niet zelfstandig, tot stand heeft gebracht of doen brengen, hierna gezamenlijk te noemen: Intellectuele Eigendom, komen toe aan Grolsch of de met haar gelieerde onderneming, ongeacht of de Intellectuele Eigendom is ontstaan gedurende of buiten werktijd, gedurende deze stageovereenkomst dan wei na beëindiging daarvan en evenzeer ongeacht of het tot stand brengen of doen brengen van de Intellectuele Eigendom in het kader van de stage zijn gedaan, zijn eigendom van Grolsch zonder dat Grolsch tot enigerlei vergoeding aan de stagiair(e) gehouden is.

6.3 De stagiair(e) is verplicht van alle Intellectuele Eigendom onverwijld mededeling te doen aan Grolsch en voorts al datgene te doen dat noodzakelijk of gewend is voor het bewerkstelligen van de overdracht van de Intellectuele Eigendom aan Grolsch.

6.4 De stagiair(e) komt geen zelfstandig recht op naamsvermelding toe met betrekking tot Intellectuele Eigendom.

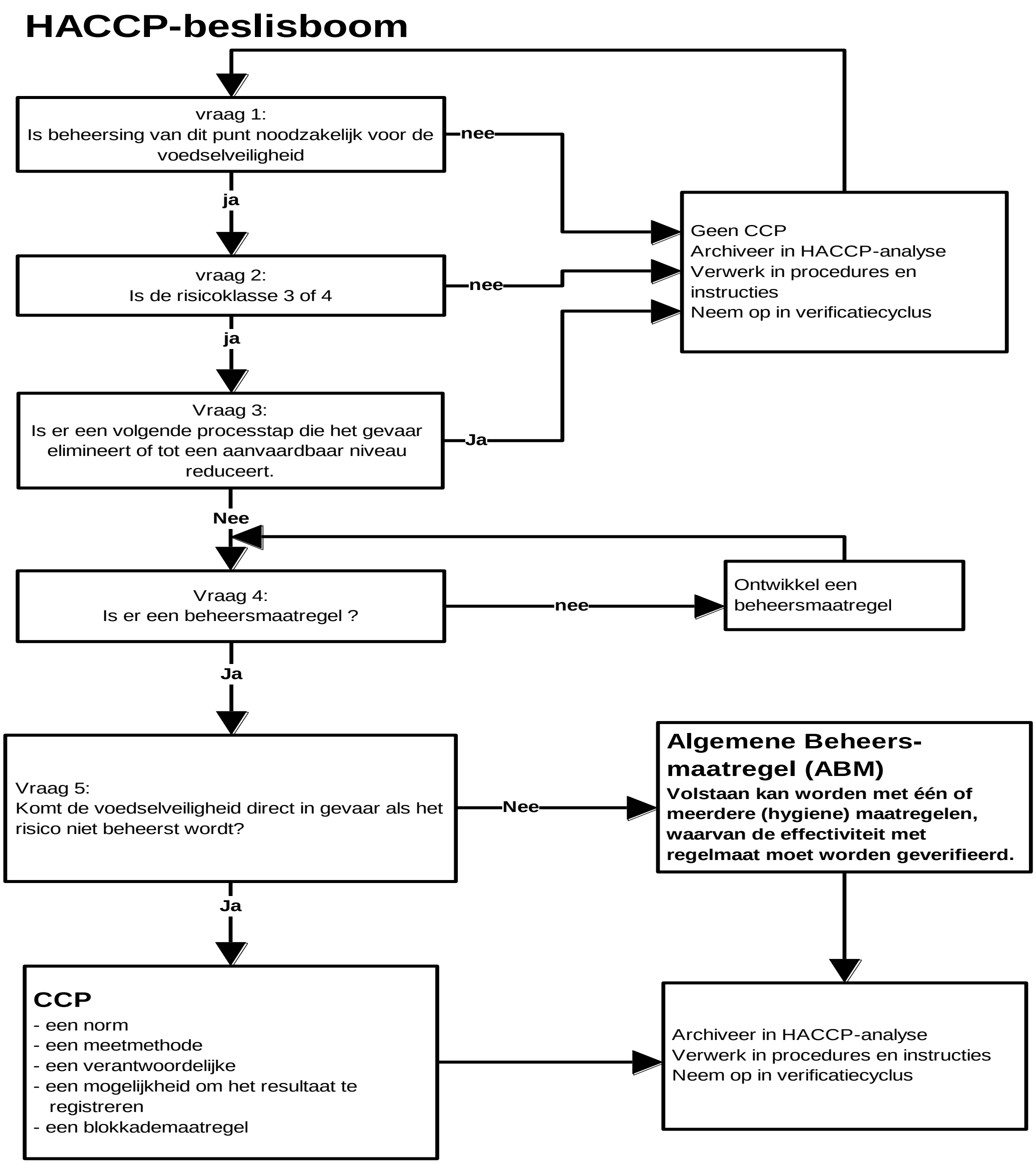
Appendix B – Screenshots of FMECA template

This appendix shows the FMECA template as used by Grolsch before with an explanation. Note that the two rows should be read as one row, as the arrow in the left corner depicts.



Appendix C – HACCP decision tree (Dutch)

This appendix shows the HACCP decision tree, as described in chapter 5.3.3.



Appendix D – Original risk matrices

This appendix shows the original risk matrices as used by Grolsch for Safety, Environment, Quality, Production Availability and Costs.

	Safety	Weighting factor	0 hour < X ≤ 1 week	1 week < X ≤ 3 months	3 months < X ≤ 1 year	1 year < X ≤ 5 years	5 years < X ≤ 10 years	X > 10 years	Risk boundary ≥
		Time between failures	*243*	*81*	*27*	*9*	*3*	*1*	
1	Lethal injury	2430	590490	196830	65610	21870	7290	2430	2430
2	Serious accident with permanent injury	810	196830	65610	21870	7290	2430	810	
3	Accident leading to sick leave	270	65610	21870	7290	2430	810	270	
4	Accident not leading to sick leave	90	21870	7290	2430	810	270	90	
5	Near accident	30	7290	2430	810	270	90	30	
6	No effect	1	243	81	27	9	3	1	

	Environment	Weighting factor	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	X > 1 year	Risk boundary ≥
		Time between failures	*243*	*81*	*27*	*9*	*3*	*1*	
1	Violation of environmental regulations (wasste, substances, packaging, etc.) with major environmental impact	1801	437643	145881	48627	16209	5403	1801	1801
2	Violation of environmental regulations (waste, substances, packaging and so on) that leads to nuisance 'within the enclosure of the company site'	600	145800	48600	16200	5400	1800	600	
3	Violation of environmental regulations (waste, substances, packaging and so on) without any direct impact	200	48600	16200	5400	1800	600	200	
4	No effect	1	243	81	27	9	3	1	

	Quality	Weighting factor	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	X > 1 year	Risk boundary ≥
		Time between failures	*243*	*81*	*27*	*9*	*3*	*1*	
1	Immediate public health hazard due to failure to comply with the legal quality requirements relating to food safety.	1621	393903	131301	43767	14589	4863	1621	1620
2	Rejection of product due to failure to comply with the legal requirements relating to food safety	180	43740	14580	4860	1620	540	180	
3	Rejection of product due to failure to comply with the in-house requirements	60	14580	4860	1620	540	180	60	
4	Non-compliance with the in-house quality requirements, not leading to rejection or reprocessing	20	4860	1620	540	180	60	20	
5	No effect	1	243	81	27	9	3	1	

	Production availability	Weighting factor	R ≤ 1 hour	1 hour < R ≤ 4 hour	4 hour < R ≤ 8 hour	8 hour < R ≤ 24 hour	R > 24 hour	R ≤ 1 hour	1 hour < R ≤ 4 hour	4 hour < R ≤ 8 hour	8 hour < R ≤ 24 hour	R > 24 hour	
		Time between failures	0 hour < X ≤ 1 day					1 day < X ≤ 1 week					
		Weighting factor	*243*					*81*					
		Downtime											
		Weighting factor	*1*	*2*	*4*	*8*	*16*	*1*	*2*	*4*	*8*	*16*	Risk boundary ≥
1	Stop entire department	567	137781	275562	551124	1102248	2204496	45927	91854	183708	367416	734832	3889
2	Production disruption critical line (consequences for the customer)	81	19683	39366	78732	157464	314928	6561	13122	26244	52488	104976	
3	Production decrease (with loss of production)	27	6561	13122	26244	52488	104976	2187	4374	8748	17496	34992	
4	Production decrease (without loss of production)	9	2187	4374	8748	17496	34992	729	1458	2916	5832	11664	
5	Loss of redundancy without an effect on production	3	729	1458	2916	5832	11664	243	486	972	1944	3888	
6	No effect	1	243	486	972	1944	3888	81	162	324	648	1296	

