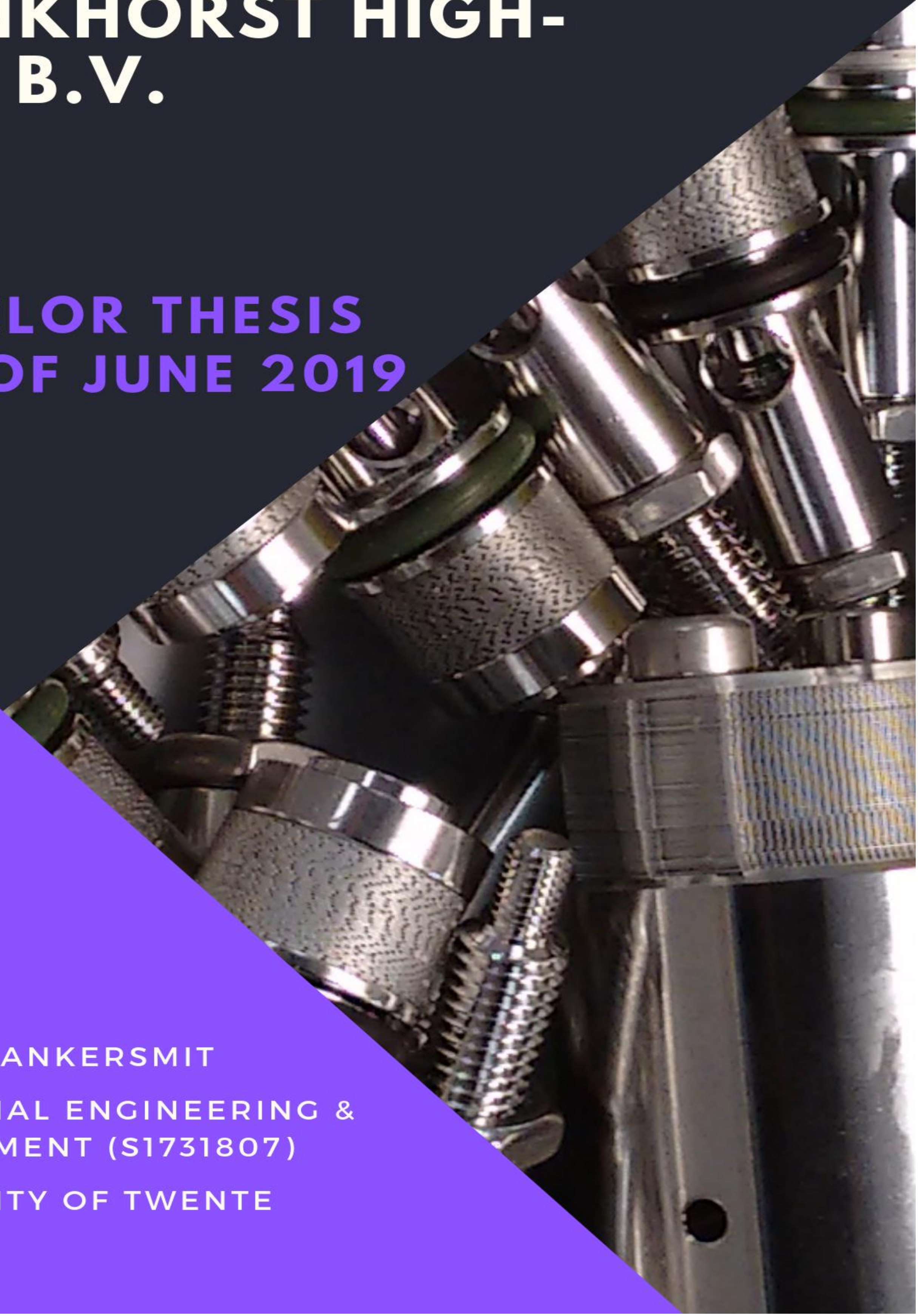
ANALYSING AND OPTIMIZING THE ASSEMBLY PROCESS OF LFE PACKAGES AT BRONKHORST HIGH-TECH B.V.

BACHELOR THESIS
25TH OF JUNE 2019



DESIREE ANKERSMIT

INDUSTRIAL ENGINEERING & MANAGEMENT (S1731807)

UNIVERSITY OF TWENTE

ANALYSING AND OPTIMIZING THE ASSEMBLY PROCESS OF LFE PACKAGES AT BRONKHORST HIGH-TECH B.V.

Bachelor thesis

Publication date: 25-06-2019

Student
D.K. Ankersmit (Desiree)
Industrial Engineering and Management
University of Twente

First supervisor
Dr. ir. W.J.A. van Heeswijk (Wouter)
University of Twente

Supervisor Bronkhorst High-Tech
T. Smith Bsc. (Thomas)
Process engineer
Bronkhorst High-Tech

Second supervisor
Dr. ir. L.L.M. van der Wegen (Leo)
University of Twente

Management summary

This thesis is done for Bronkhorst High-Tech in the process engineering department. Bronkhorst High-Tech produces flowmeters which consist out of multiple parts including an LFE package. The LFE package consists out of a number of stacked disks with grooves on one side. It determines the flow capacity of the flowmeter.

Problem statement
Bronkhorst has been having some issues with their delivery reliability which caused them to have a look at several production processes. One of the processes that stood out as seemingly very inefficient was the assembly of LFE packages. With a reject rate of approximately 4.5% and production being done manually it indeed seemed like there was potential for improvement. So the following goal was set:

The thesis will aim to provide the company with an alternative process design for the assembly of the LFE packages. This alternative design should halve the current reject rate, preferably getting the reject rate as close to the target of 2% as possible, and reduce assembly times by 15%.

Research
To get a better grasp on the current situation the process was analysed, showing several things. The assembly times consist for a significant part out of necessary but non value adding time, ranging from 15% for the easier packages to 55% for the larger packages.

The other issue, the rejects, were not what they at first seemed. It was expected that the rejects were caused by miscounted and misoriented LFEs, it turned out that those are almost not an issue at all. 77% of the rejects were seemingly caused by variation in the LFEs. This variation, caused by the manner in which the LFEs are produced, interacts with the variation found in the bodies where the package is mounted in.

In addition to the findings on the assembly times and the rejects, it was also apparent that the task of assembling the LFE packages had some other issues. The task consists out of many repetitive movements and is done for hours on end, increasing the risk of RSI. The employees do not seem to enjoy the task.

From ideas in the company and literature alternatives were formulated to address (some of) the problems associated with the LFE assembly process. Of these ideas an alternative way of supplying the LFEs got the best score in the assessment. This new supplying method would entail that the LFEs are supplied on a rod, pre-oriented and in a specific number.

Results
Based on the findings of the analysis and depending on the exact form that the new supplying method is going to have the savings could be as high as 46% in regular labour time and 77% in rework labour time. Although the savings in rework (rejects) would remain to be seen, as the problem turned out more complex than first thought.

Conclusion
The potential time savings turned out to be much greater than first thought. While it remains to be seen if the variation can be sufficiently tackled to reach the goal of a maximum reject rate of 2%, the aspect of time as set in the goal (15% savings) can be accomplished rather easily. The time savings could be as high as 46%.