	Production availability	Weighting factor	R ≤ 1 hour	1 hour < R ≤ 4 hour	4 hour < R ≤ 8 hour	8 hour < R ≤ 24 hour	R > 24 hour	R ≤ 1 hour	1 hour < R ≤ 4 hour	4 hour < R ≤ 8 hour	8 hour < R ≤ 24 hour	R > 24 hour
		Time between failures	1 week < X ≤ 1 month					1 month < X ≤ 3 months				
		Weighting factor	*27*					*9*				
		Downtime										
		Weighting factor	*1*	*2*	*4*	*8*	*16*	*1*	*2*	*4*	*8*	*16*
1	Stop entire department	567	15309	30618	61236	122472	244944	5103	10206	20412	40824	81648
2	Production disruption critical line (consequences for the customer)	81	2187	4374	8748	17496	34992	729	1458	2916	5832	11664
3	Production decrease (with loss of production)	27	729	1458	2916	5832	11664	243	486	972	1944	3888
4	Production decrease (without loss of production)	9	243	486	972	1944	3888	81	162	324	648	1296
5	Loss of redundancy without an effect on production	3	81	162	324	648	1296					
6	No effect	1	27	54	108	216	432	9	18	36	72	144

	Production availability	Weighting factor	R ≤ 1 hour	1 hour < R ≤ 4 hour	4 hour < R ≤ 8 hour	8 hour < R ≤ 24 hour	R > 24 hour	R ≤ 1 hour	1 hour < R ≤ 4 hour	4 hour < R ≤ 8 hour	8 hour < R ≤ 24 hour	R > 24 hour
		Time between failures	3 months < X ≤ 1 year					X > 1 year				
		Weighting factor	*3*					*1*				
		Downtime										
		Weighting factor	*1*	*2*	*4*	*8*	*16*	*1*	*2*	*4*	*8*	*16*
1	Stop entire department	567	1701	3402	6804	13608	27216	567	1134	2268	4536	9072
2	Production disruption critical line (consequences for the customer)	81	243	486	972	1944	3888	81	162	324	648	1296
3	Production decrease (with loss of production)	27	81	162	324	648	1296	27	54	108	216	432
4	Production decrease (without loss of production)	9	27	54	108	216	432	9	18	36	72	144
5	Loss of redundancy without an effect on production	3	9	18	36	72	144	3	6	12	24	48
6	No effect	1	3	6	12	24	48	1	2	4	8	16

	Costs	Time between failures / Weighting factor	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	X > 1 year	
		Weighting factor	*243*	*81*	*27*	*9*	*3*	*1*	Risk boundary ≥
1	Costs > € 10.000	256	62208	20736	6912	2304	768	256	256
2	€ 5.000 < Costs ≤ € 7.500	64	15552	5184	1728	576	192	64	
3	€ 2.500 < Costs ≤ € 5.000	16	3888	1296	432	144	48	16	
4	€ 0 < Costs ≤ € 2.500	4	972	324	108	36	12	4	
5	No effect	1	243	81	27	9	3	1	

Appendix E – Adjusted risk matrices

This appendix shows the risk matrices after my adjustments for Safety, Environment, Quality, Production Availability and Costs.

		Time between failures	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	1 year < X ≤ 10 years	10 years < X ≤ 30 years	X > 30 years	
	Safety	*Weighting factor*	*21900*	*2738*	*584*	*180*	*48*	*5*	*2*	*1*	Risk boundary ≥
1	Lethal injury	15267	334347300	41801046	8915928	2748060	732816	76335	30534	15267	140
2	Serious accident with permanent injury	420	9198000	1149960	245280	75600	20160	2100	840	420	
3	Accident leading to sickness	140	3066000	383320	81760	25200	6720	700	280	140	
4	Accident not leading to sickness	8	176885	22115	4717	1454	388	40	16	8	
5	Near accident	1	21900	2738	584	180	48	5	2	1	
6	No effect	0	0	0	0	0	0	0	0	0	

		Time between failures	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	1 year < X ≤ 10 years	10 years < X ≤ 30 years	X > 30 years	
	Milieu	*Weighting factor*	*21900*	*2738*	*584*	*180*	*48*	*5*	*2*	*1*	Risk boundary ≥
1	Violation of environmental regulations with major environmental impact	360	7884000	985680	210240	64800	17280	1800	720	360	360
2	Long term violation of environmental regulations leading to nuisance outside the enclosuure of the company site	72	1576800	197136	42048	12960	3456	360	144	72	
3	Short term violation of environmental regulations leading to nuisance outside the enclosure of the company site	36	788400	98568	21024	6480	1728	180	72	36	
4	Long term violation of environmental regulations leading to nuisance within the enclosure of the company site	10	219000	27380	5840	1800	480	50	20	10	
5	Short term violation of environmental regulations leading to nuisance within the enclosure of the company site	6	131400	16428	3504	1080	288	30	12	6	
6	Long term violation of environmental regulations within the enclosure of the company site without any direct impact	3	65700	8214	1752	540	144	15	6	3	
7	Short term violation of environmental regulations within the enclosure of the company site without any direct impact	1	21900	2738	584	180	48	5	2	1	
8	No effect	0	0	0	0	0	0	0	0	0	

		Time between failures	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	1 year < X ≤ 10 years	10 years < X ≤ 30 years	X > 30 years	
	Quality	*Weighting factor*	*21900*	*2738*	*584*	*180*	*48*	*5*	*2*	*1*	Risk boundary ≥
1	Immediate public health hazard due to failure to comply with the legal quality requirements relating to food safety	11681	255813900	31982578	6821704	2102580	560688	58405	23362	11681	11681
2	Rejection of product due to failure to comply with the quality requirements	180	3942000	492840	105120	32400	8640	900	360	180	
3	Reprocessing of product due to failure to comply with the in-house quality requirements	60	1314000	164280	35040	10800	2880	300	120	60	
4	Non-compliance with in-house quality requirements, not leading to rejection	20	438000	54760	11680	3600	960	100	40	20	
5	No effect	0	0	0	0	0	0	0	0	0	

		Time between failures	0 hour < X ≤ 1 day							1 day < X ≤ 1 week						
		Weighting factor	*21900*							*2738*						
		Downtime	R > 1 week	24 hour < R ≤ 1 week	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 hour	R ≤ 3 minutes	R > 1 week	24 hour < R ≤ 1 week	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 hour	R ≤ 3 minutes
	Production availability	*Weighting factor*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*
1	100% production disruption Packaging	100	7E+09	4E+09	7E+08	3E+08	1E+08	2E+07	0	9E+08	5E+08	9E+07	3E+07	1E+07	3E+06	0
2	50% production decrease Packaging	50	4E+09	2E+09	4E+08	1E+08	5E+07	1E+07	0	5E+08	3E+08	4E+07	2E+07	7E+06	2E+06	0
3	100% production disruption line	17	1E+09	7E+08	1E+08	4E+07	2E+07	4E+06	0	2E+08	9E+07	1E+07	6E+06	2E+06	512006	0
4	50% production decrease line	8	6E+08	3E+08	6E+07	2E+07	9E+06	2E+06	0	7E+07	4E+07	7E+06	3E+06	1E+06	240944	0
5	Loss of redundancy without an effect on production	0,6	4E+07	3E+07	4E+06	2E+06	657000	144540	0	6E+06	3E+06	525696	197136	82140	18071	0
6	No effect	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

		Time between failures	1 week < X ≤ 1 month							1 month < X ≤ 3 months						
		Weighting factor	*584*							*180*						
		Downtime	R > 1 week	24 hour < R ≤ 1 weel	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 ho	R ≤ 3 minutes	R > 1 week	24 hour < R ≤ 1 weel	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 ho	R ≤ 3 minutes
	Production availability	*Weighting factor*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*
1	100% production disruption Packaging	100	2E+08	1E+08	2E+07	7E+06	3E+06	642400	0	6E+07	3E+07	6E+06	2E+06	900000	198000	0
2	50% production decrease Packaging	50	1E+08	6E+07	9E+06	4E+06	1E+06	321200	0	3E+07	2E+07	3E+06	1E+06	450000	99000	0
3	100% production disruption line	17	3E+07	2E+07	3E+06	1E+06	496400	109208	0	1E+07	6E+06	979200	367200	153000	33660	0
4	50% production decrease line	8	2E+07	9E+06	1E+06	560640	233600	51392	0	5E+06	3E+06	460800	172800	72000	15840	0
5	Loss of redundancy without an effect on production	0,6	1E+06	672768	112128	42048	17520	3854,4	0	362880	207360	34560	12960	5400	1188	0
6	No effect	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

		Time between failures	3 months < X ≤ 1 year							1 year < X ≤ 10 years						
		Weighting factor	*48*							*5*						
		Downtime	R > 1 week	24 hour < R ≤ 1 week	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 hour	R ≤ 3 minutes	R > 1 week	24 hour < R ≤ 1 week	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 hour	R ≤ 3 minutes
	Production availability	*Weighting factor*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*
1	100% production disruption Packaging	100	2E+07	9E+06	2E+06	576000	240000	52800	0	2E+06	960000	160000	60000	25000	5500	0
2	50% production decrease Packaging	50	8E+06	5E+06	768000	288000	120000	26400	0	840000	480000	80000	30000	12500	2750	0
3	100% production disruption line	17	3E+06	2E+06	261120	97920	40800	8976	0	285600	163200	27200	10200	4250	935	0
4	50% production decrease line	8	1E+06	737280	122880	46080	19200	4224	0	134400	76800	12800	4800	2000	440	0
5	Loss of redundancy without an effect on production	0,6	96768	55296	9216	3456	1440	316,8	0	10080	5760	960	360	150	33	0
6	No effect	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