Preface

Before you lies my thesis called: "Analysing and optimizing the assembly process of LFE packages at Bronkhorst High-Tech b.v.". This thesis forms the finalization of the bachelor industrial engineering and management at the University of Twente. The project was executed for the process engineering department at Bronkhorst High-Tech located in Ruurlo. In this research the assembly process of LFE packages is analysed, alternatives and improvements are identified and finally an advice is given on how to improve the process.

I would like to take this opportunity to thank my supervisors from the University of Twente, Wouter van Heeswijk and Leo van der Wegen for their guidance. Both of them helped, with their advice and knowledge, to get this project off to a good start. The feedback sessions were always short and to the point, but never rushed, which was an ideal fit for me.

I would also like to thank my company supervisors, Thomas Smith and Tom Melsen, from Bronkhorst High-Tech for their support. They have made me feel welcome, provided precious insights during our feedback meetings and gave me the freedom to execute the project in an individualistic manner.

Of course the colleagues from production department TGP1 cannot be left out. They provided me with the opportunity to collect data which was critical to the analysis of the current assembly process. Every member of the department was prepared to be subjected to questions, time measurements and a curious trainee looking over their shoulder. They have formed the fundament where this research is built upon.

Lastly I would like to thank my family for their unconditional support.

I hope you will find this thesis an interesting read.

Desiree Ankersmit, June 2019

Contents

Glossary of terms

5S	Sort, Straighten, Sweep, Standardise & Sustain
BHT	Bronkhorst High-Tech
Cobot	Collaborative robot; robot used in unison with human workers
Delivery reliability	Percentage of orders shipped on time. Calculated by dividing the number of orders shipped on or before the confirmed shipment date by total number of order that should have been shipped on that date
DPMO	Defects Per Million Opportunities
Flowmeter	Instrument used to measure flows of either gasses or liquids
GWO	Groep Werk Overleg; Group work discussion. Meetings with the goal to communicate important information with the organisation
Kan Ban	Material controlling method used in pull systems
Lean	Methodology advocating the elimination of waste
Lean green belt	Qualification earned for completing a project (worth a certain amount in savings) using lean knowledge and tools
Lean yellow belt	Qualification earned for knowledge about lean concepts and tools
LFE	Laminar Flow Element
LFE package	Part of a flowmeter that determines the flow capacity
Mock-up	A physical model used for visualizing and trying out the design
NNVA	Necessary but Non Value Adding
Pareto analysis	Analysis that assumes that 20% of the causes are responsible for 80% of the issues
Poka-yoke	Lean fail-saving method
Reject rate	Percentage of products that do not adhere to specifications
Scrap	Materials that are deemed unusable and are disposed of
TGP	Thermal Gas Products
VA	Value Adding
WIS	Worker Information System

1 Introduction

In this chapter introductions will take place. First the company and responsible department will be introduced. This is followed by their motivation to tackle the issues regarding the LFE assembly process, this includes their description of the problem. The issues are put in context with one another and a core problem is identified. Lastly the approach for tackling the core problem is explained.

1.1 Bronkhorst High-Tech

This section will provide some background information on Bronkhorst High-Tech as a whole and specifically about the engineering department. This department carries the responsibility for this project.

1.1.1 The company

Bronkhorst High-Tech based in Ruurlo, The Netherlands, produces customer-specific low flow fluidics handling solutions. They make these flow meters and controllers for both gasses and liquids. They are an international company with sales and support offices in several foreign countries like Germany, Japan and the United States of America. Their products are used in a wide variety of industries, including but not limited to the semiconductor industry, the food-pharma industry and healthcare industry.

Bronkhorst High-Tech was formed in 1981, in the past 38 years the company has grown significantly with currently approximately 450 employees at the headquarter in Ruurlo. The growth can also be seen in the expansion of the production site (for a complete overview see appendix A), currently the production site has a total area of around 35.000 m^2, this does not include their most recent purchase of another 5.300 m^2.

Apart from producing the flow meters Bronkhorst High-Tech also provides several services, among others maintenance and support. But perhaps the most remarkable service the company provides is the product training, Bronkhorst High-Tech has training facilities for their customers to help them understand and work with the equipment. They offer these services for their current products, but also for their older products that might still be in use by some clients. For example ASML prefers to keep using their older versions of the flow meters since their production processes are very sensitive to any kind of change. These services not only ensure that customers might choose Bronkhorst over one of her competitors, it also reflects the company's desire to deliver a quality product and the pride it takes in doing so.

The company has adopted the Lean methodology as a way to continuously improve. Employees are required to follow a Lean yellow belt course provided by the company and they are also encouraged to take on a Lean green belt project. In production the Lean concepts of Poka-yoke (eliminating the possibilities for mistakes) and Kan Ban (having materials and tools readily available) can be found, for example tools are labelled and materials get replenished throughout the day. Since Lean is highly thought of and endorsed in the company and is a methodology fitting with Industrial Engineering and Management it will also form the theoretical backbone in this project.

1.1.2 The engineering department

The engineering department takes care of the processes within Bronkhorst High-Tech. There are, basically speaking, three different types of engineers in the department; the process engineers, the line engineers and the quality engineers. The process engineers investigate possible improvements for current processes, (re)design processes and design tooling. The line engineers are responsible for the production line and provide technical support to (after) sales. The quality-engineers provide support to production if there are technical difficulties with either the product or the process. They also implement improvements, do research and investigate technical abnormalities to prevent production from shutting down. The engineering department is also responsible for the production of tooling (both hardware and software) and for the methodical development of new processes and improvement upon existing processes.

In the department there is currently another project going on concerning a new type of production cell. In this new production cell all production steps are to be performed, including assembly, testing and calibration. There is already a prototype of this cell in one of the production halls, it is not operational yet and serves, at this moment, more the purpose of a mock-up; a way to visualize and try out the design. In the current plans a “cobot” - a robotic arm that is meant to do the calibration and end test - is incorporated in the design of the new production cell. They are also investigating other uses for the cobot.

1.2 Motivation

Currently Bronkhorst faces some issues concerning their delivery reliability (their capacity to deliver orders on time). Approximately 25% of the orders are not delivered as agreed upon, see also appendix B. This is caused by the throughput time of their products being too long. The production of Flowmeters follows generally speaking the following steps as depicted in Figure 1-1.

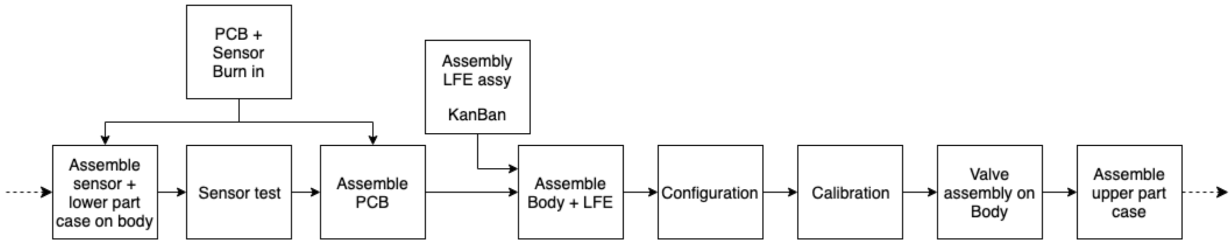


Figure 1-1. Flow chart production of flowmeters

For a complete overview of the process starting from "Order" up until "Order completion" see appendix C. The assembly of LFE packages, the assembly of the sensor and calibration are, relatively speaking, the most time consuming steps. The sensor assembly is being tackled in the project concerning the new production cell. The calibration of the flowmeters is going to be altered in the near future. That leaves the LFE package assembly process to be taken on, as also requested by the company.