		Time between failures	10 years < X ≤ 30 years							X > 30 years						
		Weighting factor	*2*							*1*						
		Downtime	R > 1 week	24 hour < R ≤ 1 week	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 hour	R ≤ 3 minutes	R > 1 week	24 hour < R ≤ 1 week	8 hour < R ≤ 24 hour	4 hour < R ≤ 8 hour	1 hour < R ≤ 4 hour	3 minutes < R ≤ 1 hour	R ≤ 3 minutes
	Production availability	*Weighting factor*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*	*3360*	*1920*	*320*	*120*	*50*	*11*	*0*
1	100% production disruption Packaging	100	672000	384000	64000	24000	10000	2200	0	336000	192000	32000	12000	5000	1100	0
2	50% production decrease Packaging	50	336000	192000	32000	12000	5000	1100	0	168000	96000	16000	6000	2500	550	0
3	100% production disruption line	17	114240	65280	10880	4080	1700	374	0	57120	32640	5440	2040	850	187	0
4	50% production decrease line	8	53760	30720	5120	1920	800	176	0	26880	15360	2560	960	400	88	0
5	Loss of redundancy without an effect on production	0,6	4032	2304	384	144	60	13,2	0	2016	1152	192	72	30	6,6	0
6	No effect	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Risk boundary ≥	Line/Department	Theoretical ME	Impact on PFH
5104696,252	Utilities	97,264%	0,3%

		Time between failures	0 hour < X ≤ 1 day	1 day < X ≤ 1 week	1 week < X ≤ 1 month	1 month < X ≤ 3 months	3 months < X ≤ 1 year	1 year < X ≤ 10 years	10 years < X ≤ 30 years	X > 30 years	
	Costs	*Weighting factor*	*21900*	*2738*	*584*	*180*	*48*	*5*	*2*	*1*	Risk boundary ≥
1	Costs > € 10.000	10000	219000000	27380000	5840000	1800000	480000	50000	20000	10000	11106000
2	€ 5.000 < Costs ≤ € 7.500	7500	164250000	20535000	4380000	1350000	360000	37500	15000	7500	
3	€ 2.500 < Costs ≤ € 5.000	3750	82125000	10267500	2190000	675000	180000	18750	7500	3750	
4	€ 0 < Costs ≤ € 2.500	1250	27375000	3422500	730000	225000	60000	6250	2500	1250	
5	No effect	0	0	0	0	0	0	0	0	0	

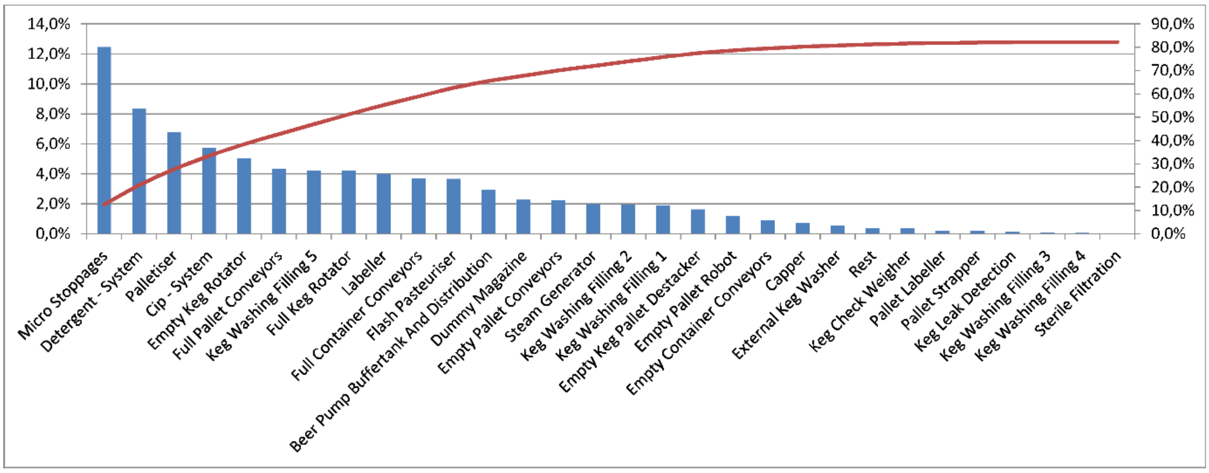
Appendix F – Theoretical ME per machine

This appendix shows the theoretical machine efficiencies per machine per line in Packaging, as described in chapter 5.3.4.

Line 1

Machine	Downtime (minutes)	Percentage of total downtime	Cumulative	Theoretical ME per machine
Micro Stoppages	2478	12,5%	12,5%	97,333%
Detergent - System	1665	8,4%	20,8%	98,208%
Palletiser	1351	6,8%	27,6%	98,546%
Cip - System	1143	5,7%	33,4%	98,770%
Empty Keg Rotator	998	5,0%	38,4%	98,926%
Full Pallet Conveyors	861	4,3%	42,7%	99,073%
Keg Washing Filling 5	842	4,2%	47,0%	99,094%
Full Keg Rotator	842	4,2%	51,2%	99,094%
Labeller	794	4,0%	55,2%	99,145%
Full Container Conveyors	737	3,7%	58,9%	99,207%
Flash Pasteuriser	729	3,7%	62,6%	99,216%
Beer Pump Buffertank And Distribution	582	2,9%	65,5%	99,374%
Dummy Magazine	453	2,3%	67,8%	99,513%
Empty Pallet Conveyors	444	2,2%	70,0%	99,522%
Steam Generator	393	2,0%	72,0%	99,578%
Keg Washing Filling 2	386	1,9%	73,9%	99,585%
Keg Washing Filling 1	374	1,9%	75,8%	99,597%
Empty Keg Pallet Destacker	322	1,6%	77,4%	99,653%
Empty Pallet Robot	238	1,2%	78,6%	99,744%
Empty Container Conveyors	177	0,9%	79,5%	99,810%
Capper	144	0,7%	80,2%	99,845%
External Keg Washer	115	0,6%	80,8%	99,876%
Rest	79	0,4%	81,2%	99,915%
Keg Check Weigher	74	0,4%	81,6%	99,920%
Pallet Labeller	41	0,2%	81,8%	99,956%
Pallet Strapper	38	0,2%	82,0%	99,959%
Keg Leak Detection	28	0,1%	82,1%	99,969%
Keg Washing Filling 3	18	0,1%	82,2%	99,981%
Keg Washing Filling 4	13	0,1%	82,3%	99,986%
Sterile Filtration	8	0,0%	82,3%	99,991%

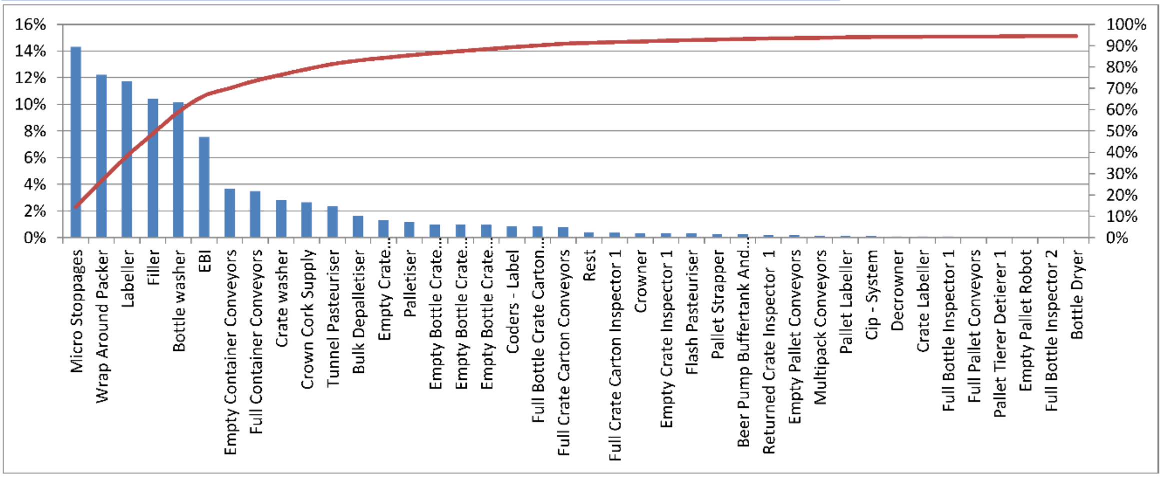
Total downtime (minutes)
19884,01547
Machine efficiency
78,6%



Line 2

Machine	Downtime (minutes)	Percentage of total downtime	Cumulative	Theoretical ME per machine
Micro Stoppages	10004	14%	14%	93,919%
Wrap Around Packer	8548	12%	27%	94,804%
Labeller	8203	12%	38%	95,013%
Filler	7273	10%	49%	95,579%
Bottle washer	7113	10%	59%	95,676%
EBI	5291	8%	66%	96,784%
Empty Container Conveyors	2550	4%	70%	98,450%
Full Container Conveyors	2447	4%	74%	98,512%
Crate washer	1950	3%	76%	98,815%
Crown Cork Supply	1849	3%	79%	98,876%
Tunnel Pasteuriser	1639	2%	81%	99,004%
Bulk Depalletiser	1162	2%	83%	99,293%
Empty Crate Stacker/Unstacker	914	1%	84%	99,445%
Palletiser	812	1%	85%	99,506%
Empty Bottle Crate Unpacker	695	1%	86%	99,577%
Empty Bottle Crate Conveyors	687	1%	87%	99,582%
Empty Bottle Crate Depalletiser	673	1%	88%	99,591%
Coders - Label	604	1%	89%	99,633%
Full Bottle Crate Carton Packer	579	1%	90%	99,648%
Full Crate Carton Conveyors	531	1%	91%	99,677%
Rest	272	0%	91%	99,834%
Full Crate Carton Inspector 1	249	0%	92%	99,848%
Crowner	246	0%	92%	99,850%
Empty Crate Inspector 1	236	0%	92%	99,856%
Flash Pasteuriser	231	0%	93%	99,859%
Pallet Strapper	187	0%	93%	99,886%
Beer Pump Buffertank And Distribution	182	0%	93%	99,889%
Returned Crate Inspector 1	158	0%	93%	99,904%
Empty Pallet Conveyors	119	0%	94%	99,927%
Multipack Conveyors	113	0%	94%	99,931%
Pallet Labeller	113	0%	94%	99,931%
Cip - System	98	0%	94%	99,941%
Decrowner	68	0%	94%	99,959%
Crate Labeller	58	0%	94%	99,964%
Full Bottle Inspector 1	56	0%	94%	99,966%
Full Pallet Conveyors	43	0%	94%	99,974%
Pallet Tierer Detierer 1	20	0%	94%	99,988%
Empty Pallet Robot	17	0%	94%	99,990%
Full Bottle Inspector 2	5	0%	94%	99,997%
Bottle Dryer	2	0%	94%	99,999%

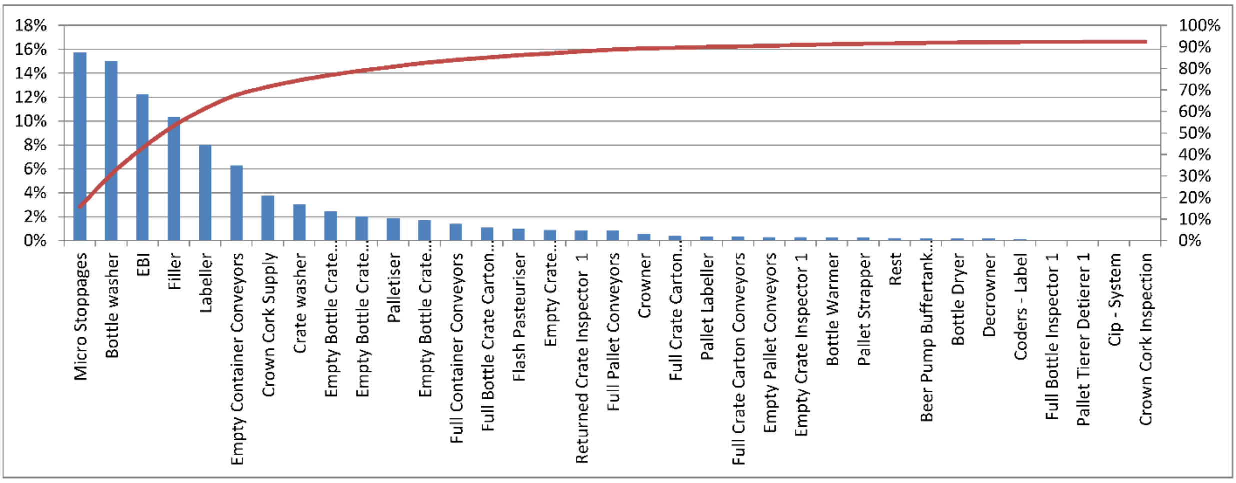
Total downtime (minutes)
69916,8087
Machine efficiency
57,5%



Line 3

Machine	Downtime (minutes)	Percentage of total downtime	Cumulative	Theoretical ME per machine
Micro Stoppages	7264	16%	16%	97,137%
Bottle washer	6942	15%	31%	97,264%
EBI	5666	12%	43%	97,767%
Filler	4774	10%	53%	98,118%
Labeller	3694	8%	61%	98,544%
Empty Container Conveyors	2899	6%	68%	98,857%
Crown Cork Supply	1747	4%	71%	99,311%
Crate washer	1410	3%	74%	99,444%
Empty Bottle Crate Conveyors	1122	2%	77%	99,558%
Empty Bottle Crate Unpacker	943	2%	79%	99,628%
Palletiser	857	2%	81%	99,662%
Empty Bottle Crate Depalletiser	810	2%	83%	99,681%
Full Container Conveyors	649	1%	84%	99,744%
Full Bottle Crate Carton Packer	512	1%	85%	99,798%
Flash Pasteuriser	471	1%	86%	99,814%
Empty Crate Stacker/Unstacker	408	1%	87%	99,839%
Returned Crate Inspector 1	401	1%	88%	99,842%
Full Pallet Conveyors	391	1%	89%	99,846%
Crowner	248	1%	89%	99,902%
Full Crate Carton Inspector 1	181	0%	90%	99,929%
Pallet Labeller	163	0%	90%	99,936%
Full Crate Carton Conveyors	142	0%	90%	99,944%
Empty Pallet Conveyors	136	0%	91%	99,946%
Empty Crate Inspector 1	133	0%	91%	99,947%
Bottle Warmer	129	0%	91%	99,949%
Pallet Strapper	126	0%	91%	99,950%
Rest	100	0%	92%	99,961%
Beer Pump Buffertank And Distribution	95	0%	92%	99,963%
Bottle Dryer	76	0%	92%	99,970%
Decrowner	75	0%	92%	99,970%
Coders - Label	45	0%	92%	99,982%
Full Bottle Inspector 1	23	0%	92%	99,991%
Pallet Tierer Detierer 1	16	0%	92%	99,994%
Cip - System	11	0%	92%	99,996%
Crown Cork Inspection	9	0%	92%	99,997%

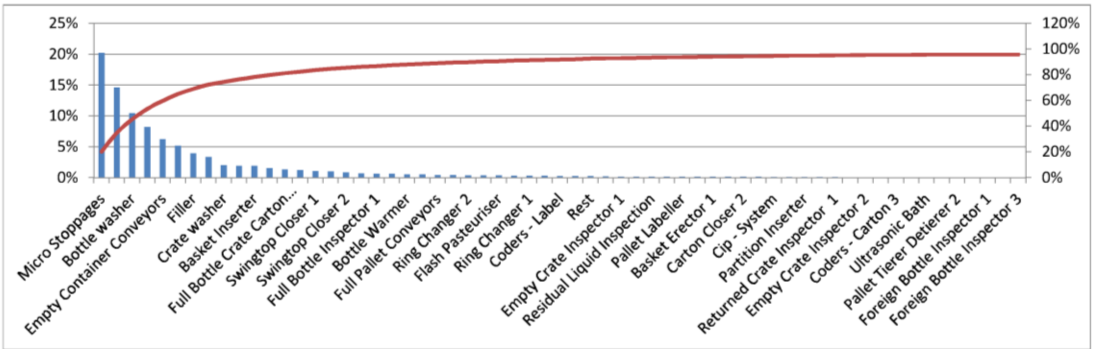
Total downtime (minutes)
46175,29001
Machine efficiency
81,8%



Line 4

Machine	Downtime (minutes)	Percentage of total downtime	Cumulative	Theoretical ME per machine
Micro Stoppages	11368	20%	20%	94,740%
EBI	8241	15%	35%	96,187%
Bottle washer	5904	11%	45%	97,268%
Labeller	4627	8%	54%	97,859%
Empty Container Conveyors	3514	6%	60%	98,374%
Carton Erector	2919	5%	65%	98,649%
Filler	2231	4%	69%	98,968%
Palletiser	1910	3%	72%	99,116%
Crate washer	1158	2%	75%	99,464%
Pallet Shrinkwrapper	1097	2%	76%	99,492%
Basket Inserter	1081	2%	78%	99,500%
Empty Bottle Crate Conveyors	879	2%	80%	99,593%
Full Bottle Crate Carton Packer	763	1%	81%	99,647%
Basket Erector 2	700	1%	83%	99,676%
Swingtop Closer 1	610	1%	84%	99,718%
Empty Bottle Crate Unpacker	587	1%	85%	99,728%
Swingtop Closer 2	486	1%	86%	99,775%
Empty Crate Stacker	412	1%	86%	99,809%
Full Bottle Inspector 1	363	1%	87%	99,832%
Ring Changer 4	358	1%	88%	99,834%
Bottle Warmer	318	1%	88%	99,853%
Full Container Conveyors	312	1%	89%	99,856%
Full Pallet Conveyors	239	0%	89%	99,889%
Swingtop Opener	239	0%	90%	99,889%
Ring Changer 2	228	0%	90%	99,895%
Carton Closer 1	226	0%	90%	99,896%
Flash Pasteuriser	217	0%	91%	99,899%
Empty Bottle Crate Depalletiser	204	0%	91%	99,905%
Ring Changer 1	189	0%	91%	99,913%
Bottle Divider	181	0%	92%	99,916%
Coders - Label	158	0%	92%	99,927%
Full Crate Carton Conveyors	157	0%	92%	99,927%
Rest	150	0%	93%	99,930%
Empty Pallet Conveyors	144	0%	93%	99,933%
Empty Crate Inspector 1	116	0%	93%	99,946%
Beer Pump Buffertank And Distribution	114	0%	93%	99,947%
Residual Liquid Inspection	112	0%	93%	99,948%
Pallet Strapper	111	0%	94%	99,949%
Pallet Labeller	98	0%	94%	99,955%
Full Crate Carton Inspector 1	96	0%	94%	99,956%
Basket Erector 1	93	0%	94%	99,957%
Coders - Carton 1	89	0%	94%	99,959%
Carton Closer 2	88	0%	94%	99,959%
Empty Crate Unstacker	87	0%	95%	99,960%
Cip - System	80	0%	95%	99,963%
Returned Crate Inspector 2	79	0%	95%	99,964%
Partition Inserter	66	0%	95%	99,969%
Full Crate Carton Inspector 2	61	0%	95%	99,972%
Returned Crate Inspector 1	59	0%	95%	99,973%
Bottle Dryer	54	0%	95%	99,975%
Empty Crate Inspector 2	47	0%	95%	99,978%
Coders - Carton 4	46	0%	96%	99,979%
Coders - Carton 3	33	0%	96%	99,985%
Carton Conveyors	30	0%	96%	99,986%
Ultrasonic Bath	28	0%	96%	99,987%
Ring Changer 3	26	0%	96%	99,988%
Pallet Tierer Detierer 2	22	0%	96%	99,990%
Pallet Tierer Detierer 1	12	0%	96%	99,995%
Foreign Bottle Inspector 1	8	0%	96%	99,996%
Basket Conveyors	5	0%	96%	99,998%
Foreign Bottle Inspector 3	2	0%	96%	99,999%