The company identified the following problem: The current LFE package assembly process does not seem efficient and is prone to human mistakes. The stacking of LFEs is currently done by hand, all the sub processes take a substantial amount of time. There should be alternatives to stacking them by hand that save time and make the process less prone to mistakes. Possible solutions might be using a robotic arm to stack the LFEs or to discuss with the supplier of the LFEs if there are possibilities to get the LFEs delivered in readymade packets. All the sub processes are currently sensitive for human mistakes, especially if the employee working on the LFE packets loses some focus. People might miscount when picking the right number of LFEs out of the container. Also, the LFEs might stick together a bit, possibly causing problems with both the number of LFEs and the orientation of them. As stated in §1.1.2 the engineering department is working on a new type of production cell for the production of flow meters, this has to be taken into account in this project.

1.3 Problem context

The starting problem that was given states that the assembly process of the LFE packages is inefficient. To effectively connect the underlying problems to the inefficiency of the process there needs to be a clear definition of what inefficient actually means, for it is not just a feeling. *"Inefficiency; failure to make the best use of time or resources"* (Oxford University Press, 2019). This definition fits the problem like a glove, there are indeed issues with time and quality in the assembly process. The cycle time is too long and extra costs are attributed to the assembly process due to defects in the LFE packages. Time is lost in the process in several ways; the right materials and tools are not always readily available at the workstation putting the entire process on hold before it has even started. The assembly process contains steps that would have been redundant if the LFEs where supplied in a more practical manner. Due to these extra process steps, the fact that mistakes are easily made (not Poka Yoké) and that the assembly process has not changed in the last decade to conform to the new demands (more variety, more orders), the process is sensitive for human mistakes. Which brings us to the second part of inefficiency: Resources. When mistakes are made during assembly of the LFE packages the flow meters will not be up to spec. These defects in the LFE packages have to be reworked resulting in additional costs (labour, scrap if the defect is too severe or when there is no time to rework, additional materials, etc.) and time. To visualize these problems and their relationships a problem cluster was made, see Figure 1-2.

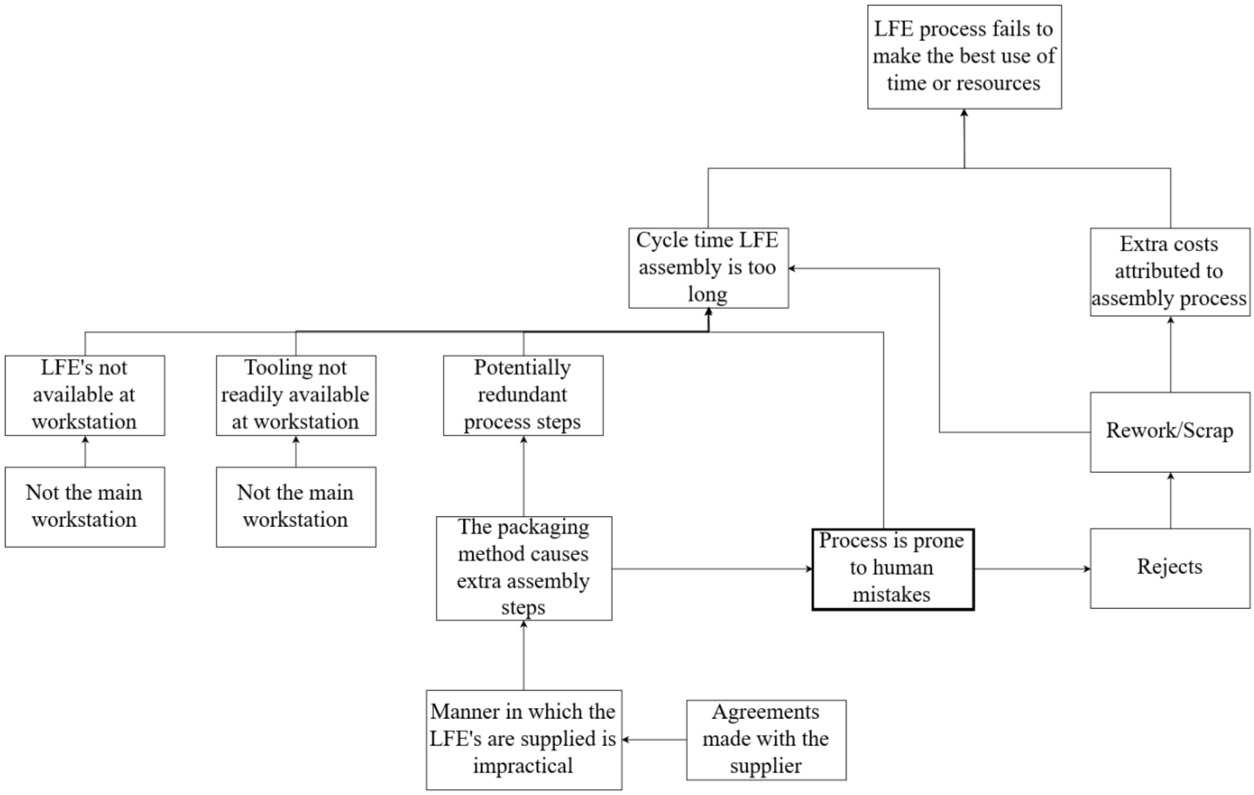


Figure 1-2. Problem cluster

1.4 Core problem

In the problem cluster several potential core problems can be identified. Due to the time limit associated with a bachelor assignment not all problems can be tackled, one of the problems will be chosen to be the main focus of the thesis. To narrow down the wide array of potential core problems some options will be eliminated.

The issues concerning the availability of materials and tools only have a small effect on the initial problem. There is definitely time to be won here, but that won time will only be in the set-up time, not the production time itself. Set-up occurs only once for maybe 20-30 LFE packages of the same type. Therefore it will only save time once, while an alteration in the production processes themselves will save time each time a product is made. Since the core problem needs to be the problem with the most potential gains these two problems (the missing tools and the missing materials) are eliminated from consideration.

The branch on the problem cluster concerning the way materials are packed and supplied by the supplier is eliminated from consideration. One rule to choosing a proper core problem is the fact that the problem needs to be a problem that can be sufficiently influenced. Considering that in these problems an external party is involved, that the supplier is located in England and that negotiations usually take a long time the influence is limited. This potential core problem is eliminated, due to lack of influence.

The problem that is relatively easily influenced and which has great potential gains affecting both sides of the spectrum (time and resources) is the outdated process design of the LFE package assembly. The process has not changed in recent years even though the company has grown significantly and the demands of customers have changed. The assembly of LFE packages is still done manually and is sensitive for mistakes. LFEs can be wrongly counted, have mixed orientations or be assembled while two of them stick together. Due to the fact that this production step can be properly influenced and the potential gains seem promising, this problem is chosen as the core problem. The core problem is defined as followed:

The current process design is a cause of the reject rate being approximately 4.5% instead of the targeted 2%, additionally the current process design leaves room to improve on the assembly time.