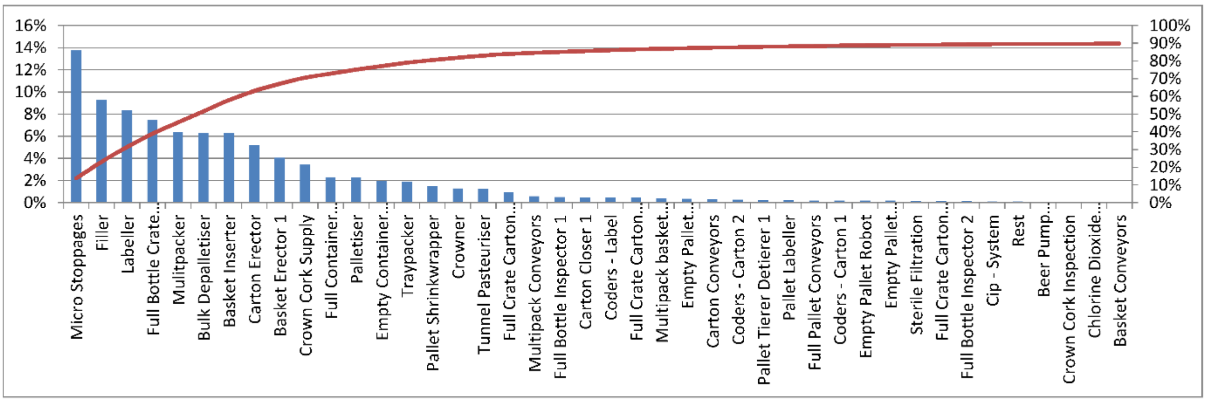
Total downtime (minutes)	56188,65807
Machine efficiency	74,0%



Line 7

Machine	Downtime (minutes)	Percentage of total downtime	Cumulative	Theoretical ME per machine
Micro Stoppages	7440	14%	14%	96,503%
Filler	5033	9%	23%	97,634%
Labeller	4498	8%	31%	97,886%
Full Bottle Crate Carton Packer	4041	7%	39%	98,100%
Mulitpacker	3437	6%	45%	98,385%
Bulk Depalletiser	3407	6%	52%	98,399%
Basket Inserter	3398	6%	58%	98,403%
Carton Erector	2810	5%	63%	98,679%
Basket Erector 1	2197	4%	67%	98,967%
Crown Cork Supply	1861	3%	71%	99,125%
Full Container Conveyors	1247	2%	73%	99,414%
Palletiser	1220	2%	75%	99,427%
Empty Container Conveyors	1055	2%	77%	99,504%
Traypacker	1039	2%	79%	99,511%
Pallet Shrinkwrapper	806	1%	80%	99,621%
Crowner	704	1%	82%	99,669%
Tunnel Pasteuriser	671	1%	83%	99,685%
Full Crate Carton Inspector 1	514	1%	84%	99,758%
Multipack Conveyors	313	1%	85%	99,853%
Full Bottle Inspector 1	280	1%	85%	99,868%
Carton Closer 1	261	0%	86%	99,877%
Coders - Label	252	0%	86%	99,882%
Full Crate Carton Conveyors	243	0%	86%	99,886%
Multipack basket Divider	205	0%	87%	99,904%
Empty Pallet Conveyors	186	0%	87%	99,912%
Carton Conveyors	157	0%	87%	99,926%
Coders - Carton 2	148	0%	88%	99,931%
Pallet Tierer Detierer 1	125	0%	88%	99,941%
Pallet Labeller	115	0%	88%	99,946%
Full Pallet Conveyors	110	0%	88%	99,948%
Coders - Carton 1	99	0%	89%	99,954%
Empty Pallet Robot	98	0%	89%	99,954%
Empty Pallet Inspector 1	98	0%	89%	99,954%
Sterile Filtration	84	0%	89%	99,960%
Full Crate Carton Inspector 2	71	0%	89%	99,967%
Full Bottle Inspector 2	70	0%	89%	99,967%
Cip - System	61	0%	89%	99,971%
Rest	58	0%	90%	99,973%
Beer Pump Buffertank And Distribution	40	0%	90%	99,981%
Crown Cork Inspection	18	0%	90%	99,992%
Chlorine Dioxide Dosing	15	0%	90%	99,993%
Basket Conveyors	13	0%	90%	99,994%

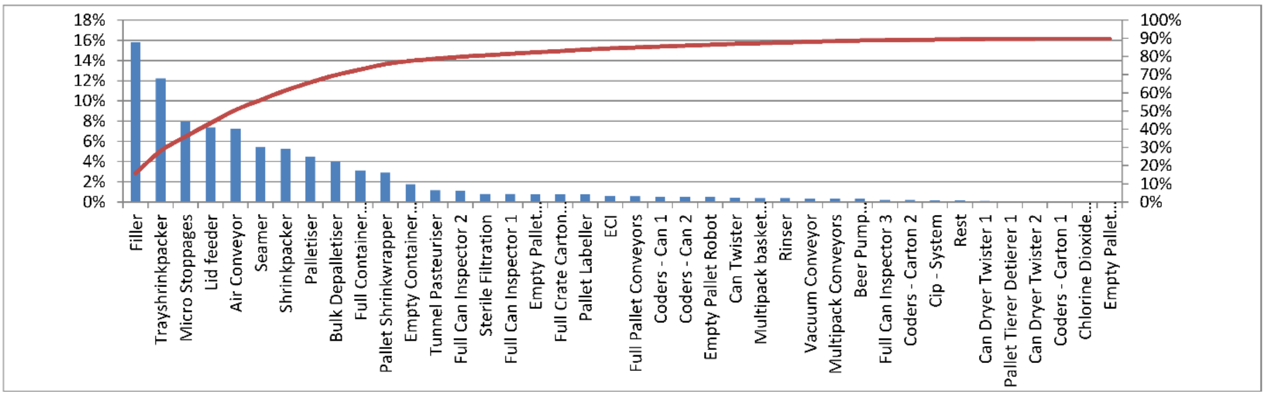
Total downtime (minutes)
54039,24519
Machine efficiency
74,6%



Line 8

Machine	Downtime (minutes)	Percentage of total downtime	Cumulative	Theoretical ME per machine
Filler	8072	16%	16%	97,632%
Trayshrinkpacker	6258	12%	28%	98,164%
Micro Stoppages	4047	8%	36%	98,813%
Lid feeder	3776	7%	43%	98,892%
Air Conveyor	3694	7%	51%	98,916%
Seamer	2798	5%	56%	99,179%
Shrinkpacker	2688	5%	61%	99,211%
Palletiser	2294	4%	66%	99,327%
Bulk Depalletiser	2025	4%	70%	99,406%
Full Container Conveyors	1607	3%	73%	99,528%
Pallet Shrinkwrapper	1488	3%	76%	99,564%
Empty Container Conveyors	907	2%	78%	99,734%
Tunnel Pasteuriser	601	1%	79%	99,824%
Full Can Inspector 2	582	1%	80%	99,829%
Sterile Filtration	412	1%	81%	99,879%
Full Can Inspector 1	404	1%	81%	99,881%
Empty Pallet Conveyors	393	1%	82%	99,885%
Full Crate Carton Conveyors	390	1%	83%	99,885%
Pallet Labeller	385	1%	84%	99,887%
ECI	324	1%	84%	99,905%
Full Pallet Conveyors	284	1%	85%	99,917%
Coders - Can 1	272	1%	85%	99,920%
Coders - Can 2	253	0%	86%	99,926%
Empty Pallet Robot	252	0%	86%	99,926%
Can Twister	219	0%	87%	99,936%
Multipack basket Divider	204	0%	87%	99,940%
Rinser	193	0%	88%	99,943%
Vacuum Conveyor	187	0%	88%	99,945%
Multipack Conveyors	172	0%	88%	99,950%
Beer Pump Buffertank And Distribution	171	0%	89%	99,950%
Full Can Inspector 3	105	0%	89%	99,969%
Coders - Carton 2	101	0%	89%	99,970%
Cip - System	87	0%	89%	99,974%
Rest	83	0%	89%	99,976%
Can Dryer Twister 1	58	0%	90%	99,983%
Pallet Tierer Detierer 1	42	0%	90%	99,988%
Can Dryer Twister 2	31	0%	90%	99,991%
Coders - Carton 1	28	0%	90%	99,992%
Chlorine Dioxide Dosing	15	0%	90%	99,996%
Empty Pallet Inspector 1	13	0%	90%	99,996%

Total downtime (minutes)	51124,9123
Machine efficiency	85%



Appendix G – interviews with subjects at Grolsch

This appendix shows a layout of the interviews I conducted with the people at Grolsch. First, the individual interviews are shown, then the commentary on the intermediate presentation is shown and lastly the FMECA sessions are summarised.

Conversation with Garma Stubbe (Quality Assurance Specialist), 22 May 2017, 12.45-14.00

Note: I spoke very shortly to Henk Rensink (Packaging Material Analyst) and Jitze Bakker (Quality System Manager) too

What happens to the beer when it is rejected, based on different reasons (legal, own)?
It is always destroyed. What the reason was does not matter, Grolsch wants a certain quality.

What is the difference between production decrease without loss and with loss of quality? (what happens to the beer? Sold for a lower price, destroyed, reworked?)
See previous question: destroyed. Unless it can be reworked, otherwise Grolsch cannot guarantee the quality.

What is IQMS brewing/packaging/micro?
IQMS is Integrated Quality Management System. It looks at the processes. Examples:

- IQMS micro: quality of the beer looking at microbiology (bacteria, yeast after filtration)
- IQMS brewing: sugar content, time, temperature, bitterness, oxygen
- IQMS packaging: washing, pasteurising, filling, sealing

On those criteria a certain score is given, all the scores together represent the IQMS. Note that IQMS is done in random sampling.

PPQA means Packaged Product Quality Assessment. In this assessment the quality of the packed products is determined: skew stickers, codes, dust etc

There are some CCP's (critical control points) which are investigated a lot right now. They are most of the time about food safety.

Find online: GMS (Grolsch Management System) with the standards book, Algemene Beheersmaatregelen (ABM)

Most of the time, the following applies: lower brand limit, lower limit, lower specification, target, upper specification, upper limit en upper brand limit. Different people for different limits/target determine whether a product can be sold or not.

Maybe calculate total amount of destroyed products (PPQA is dpmo, defects per million opportunities). How often are test bottles used? In other words, how much has to be destroyed when there is a blockade?

Quality tour with Henk Rensink (Packaging Material Analyst), 24 May 2017, 13.00-15.00

We have seen Line 3 (Premium pils, RB) and line 8 (cans). At line 3 we saw the EBI (Empty Bottle Inspector) which we discussed in the FMECA session before. We have seen a set of test bottles going through the EBI, and they were rejected. After going through the EBI a couple more times, the bottle finally was accepted. Every 30 minutes the testing bottles needs to go through the EBI. If the test bottle is not accepted within a couple of minutes, then the line will block. Line 3 has a line speed of 60.000 bottles per hour, so then 30.000 bottles will be blocked. Then will be checked which bottles can be

released, which bottles need to be reworked and which bottles have to be destroyed. Every line has its own speed, maybe I can do something with that. Numbers at Joost Nawijn.
We also went to Warehouse, but that was nothing special.

Conversation with Susan Ladrak (Engineering Manager), 30 May 2017, 10.30-11.00

When talking to people at Grolsch about FMECA, it is important to emphasize the importance of FMECA.

Safety: serious accident causing permanent injury should never be acceptable, according to Susan. Also talk with Eino Staman about this safety issue. Check the average number of incidents in the Netherland.

There is no budget for contingencies.

Conversation with Marcel Hems (Packaging Manager), 31 May 2017, 12.30-13.30

Meije has the lead on FMECAs, so for questions regarding FMECA, target Meije.

Line 1 (kegs) = not always occupied
Line 2 (special beer) = not always occupied
Line 3 (Grolsch premium) = 5 days a week, Saturday is meant for delays
Line 4 (swingtop) = every two weeks occupied
Line 7 (new bottles) = every two weeks occupied
Line 8 (cans) = always occupied, no room for delay
Line 24 (swingtop assembly line) = always occupied, defect = assemble manually, takes more time, higher costs

ME target is 85%, then 86, 87 and 90.
Best class target for line 8 is 90,6% and for Line 3 91,8%

The filler is almost always critical (slowest). There is a buffer in other machines, but that is not much (minutes)

V graph from each line, unit managers can give this V graph:
Brit Brons, unit 3
Jeroen Leus, unit 1
Mieke Mannak, unit 2
Paul Stol, unit 4

Capacity per Line (bottles/cans/kegs per hour):
Line 3 = 60.000
Line 2 = 60.000
Line 4 = 40.000
Line 8 = 72.000
Line 7 = 40.000
Line 1 = 300-400 (Weizen is lower due to fermentation process)
Line 24 = 4.000
Goal is to have no injuries causing sick leave. Every employee in Packaging needs to make three mentions of safety per year (safety in general: wet areas, no safety glasses etc.)

Independency of failures? Is there a causal relation between? Will the line stop producing?

Environmental regulations will make costs, but you can also look at sustainability.

How will you check the PM tasks/measures taken? At the moment, there is no checklist for.
What-if scenario for the top 3 machines which cause the most downtime.

Conversation with Ilco Kuiper (Maintenance Planner), 1 June 2017, 13.00-14.00

Problems with filling in the FEMCA:

- What will be the hierarchy? Do you use a OEM bill of materials, do you use the SAP hierarchy (why is SAP and OEM not always the same?) or do you make a layout yourself?
- Costs → just the costs of repair or do we include other costs as well? (costs of external mechanic, paid information/advice, but no reputational costs, because that is already included in the other variables)

Whether you need to fill in every component, depends on how well you know the machine.

Recommendation: make a selection of standard failure modes

Exact vs interval: in an early stage, intervals are fine, but when comparing to company goals, you better could use exact data.

MTTR should have categories above '> 24 hours'

Meije Lammers knows more about the weighting factors, he introduced FMECA at Grolsch.
Meije worked before at FrieslandCampina and they used FMECA over there.

Environmental categories are hard to interpret when having no knowledge about environment (violation of regulations). Martin Bosscher made the categories more understandable.

Ilco recommends to define actions/measures precisely (example: make PM task 11 on machine 420). If the task doesn't exist yet, it is easier to find out.

Categories in costs are way too high (> 150,000). But if costs will be filled in exactly, intervals won't be a problem anymore.

Conversation with Meije Lammers (Packaging Engineer), 2 June 2017, 11.00-12.00

The concept of FMECA has been explained clearly. First do a quick FMECA on brewery level to check which departments has the biggest risks. Then find out on department level where the risk is located (in packaging: what is the critical line?). Next, on production line level you are going to find the causes of the risks. Do this until you are on component level and you have found the root cause. Right now, an FMECA on the bottle washer of line 3 is made, but before that, the machine has been identified as critical by making a quick FMECA.
Important is that when doing an FMECA, the effects on the brewery needs to measures, and not on the machine.

The problem at Grolsch is that they wanted to do more proactive maintenance (risk based maintenance). They wanted to better map its risks, and therefore FMECA has been introduced. Currently approximately 90% of maintenance is corrective maintenance.

In Packaging the utilisation factor (the amount of time the department is in use) is very low (35%). There are no real production availability issues. Meije lowered the boundary levels a bit to find some problems.

Follow-up conversation with Meije Lammers (Packaging Engineer), 12 June 2017, 10.00-11.00

I got more information about the risk matrices and the goals. Usually an FMECA agency delivers a basic matrix which is uniform for the industry. This matrix will then be reviewed by the unit managers to check if it is realistic for them and the matrix is changed where necessary.

Conversation with Eino Staman (SHE specialist) and Martin Bosscher (Manager Utilities), 12 June 2017, 16.15-17.00

In general the current categories and weights for environment are fine. There is no summation, since an environment violation is taken independently by the municipality if it is caused by different machines. So the current matrix can be used on machine level, but not on component level. The categories cannot be summed up together, but for each category there is an acceptability level per machine. So the MTTF needs to be summed up per severity category and judged on machine level.

Eino and Martin mentioned that environmental failures with impact on the outer world is acceptable if it happens less than once per 3 year. So categories might have to change.

Conversation with Garma Stubbe (Quality Assurance Specialist) and Rob Leurink (Supervisor and Asset Care Engineer), 13 June 2017, 16.00-17.30

Beer quality complaints at packaging are due to brewing and will be seen in the scores of brewery.

Blocked products is total amount of products eliminated due to a problem
Blockades are the products eliminated from the line, divided into re-brewed, sold or destroyed.