To gain insight into the magnitude of the core problem the following indicators are identified:

Reject rate LFE packages
The percentage of LFE packages that gets rejected. This indicator gives insight into the quality of output from the LFE package assembly process. Subsequently it also provides some insight in the sensitivity for mistakes in the process. Additionally the reject rate will be used in the evaluation of the solution.

Assembly time LFE packages
The time it takes to assemble a LFE package, from picking up the first part till putting the finished LFE package down on the workbench, set-up time and cleaning are not included in case of the single timed assembly times (§2.3.1). This indicator is used to provide insight in the duration of the LFE package assembly. It will prove useful in evaluating the solution, as every bit of time saved adds to making the process more efficient.

Scrap/reject costs
The costs incurred by rejected LFE packages, this includes the materials that get scrapped, the labour used for the possible rework and any new materials that may be used to rework an existing rejected LFE package. This gives insight in the monetary value of rejecting LFE packages, giving a look at the magnitude of the reject rate.

The eventual goal of this project is as follows:
The thesis will aim to provide the company with an alternative process design for the assembly of the LFE packages. This alternative design should halve the current reject rate, preferably getting the reject rate as close to the target of 2% as possible, and reduce assembly times by 15%.

1.5 Approach

To tackle this problem certain steps will be taken, these steps will be described in this section and correspond with the other chapters of this thesis. The first step towards solving the problem is analysing the current situation. Once the current situation is sufficiently clear alternative process designs will be formulated. These alternatives will be assessed and the most fitting will eventually be chosen and recommended. This recommendation will include an implementation plan.

Limitations
Of course as with any project there are certain limitations, both in time and resources. This project must be executed within 10 weeks, this does not only partially limit the scope but also the amount of data that can be gathered from measurements and experiments. This is especially the case with the collection of rejects. On the other hand there is also the aspect of resources, the production department that is available for field research is TGP1. However any experiment or measurement is of course dependant on the production schedule of this department. Another resource is of course information, there will be literature studies done in this project, these studies might be limited by the availability of certain papers.

1.5.1 Analysis of current situation

To gain a better understanding of the current situation data needs to be gathered and processed. With this data the extent and detail of the problem should get clearer and will make formulating alternatives in the following phase easier. The data that is needed are the assembly times of LFE packages and their reject rate, this raises the following research questions:

What are the current assembly times for LFE packages?
To determine the time that the assembly of LFE packages takes measurements need to be done. The production department TGP1 can be used for observations/measurements. This department makes a wide array of LFE packages and thus gives a representative image of the LFE package assembly.

Two types of measurements will be done, first each type of LFE package will be looked at in an individual manner then some types will be measured when treated as a batch. In the first case the assembly time does not include the set-up time, while in the batch measurements the set-up time is included. This is due to the fact that set-up occurs only once for each batch, when looking at individual LFE packages it would give a skewed image if set-up time was taken into account for the one package.

What is the current reject rate of LFE packages?
Rejected LFE packages are not currently registered. The rejects are collected in the production department and once it's a substantial amount one of the employees takes a look at the rejects. To get some insight in the rate at which LFE packages are rejected they will need to be monitored.

The collection of rejects will also be done with help of the TGP1 production department. They agreed to collect the rejects, periodically handing them over so they can be documented and investigated. In the first period (during the writing of the project plan), to gain a general idea of the reject rate, the rejects were collected once every three weeks. In the second period (the actual conduction of research) the rejects are collected every week.

1.5.2 Creation of alternative process designs

The current process seems to be non-satisfactory, so more appropriate alternatives should be formulated. Lean is a widely promoted and accepted methodology in the organization, it could provide methods to improve upon the existing process. Alternatively the entire process can be redesigned, the basis for these alternatives should be looked for in literature and of course within the company itself. By using these different approaches several alternative process designs should be formulated. The accompanying research questions in this phase are as follows:

What Lean methods could be used to improve the current process?
Since Lean is a widely adopted and promoted methodology within the company and by definition suitable to optimize processes, it would fit to use it to improve this particular process as well. However the specific methodologies within Lean that could be applicable to this process are currently unknown.

A systematic literature review should provide insight in the available and applicable Lean methods. The focus of the search for literature (besides Lean) will be on the manual aspect of the current assembly process. This should narrow the wide range of applications Lean has to more fitting methods for this particular instance.

What methods are available for the redesign of manual production/assembly processes?
The current process is not adequate and thus alternatives should be found. While Lean is an already accepted methodology in Bronkhorst High-Tech, it is not the only methodology that is out there. Additionally Lean often works in unison with other methodologies. Therefore it would be helpful to know which other methods are already present in literature to tackle the redesign of a manual production/assembly process.

Yet again a systematic literature review should provide insight in the available and applicable methods. Similar to the research done on Lean methods the focus will be on the manual aspect of the assembly process.

Which ideas are already present in Bronkhorst High-Tech on how to improve/alter the LFE assembly process?
There is a common consensus amongst the employees that the LFE package assembly process is far from optimal. Where there are whispers of discontent with a process, there are bound to be ideas on how to improve it. Interviews might prove a too heavy tool for the intended research in this case, instead some semi-casual conversation will be held with employees most closely involved in the process. This includes the production personnel and the engineers of the engineering department. The found ideas will be put in an overview. Then after doubles have been eliminated and similar ideas have been paired, the ideas will be filtered on feasibility. In the end some of the best ideas might be taken into account.

1.5.3 Assessment of alternative process designs

The alternative process designs, which were formulated in the previous phase, should be assessed to determine which one benefits Bronkhorst High-Tech the most. To do so an assessing method needs to be deployed and the wishes from within the company need to be known. This results in the following research questions:

What criteria would a new process design need to meet?
The new process design will need to be within the boundaries set by the company. There will be certain demands and wishes for the process which will need to be taken into account. To properly choose a final process design these demands and wishes need to be known.

Through interviews the demands and wishes for the new process design should become clear. The interview will consist out of questions directly focused on what the new design would need to accomplish with some room for elaborations. The interviews will be conducted in both the process engineering department and the production departments where both production leaders and regular employees will be questioned.

What assessment method is suitable/preferred by experts in the field for the assessment of a process design?
Once several alternatives are formulated their usefulness/effectiveness needs to be determined. There are several methods of assessing multiple concepts. It would be helpful to know what methods are commonly used and preferred in a production environment, so one of these methods can be deployed in this project as well.

Again literature will be consulted. Once several assessment methods are found they will be paired with the criteria that surfaced from the interviews. The pairing, that seems most suitable (based on literature and criteria) will eventually be used to assess the alternative designs.

1.5.4 Choice of alternative process design
After the results of the assessments are known, they can be further discussed. One of the (by the assessment) proposed will be chosen to be the alternative that is going to be pursued. This alternative will be elaborated upon by the means of an implementation plan. The implementation plan should provide the company with a clear path they can take, sufficiently clear that it can be executed without necessarily reading the accompanying thesis. This raises one final research question;

What are methods for writing an implementation plan are commonly used?
There are many different ways to propose the implementation of a new process, to give is some structure a certain method or lay-out for an implementation plan could be very useful. Preferably a company standard or else an industry standard could be used in formulating the final implementation plan.

First of all there will be checked if there is a standard template for a production plan present in the company. If that is not the case or the template does not seem sufficient, literature will be consulted to find another method for formulating the implementation plan.

1.5.5 Conclusions and recommendations
The findings of the thesis will results in certain conclusions. The findings will be generally summarized, followed by a look back to the goal set in §1.4, a reflection on that goal with the new found findings in mind and eventually an overall conclusion. The conclusions of course lead to certain recommendations and potentially considerations. All recommendations and considerations will be shortly discussed, these can range from actions to be taken to suggestions for further research.

2 Analysis of current situation

In this chapter the current situation will be looked at. First the LFE assembly will be looked at by the means of a bird-eye view, this will include a throw-back to earlier years and some insight into the production department TGP1 (Thermal Gas Products). Then, when the general situation around the LFE assembly process is clear, the process itself will be explained more thoroughly by the means of a detailed explanation accompanied by flowcharts. Once the process is discussed in sections 2.1 and 2.2, section 2.3 and 2.4 will give a more quantitative insight in the assembly process and its issues. When both the qualitative and quantitative aspects have been discussed the findings will be summarized in section 2.5.

2.1 General

As mentioned in section 1.2 Bronkhorst has some issues regarding the delivery reliability (appendix B). A substantial number of orders are not shipped on time. This issue started in 2016, after approximately 2 years of being above the targeted delivery reliability. In this year the initial significant drop in delivery reliability can be seen, heralding more troubled times to come. Throughout 2016 and 2017 the delivery reliability kept dropping with an occasional uplift. By the end of 2017, early 2018 the delivery reliability dropped dramatically. On the 6th of august 2018 the delivery reliability reached an all-time low of 31.28%.

This drop had several causes, as can be identified by examining the GWOs (Group Work Discussion; meetings with the goal to communicate important information with the organisation) from this and the following periods. There was an unexpected increase in new orders, production was plagued by faulty sensors and due to the inability of suppliers to supply more materials in this period overtime was not always an option to tackle the number of orders. The sensor issues were tackled in cooperation with the suppliers of the (faulty) sensor parts. The sole supplier of LFEs was one of the suppliers struggling with supplying enough materials, this revelation prompted the search for an additional supplier capable of making these precision parts. The plans for this new supplier of LFEs are still being drawn, however it is already known that at first only 1 or 2 types of LFEs will be produced there.

The need for materials in the period where the delivery reliability dropped, in particular LFEs, can be well observed when looking at the purchasing data of the LFEs. In 2018 more than 3 million LFEs have been purchased, this is a 92% increase relative to 2017. The purchasing data also provides a view of the increase in workload for the LFE package assembly process. When looking at the purchasing data since 1995 (which can be found in Appendix D) an average yearly increase of 14% can be seen in the amount of purchased LFEs. Again just like the revenue, personnel numbers and the acreage another indicator of the growth Bronkhorst is experiencing.

Interestingly 80% of the LFEs bought in 2018 consist of only 5 different types out of a total of 19 types. 4 of these LFE types are used in the larger packages containing a greater number of LFEs. Additionally these 4 types are used in multiple production departments. For example production department TGP1 uses these 4 types. In 2018 69% of the LFE packages made by TGP1 were made with these 4 types, most notable is 1 type that makes up 33% of the total number of packages made in that year. This type is used for 4 different LFE packages, both small (7 LFEs) and larger (up to 65 LFEs) packages.

Equally interesting is the fact that the TGP1 production department processed approximately 1.6 million LFEs in 2018, which is about half of the total number of LFEs purchased in that year. TGP1 consists out of a team of approximately 30 people, most people of this department are instrument makers and they don’t have a set function in the production of flowmeters. As they enter the production facility they can choose which task they pick up (of course given the priority set by the schedule), it could be assembling a LFE package, a sensor or even the final assembly of the flowmeter. They are relatively free in which task they pick up and can switch during the day.

2.2 The process

In this section the production processes and the reject process will be discussed. Each process will be shown in a visual manner through a flow chart and further elaborated upon in their own paragraphs.

2.2.1 The production processes

Even though Bronkhorst has experienced quite a bit of growth (and is still growing) and processes an increasingly impressive amount of LFEs as shown by the number of purchased LFEs, the assembly process in itself has remained much the same since the company's founding in 1981. The LFE packages are manually assembled on a flow bench with variations mostly in the number of LFE, type of LFE and in some cases the way of making sure the right number of LFEs is included in the package. The LFE packages are generally made in batches of varying sizes.

For this research the production department TGP1 (Thermal Gas Products) was available for observations, questions and basically everything that might be needed to conduct the research, of course within the limits of the production schedule. In this department 14 different types of LFE packages are made, previously 16, however they moved the production of two types to TGP2. These 14 types can be divided in roughly 3 categories; the spindle packages, the 50/70K packages and the M-packages. They all have very similar process, but there are slight differences in their assembly.

Spindle Packages

With ten different types this category of packages forms the majority of package types within TGP1, the packages included in this category are: 020, 050, 100, 200, 500, 1K0, 2K0, 5K0, 10K, 20K. The number of LFEs per package ranging from 2 till 65 with three different types of LFEs to go around. The assembly process is the same for all of these package types. The process is shown by the means of a flowchart in Figure 2-1. The process steps within the rounded rectangle are the steps that are described in the work instructions, the steps outside of it are not described but they are performed and currently necessary.

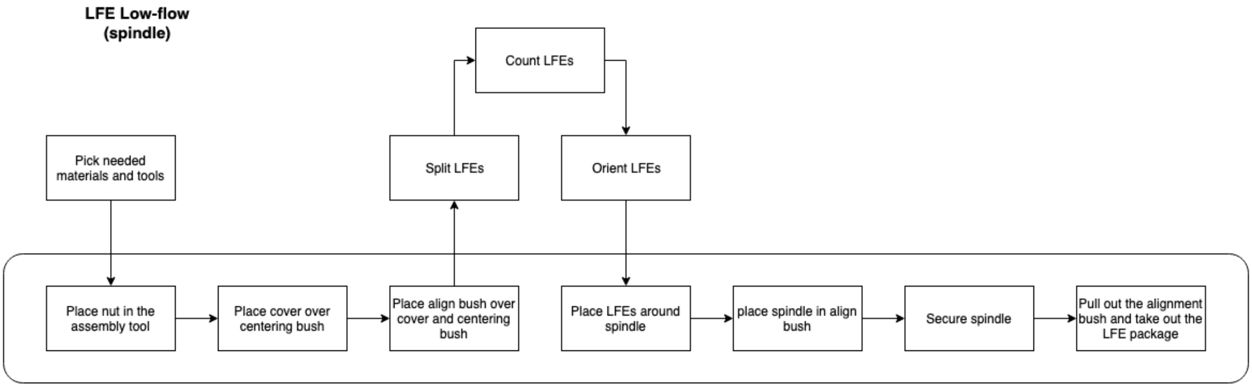


Figure 2-1 Process flow chart spindle packages

The LFEs are counted by hand and due to their tendency to stick together they often need to be separated during or before counting them. The LFEs used in these packages get supplied in small plastic bags containing a fairly random number of LFEs. In case of the Spindle packages the LFEs are stacked on a spindle.

50/70K packages

The smallest category of package types, containing only two different packages; the 50K and 70K. They either contain 55 or 74 LFEs, both use the same type of LFE. The assembly process is the same for these two packages and can be seen in Figure 2-2.

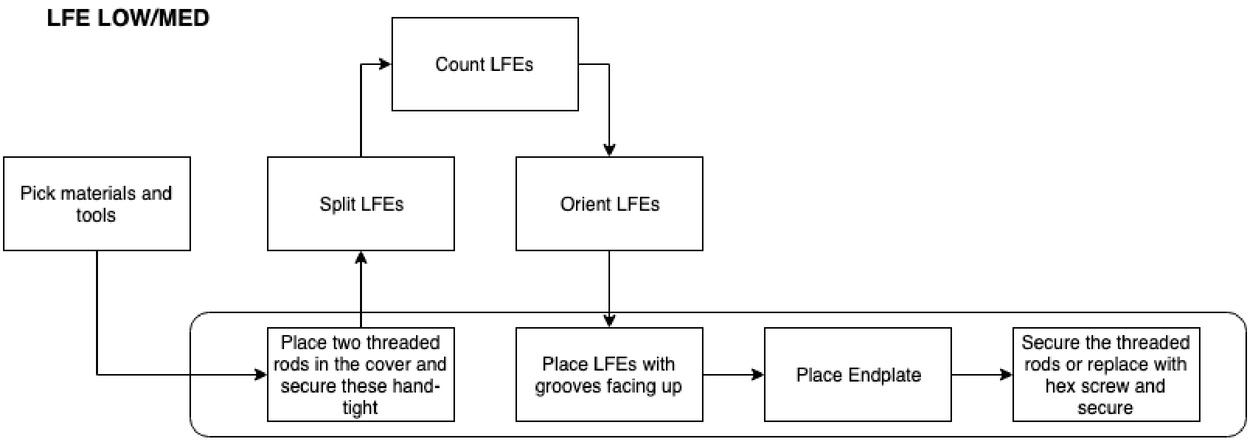


Figure 2-2 Process flow chart 50/70K packages

The process steps within the rounded rectangle are the steps that are described in the work instructions, the steps outside of it are not described but they are performed and currently necessary. The LFEs used in these packages are also supplied in plastic bags with a fairly random number of LFEs in them. The LFEs get mounted on a cover in case of the 50/70K packages.

The M-packages
The category of packages that have the highest flow capacity in the TGP1 department. This category contains 4 different types of LFE packages; the M10, M20, M50 and 1M0. The number of LFEs used in these packages ranges from 80 till 361 LFEs and have two different types. The process is quite a bit different from the previous two categories, instead of counting the LFEs they now measure a stack of them to see if they have enough LFEs. As can also be seen in the flowchart of this process in Figure 2-3, the process steps within the rounded rectangle are the steps that are described in the work instructions, the steps outside of it are not described but they are performed and currently necessary.

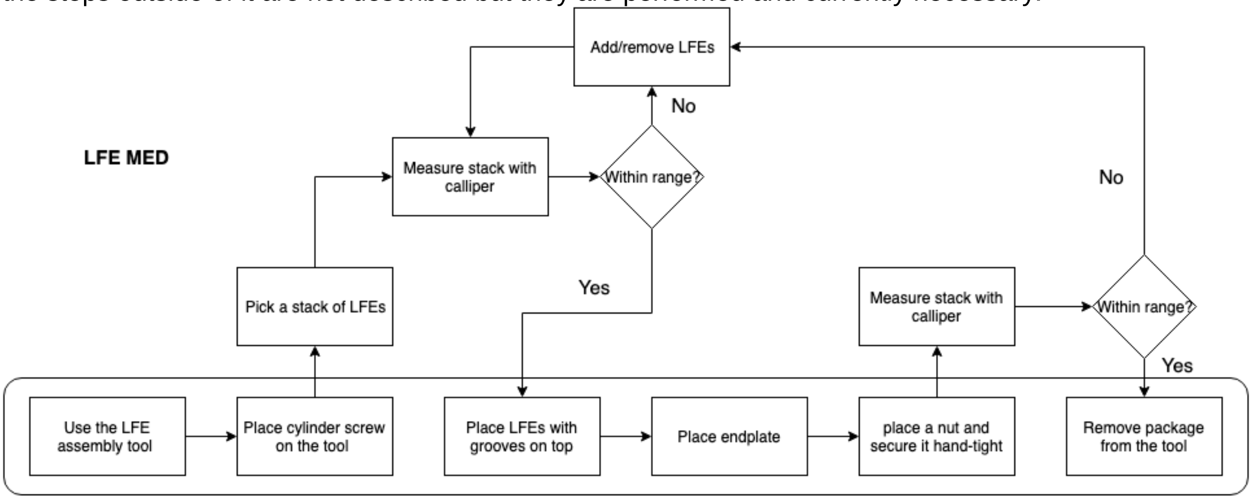


Figure 2-3 process flow chart M-packages

The LFEs used in these packages are supplied on rods, they are pre-oriented and the number of LFEs on a rod is either 450 or 500 depending on the type. The LFEs in these packages are larger and differently shaped than the ones in the spindle or 50/70K categories, this enables this specific manner of supplying them.

2.2.2 The reject process

Whereas the production process has been clear since the beginning the reject process has been as vague. A different process is defined each time a different person is asked about it and all of them seem convinced that their version is the right one. The company's documents do not help the situation, the work instructions simply state to alert the team coordinator. This does not seem to happen in practice, production employees usually solve the situation themselves unless something is exceptionally wrong.

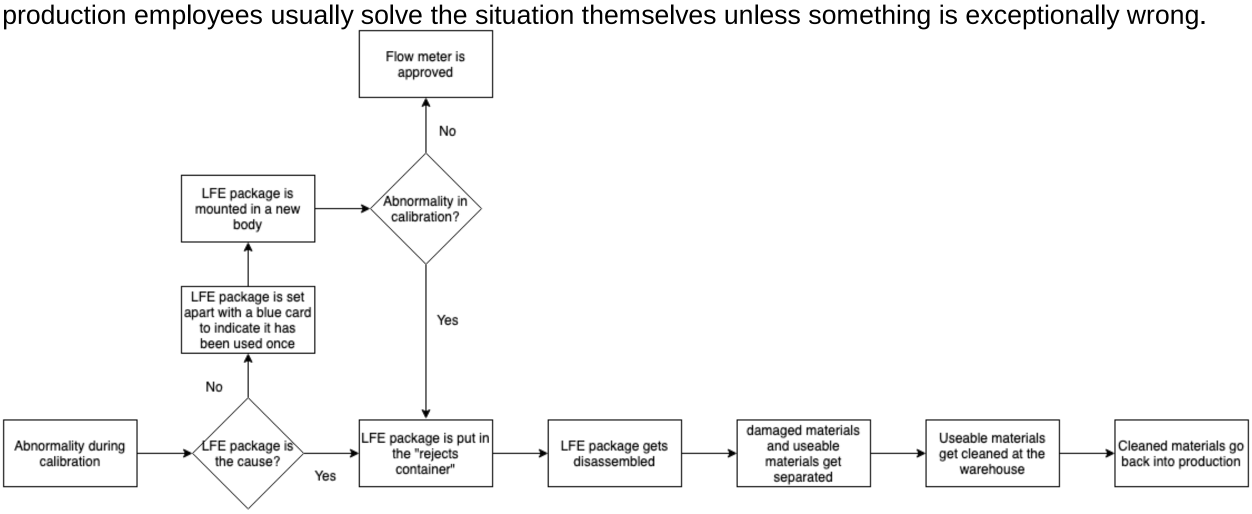


Figure 2-4 Rejection process

The flowchart depicted in Figure 2-4 shows the rejection process according to the team coordinator. The step in which it is checked if the LFE package is indeed the reason for the abnormality is relatively new. They used to take out the LFE package without checking if it truly was the issue and put it directly in the reject container. The disassembly of rejected packages occurs roughly every two weeks. Once the reclaimed materials have been cleaned there is no way to tell them apart from the other materials. Traceability is not ensured for these materials. Traceability is a bit of an overall issue in the LFE package process. Where the other production steps are signed for by the employee that performed them the LFE package does not come with any documentation, signature or even a date of when it was made or by whom.

It also stands out that the rejection documentation system (PAR system) is not included in the process. The rejected LFE packages do not get registered or documented in any way, shape or form. One of the older employees in TGP1 did mention that according to (an old) procedure they actually should register the rejects in the system. It seems this never made it into the routine of production, even though it might have been the intention.

The process, as described by the team coordinator, is quite clear. However, as said, when the employees were asked about the process the answers differ from this process and from one another. This could be due to recent changes to the rejection process, which might not have been as clearly communicated as was necessary. The fact that this process cannot be found in writing is not helping either, people have no other choice than to ask the team coordinator or one of the other employees what they are supposed to do. Having to ask the team coordinator something that might be deemed trivial could deter the employees from asking the team coordinator and instead ask the question among the other employees, who might not know the exact process either. Having a simple instruction available could solve any confusion about the process in a very accessible manner. The process would then no longer be shrouded in mystery.

2.3 The assembly times

To gain more insight in the process and its shortcomings several measurements were taken concerning the assembly times. First, to gain a general idea of the assembly times and the differences between package types, measurement were taken of the assembly of individual packages. Then, to gain a more representative picture, normal production was measured. In this section the findings of these measurements will be discussed.

2.3.1 Assembly times per package type

To gain insight in the assembly procedure, (possible) influencing factors and assembly times the first measurements were done separate from regular production. In this case 4 people from TGP1 were asked to make 2 of each type of package, for each separate package a time measurement would be done. The time measurements do not include set-up time. The experiment/observation involved two experienced employees and two less experienced employees. Measurements were both conducted in the morning and afternoon, both with an experienced and a less experienced employee. The data gathered from this experiment/observation can be found in appendix E and will be further discussed in this paragraph.

Average assembly times

First, without differentiating between the data, the average assembly times are calculated and presented in a graph (see Figure 2-5). This graph provides several interesting (and perhaps somewhat predictable) insights. The transition between different LFE types is clearly visible. The graph builds due to an increasing number of LFEs in the packages, to then drop again when the next type of LFE comes into play, needing less LFEs to make the package. The number of LFEs necessary to make each type of package can be found in appendix F. The transition can be seen at type 100 and 1K0.

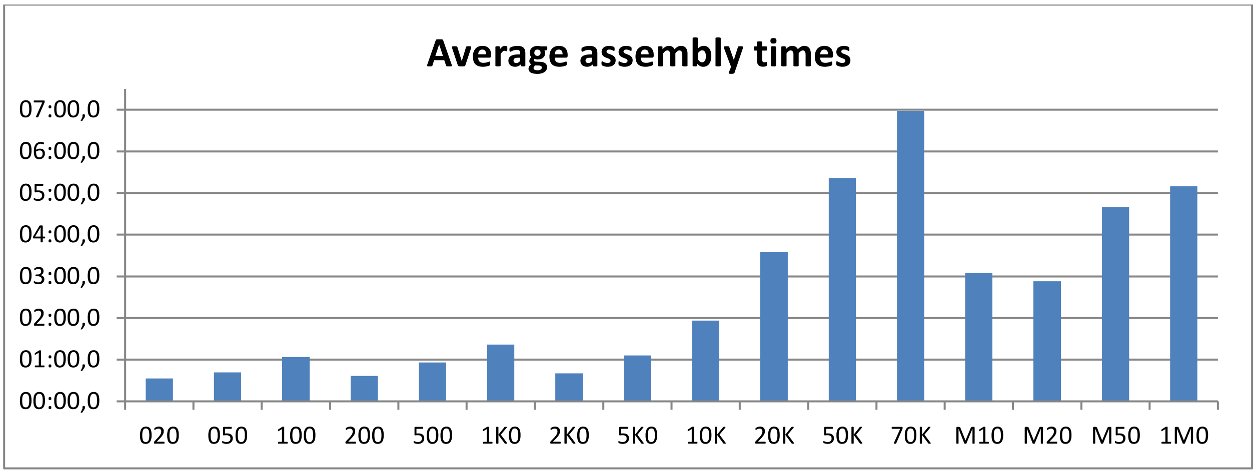


Figure 2-5 average assembly times (in minutes) per package type

The package with the longest average assembly time is also the package with the highest number of LFEs that are still manually counted instead of measured. The graph shows the correlation with the number of LFEs and the assembly times clearly for the manually counted packages. As for the M-packages, which are measured with a calliper, it seems curious that the M50 and the 1M0 take quite a bit longer than the M10 and M20. The M50 and 1M0 are considerably larger, but since these packages are measured rather than counted, this shouldn't make much difference. However as stated earlier in section 2.2 the M50 and 1M0 were moved to a different production department. The TGP1 employees were so kind to include these for this project but they were a bit out of practice, increasing the assembly times for the M50 and 1M0.

Experience

This time the data is split between the experienced and the less experienced employees. The task of assembling the LFE packages is generally viewed as a simple one. But there isn't a saying "Easy to learn, difficult to master" for nothing. To gain insight in the importance of experience the two data sets are compared in Figure 2-6.

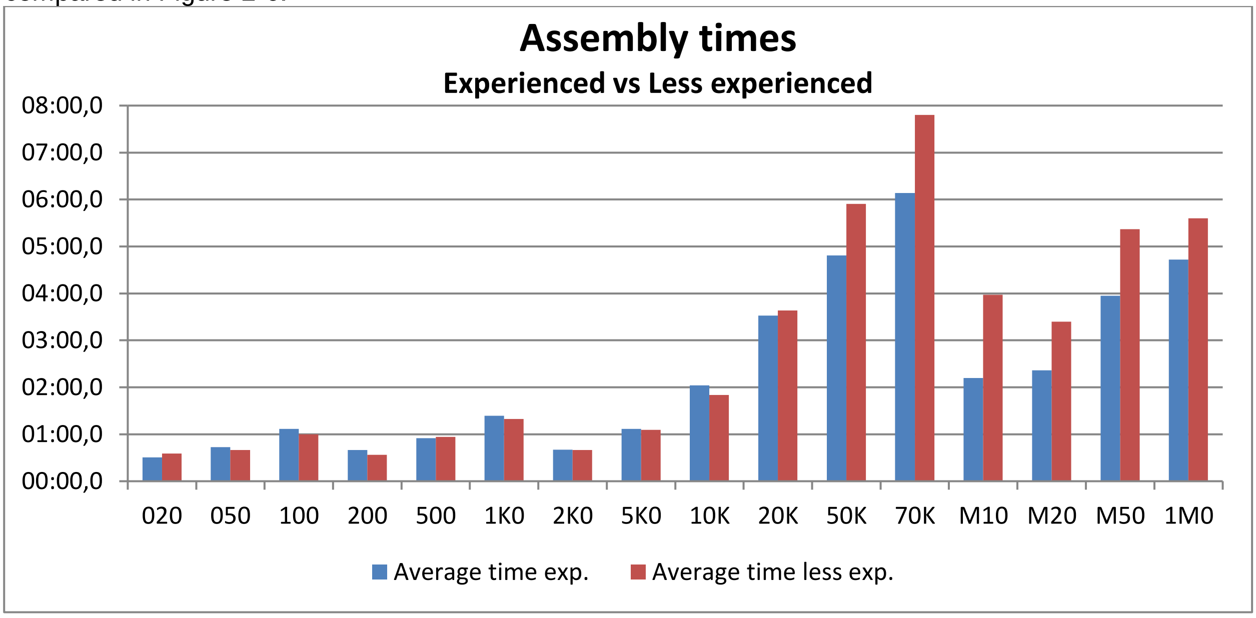


Figure 2-6 Assembly times (in minutes) experienced vs less experienced employees

Surprisingly the experienced employees are generally a bit slower up until the 10K packages and then overtake the less experienced employees with the larger packages. This can, however, be explained; the more experienced employees are often more methodical, creating little pairings of LFEs before stacking them, making it easier to keep count. Some of the less experienced employees count the LFEs while stacking them, making them somewhat faster. With the larger packages however the immediate stacking of the LFEs isn't deemed convenient anymore by the less experienced employees and they too refer back to methodical counting. This is where the experience from the experienced employee comes in handy. Where this experience is perhaps even more essential are the M-packages, as the employees have to make an initial estimate on the size of the stack of LFEs that they pick. An experienced employee generally makes a more accurate estimate and needs less measurement cycles to have the right number of LFEs.

Time of day

Apart from experience, the time of day might also affect the employees and consequently the assembly times. Assembling LFE packages is a precision task and it isn't all too hard to imagine that after a morning of hard work the focus of employees might be wavering a bit, increasing assembly times.

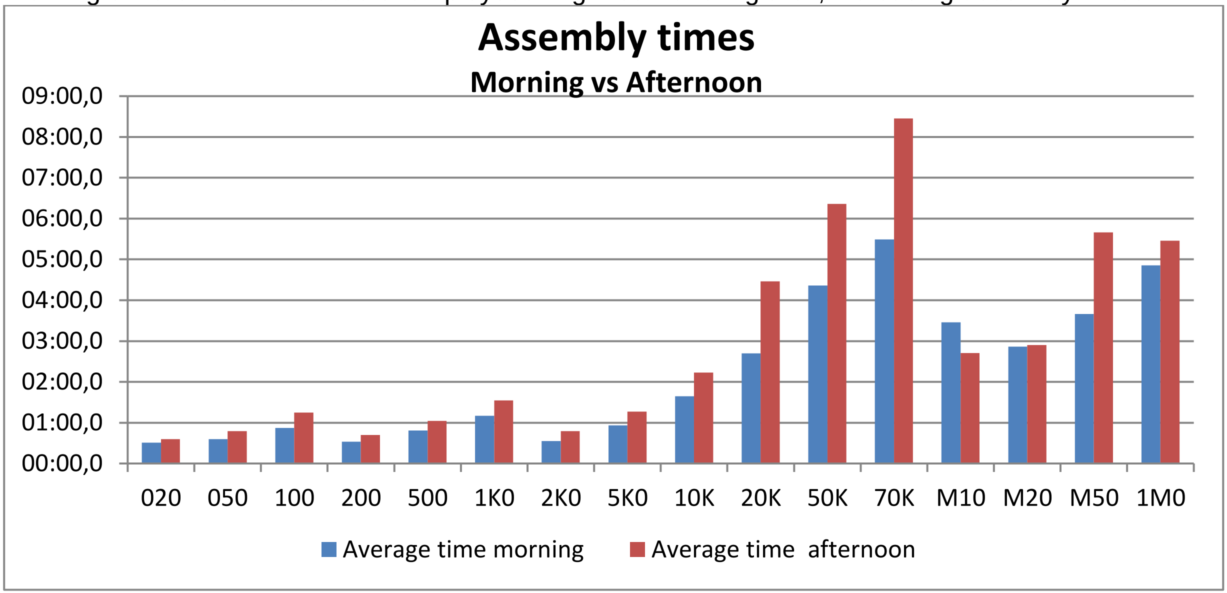


Figure 2-7 assembly times (in minutes) morning vs afternoon

This premonition turns out to be likely when looking at the data in Figure 2-7. For nearly all LFE package types the assembly times are longer in the afternoon. To be more precise; on average the assembly times in the morning are 21.8% faster than the assembly times in the afternoon. Due to the limited nature of this data, no hard conclusions can be drawn, however it is most certainly worth keeping this discrepancy in mind.

2.3.2 Batch (regular) assembly times

To gain a more wholesome view of the assembly times regular assembly was timed, this included set-up time, picking materials during assembly, counting and orienting the LFEs, cleaning/tidying the workspace and of course the assembly itself. Due to the fact that regular production was timed there is only data on certain types of LFE packages. A total of eleven measurements where done. The main findings are depicted in Table 2-1, for a more elaborate table please refer to appendix G.

Type	Number of packages	Number of activities	Total time	Average time per package	Fraction of time NNVA	Fraction of time VA	included in assembly times (assembly strategy)
20K	11	26	0:48:54	04:26.7	68.66%	35.06%	pure assembly
50K	9	23	0:41:37	04:37.5	51.67%	48.33%	pure assembly
500	26	11	0:28:49	01:06.5	41.53%	58.45%	pure assembly
100	14	8	0:17:47	01:16.2	34.61%	65.25%	counting
020	20	3	0:09:38	00:28.9	23.81%	76.19%	counting
020	28	6	0:15:30	00:33.2	23.03%	76.97%	pure assembly
5K0	20	9	0:24:37	01:13.9	17.75%	82.23%	counting & orienting
2K0	20	3	0:12:47	00:38.4	17.13%	82.87%	counting & orienting

M20	15	9	1:00:29	04:01.9	17.11%	82.90%	N/A
M10	6	4	0:22:34	03:45.7	11.06%	88.94%	N/A
10K	20	4	0:31:57	01:35.9	2.63%	97.37%	counting & orienting

Table 2-1