In PLC-KPI (Operations Weekly/Monthly report), these blockades and other KPIs can be found (more detailed). Stefan Fransen is the one responsible for this sheet.

Consumer Index (CI) is a brewing thing.

There is a trade-off between costs and buying a new or extra machine.

Smile is a system which keeps track of the customer complaints. In Smile you can see the different categories of failure modes.

Process steps HACCP, quite similar to FMECA.

Do we want to include reputational damage? Marketing top 5?

Maybe we have to redefine our categories, like environment:

- Quality complaints regarding food safety outside the brewery
- Quality complaints outside the brewery

- Quality complaints inside the brewery with rejection of products
- Quality complaints inside the brewery without rejection of products
- No quality complaints

Check GMS → HACCP wetgeving

Conversation with Bart Velner (Commercial Finance Manager) and Rob Leurink (Supervisor and Asset Care Engineer), 15 June 2017, 10.00-11.00

There is no budget for inconveniences, it would be the first budget to be cut down. There is also no necessity to have one. Other budgets are somewhat larger budgeted to compensate for inconveniences.

There is a maintenance budget, where costs are divided into corrective maintenance, preventive maintenance and breakdowns. This can be used as a goal per machine.

Where do we want to include insurances? (Frank Svenhuis, Marco Gerritsen)

Take external costs of a breakdown into account (external mechanic, express delivery)

General database for costs → manufacturer of the parts has a spare part recommendation, probably depending on the working hours of the machine. Watch out for obsolete stock (incourantie)

Conversation with Wilco Hekkert (Senior Account Manager Food and Beverage at MaxGrip) and Rob Leurink (Supervisor and Asset Care Engineer), 15 June 2017, 11.30-12.30

The company gets a basic matrix from MaxGrip, which is an example of another brewery or company in the food/beverage market. This basic matrix needs to be tuned to fit the company. Maybe multiple matrices needs to be made, but this is not recommended.

Guide risk boundaries/matrices: done by management and/or technical service.

It is opinion based, need to be more objective

1. To what level will I go?
2. Balance detail level
3. For adding you almost need software

Get into depth based on Pareto

Include all direct costs, excluding costs already represented by the effect categories.

Conversation with Eino Staman (SHE Specialist), Paul Somers (Maintenance Planner) and Rob Leurink (Supervisor and Asset Care Engineer), 19 June 2017, 10.00-11.00

A lot of RI&Es (Risk Inventory and Evaluations) are already made looking at safety. Just look at some RI&Es to get the feeling.

In the company goals, there is just one target on ‘disabling injuries’, while the FMECA makes a differentiation in duration of the disabling. Grolsch makes a distinction in disabling injuries using differ and disser. The differ is based on working hours (on a machine which operates full time, there is a higher chance on an accident than on a machine which operates part time). The disser makes a distinction in duration of the injury.

Eino mentioned that most of the safety issues are caused by human failures. He estimated that 95% is due to human failure and just 5% is due to mechanical failures.

Think bigger than just machines in an FMECA. Also pipes and depositories of dangerous substances should be taken into account.

Conversation with Ilco Kuiper (Maintenance Planner), Paul Somers (Maintenance Planner) and Rob Leurink (Supervisor and Asset Care Engineer),19 June 2017, 13.00-14.00

In a production line, there is some buffer time. Not every stop results in a line stop. Micro stops are stops with an MTTR of less than 3 minutes. Those stops are considered to have no impact in general.

In Brewing, Utilities and Warehouse, production availability is not a problem/target. There is a lot of redundancy in those departments (especially in Brewing/Utilities) and a production stop in those departments does not necessarily result in a production stop in Packaging. In Packaging it is a target, so it might be a good idea to link production stops in Utilities/Brewing/Warehouse to production availability in Packaging. A part of service stops in Packaging (affect FE) is caused by other departments. So new production availability categories can be something like:

- 100% stop packaging
- 70% stop packaging
- 30% stop packaging
- Stop in brewing/utilities/warehouse
- Loss of redundancy
- No effect

Conversation with Stefan Fransen (Operations Reporting Specialist), 20 June 2017, 9.30-10.30

Weekly operations report and monthly operations report, monthly is somewhat more reliable (more formal, looked over some times).

Things to take into account: when packaging is ahead on schedule and supply from other departments is on time, packaging can act like the supplies are too late (the line is down for a while), but that is because packaging is ahead on schedule.
Another thing is that you can argue that there might be too little mechanics. Then the MTTR will increase. Probably for the FMECA it is the best to assume that there is an infinite amount of mechanics available.

Micro stops is everything less than 3 minutes.

Conversation with Sander Janssen (Senior Specialist at MaxGrip) and Rob Leurink (Supervisor and Asset Care Engineer), 21 June 2017, 11.00-12.00

Objectifying FMECA

Sander answered some questions regarding the interpretation of results and the measurements. He said it could be useful to have a decision tree for choosing measures (preventive inspection, preventive replacement, modification, spare parts etc.). Modification usually results in a lower MTTF and a smaller effect, spare parts result in a lower MTTR. He further split up MTTR in reaction time (detection, hard to reach, maybe take an average if necessary), delivery time (take the regular delivery time, not express mail) and repair time. This makes it easier to determine the measure to be taken. He also did not recommend having a lot of spare parts, due to costs and possible obsoletes.

Component vs system (add up)
Sander did not recognise this problem. He only acknowledged it with availability. He also said that sometimes if there are many parts close to the boundary level, he would take action.

Process mechanical industries (brewery/utilities vs warehouse/packaging)
There is a difference, but this will be visible in the FMECA. In the process industry many measures are already taken due to safety and other regulations. Furthermore, there is usually more redundancy in the process industry (in parallel) then in mechanical industries (in series). So, do not make another matrix for these industries; you have to do more maintenance in mechanical then in process industries.

Excluding machines
Simulating usually results in a top 10 or top 5 of machines which are critical to the system.
Another way to select machines is doing a quick FMECA which is a bit more abstract. The focus should really be on technical failures.

Tips for conducting an FMECA
- Use exact numbers instead of intervals for MTTF, MTTR and costs. Sometimes it is hard to estimate, then an average can be taken. Probing questions are really important in estimating. Just name a quite low or high number and people will be doubting. Constantly suggest new numbers and finally you will come up with a number. Most of the time costs can be looked up, and MTTF can sometimes be retrieved from the manufacturer of the parts/machines.
- MTTF is really important, this is a factor contributing a lot in your FMECA. Try to estimate this as correctly as possible.
- Always think of the worst case scenario, but using the current maintenance plan.
- Use a situation sketch (what if) in FMECA sessions: what if this component would fail right now? This will make it more tangible for the people in the session.
- Make the translation from a corporate matrix to a matrix for FMECA where only mechanical failures are taken into account.
- Use P&ID and tag list (function) instead of BoM (parts) or observation (forgetting things)

Intermediate presentation, 5 July 2017, 15.00-17.30

Present: Rob Leurink (Supervisor and Asset Care Engineer), Ilco Kuiper (Maintenance Planner), Marcel Hems (Packaging Manager), Ruud van Westen (Maintenance Planner), Stefan Fransen (Operations Reporting Specialist), Paul Somers (Maintenance Planner)
Human failures in downtime? Maybe approach the same way as safety
What is the difference in duration at environment between long term and short term?
You took the mean of the intervals. The mean, mode and median can differ, and sometimes mode/median is better than mean → by filling in the MTTF/MTTR/costs exactly, this is not a problem anymore.
People were very positive on the theoretical machine efficiency.

FMECA sessions

EBI Line 3 (empty bottle inspector)
23 May 2017, 13.00-15.00

Ruud van Westen – Maintenance Planner – FMECA leader
Jacquelien Aldenkamp Stokkingreef – Shift Teamleader Packaging
Jos Loskamp – Line Operator Packaging

Marcel and Meije (and the unit managers) have determined the weighting factors and boundary levels.

They do not ignore everything that stay green. If everyone thinks that something has to be done, then a measure will be taken.

Only mechanical failures.

Method until now:
- Identify main parts (in an office)
- Identify sub parts (in an office)
- Check if we miss pieces (on the line)

Vaguenesses:
- What do you fill in when there are multiple pieces of a component?
- What will be the depth on component level?

Template and differences:
- Data validation disappears
- Add general part of a machine
- Hierarchy in the template
- Global → detailed: can we say something on machine level about the variables? Are there on machine levels variables we already can exclude? Environment in Packaging, availability in brewing, quality in packaging, environment in warehouse etc.)

Questions:
- Can we estimate exact numbers?
    - Will be hard, intervals are fine up to now.
- Why do you make your own "bill of materials"? It takes a lot of time
    - Most of the time, a BoM does not mention the parts in sequence
    - Too small component levels
    - Names in BoM are not known to everyone: abbreviations etc.

Bottle Washer
30 May 2017, 13.00-15.00
Ruud van Westen – Maintenance Planner – FMECA leader
Richard Stein – Shift Teamleader Packaging

FMECA is now used to be conscious of what could happen, not judging based on the acceptability according to the tool, but according to the people themselves.

Maybe a trade-off between costs of preventive maintenance and corrective maintenance can be made.

MTTR > 24u as highest category is too low. One category above (more than 1 week) would be desirable.

Safety: Ruud, as well as Susan, thinks that a serious incident causing permanent injury should never be allowed.

EBI Line 3 (empty bottle inspector)
13 June 2017, 13.00-15.00
Ruud van Westen – Maintenance Planner – FMECA leader
Jacquelien Aldenkamp Stokkingreef – Shift Teamleader Packaging
Jos Loskamp – Shift Operator Packaging

Maybe we have to make different matrices per line/department: line 3 for example just operates Monday to Friday and has Saturday and even Sunday for delays. Line 8 does not have any room for delay, since they produce 7 days a week.

Appendix H – Manual for using the FMECA

Note upfront: this manual is based on the original FMECA template, as provided by Grolsch in May 2017. When the template is changed, this manual should be changed a bit too.

Preparing the template

First the template needs to be prepared. Every machine has other objectives which need to be used in the FMECA. The acceptability on Production Availability is based on the Machine Efficiency and the acceptability on Costs is based on the maintenance budget.

Step 1

The first step in preparing the template, is adjusting the boundary levels of Production Availability and Costs to the specific machine under investigation. Once the boundary levels are calculated, they can be filled in in the Excel tab "Bedrijfsdoelstellingen" of the FMECA template. The boundary levels can be determined as follows:

Boundary level Production Availability for a machine in Packaging

$$Boundary\ level = (1 - Theoretical\ ME) * Machine\ Hours\ per\ year * 30 * 20 * 17$$

The Theoretical ME can be found in the Excel sheet "Theoretical ME per machine".

For example: according to the Excel sheet "Theoretical ME per machine" the Filler on Line 8 needs to achieve a ME of 97.632% when Line 8 needs to achieve 85% ME. The machine hours of Line 8 in 2016 were 3850 hours. In this case the boundary level for the Filler on Line 8 in 2016 is calculated as follows:

$$Boundary\ level\ Filler\ Line\ 8 = (1 - 0.97632) * 3850 * 30 * 20 * 17 = 929{,}914$$

Boundary level Production Availability for Warehouse, Utilities or Brewing

$$Boundary\ level = PFH\ Packaging\ per\ year * allowed\ percentage\ of\ PFH * 30 * 20 * 100$$

The allowed percentage of PFH depends on the department:

Department	Percentage of PFH (%)
Warehouse	1.5
Utilities	0.3
Brewing	0.4

For example: in 2016 the Paid Factory Hours (PFH) of Packaging were 28,991 hours. The boundary level for Brewing is calculated as follows:

$$Boundary\ Level\ Brewing = 28{,}991 * 0.004 * 30 * 20 * 100 = 6{,}957{,}840$$

Note that this boundary level is a boundary level for the whole department. If you want to do an FMECA on a specific machine in Utilities, Warehouse or Brewing, then the impact of that specific machine on the total downtime needs to be estimated. The boundary level for a specific machine will then be:

$$Boundary\ level\ individual\ machine = boundary\ level\ department * impact\ of\ machine$$

For example: the downtime in Packaging caused by Brewing, is caused for 2% by machine X in Brewing. The boundary level for machine X will be:

$$Boundary\ level\ machine\ X = 6{,}957{,}840 * 0.02 = 139{,}157$$

Boundary level Costs

$$Boundary\ level = maintenance\ budget * 30$$

The maintenance budget is the budget available for the machine, line or department on which the FMECA is executed. The maintenance budget should be filled in as euros.

For example: the maintenance budget of Line 8 of Packaging in 2016 was [redacted]. The boundary level for Line 3 in 2016 is calculated as follows:

$$Boundary\ level\ Line\ 3 =$$ [redacted] $$* 30 =$$ [redacted]

Step 2

The second step is writing down all the components of the machine. If there are multiple equal components working parallel, write it in one row, with the amount of components in brackets, e.g.: chain-wheel (58x).

Executing FMECA

Now the template needs to be filled in. It is important to keep the following starting points in mind:

1. Only address technical failures. Human failures are excluded.
2. Fill in the effects based on current maintenance
3. Think of worst case scenarios if a component breaks down

Step 3

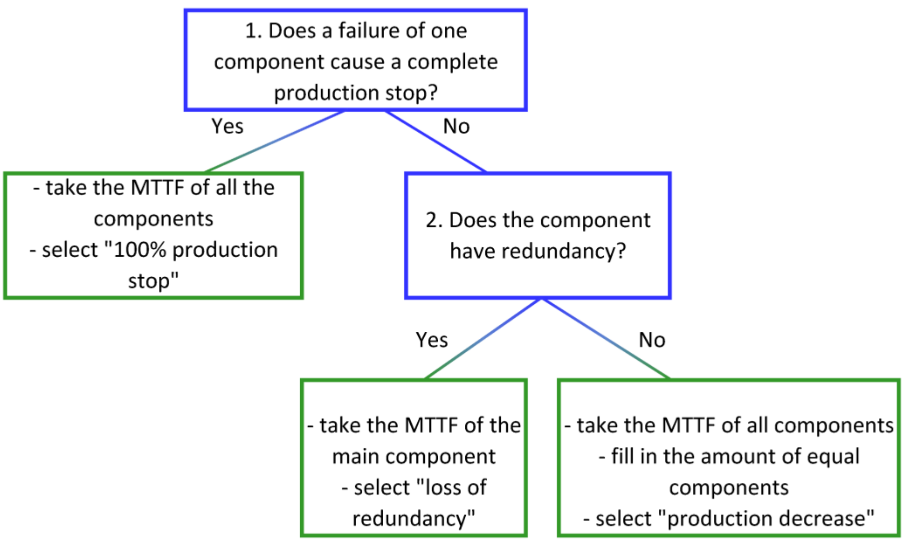
Then all the effects on the variables (MTTF, MTTR, Safety, Environment, Quality, Production Availability, Costs) needs to be filled in. There are some vaguenesses which are clarified here.

MTTR

The MTTR is the total downtime, from failure until working again. This includes the following five stages: detection, problem analysis, delivery time of the component(s), repair time and validation time.

Equal components

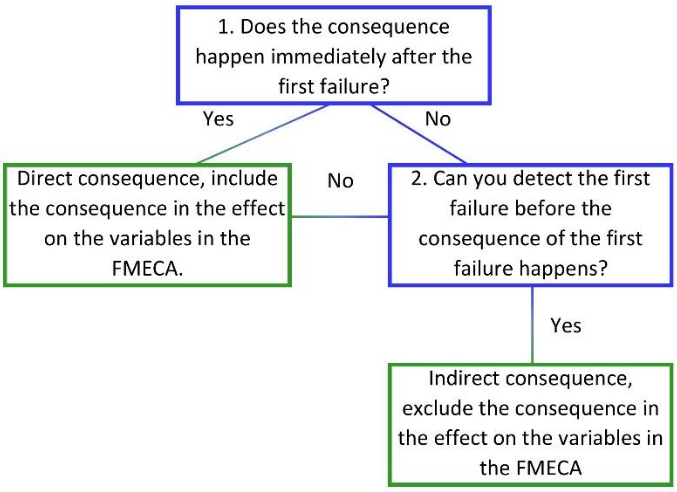
It is possible that there are multiple components in parallel, like the chain-wheels in step 2. The decision tree below explains what to do in the different cases.



For example: there are 10 components which have each an MTTF of 1 year. If each component can cause a complete production stop, take the MTTF of all components together: 1 / 10 = 0,1 year. If the failure of one component causes a production decrease, again the MTTF of all components needs to be taken (0,1 year) and the number "10" needs to be filled in at the number of equal components. If 1 of the 10 components is working and the other 9 components are stand-by in case of failure for the main component (redundancy), then the MTTF of the main component needs to be taken: 1 year.

Consequences

What consequences of the failure need to be included? The decision tree below will give an answer.



Costs

The last vagueness is about costs. What to include in costs? All the direct costs should be included in the FMECA, but costs which are already in other variables, should be excluded. For example, reputational damage from quality is already included in the highest category of Quality and costs of downtime is already included in Production Availability. Examples of costs which should be included are material costs, costs of external mechanics, overtime bonus, external advice etcetera. Note: whether a cost is direct, should be the outcome of the decision tree above.

Criticality analysis

Every variable has its own criticality analysis. This is divided into an analysis on component level, on machine level, on line level and on department level:

Variable	Level of criticality analysis
Safety	Component
Environment	Machine
Quality	Component
Production availability	Department / machine
Costs	Department

Step 4

Make a criticality analysis per variable using the following methods:

Safety and quality can be judged on component level. Because the analysis give an acceptability of the risks on component level, the scores of the variables does not need to be added up.

All the environment scores of one machine need to be added up, because the analysis gives an acceptability of the risks on machine level. The summation needs to be lower than the boundary level of environment.

If an FMECA is conducted on a machine in packaging, then all the scores of a machine of Production Availability needs to be summed up and they need to be lower than the boundary level. If an FMECA is done in Warehouse, Utilities or Brewing, there needs to be a distinction between department and machine. In step 1, the boundary level is determined, either for the whole department or for an individual machine. The scores of Production Availability needs to be summed up either on machine level or on department level, corresponding with the boundary level defined in step 1.

The scores of costs needs to be added up to department level and it needs to be lower than the boundary level.

Selecting measures

Step 5

If a component is not acceptable, then a measure needs to be taken to reduce or take away the risk. To make a more objective approach of selecting the measure, the following decision tree should be used: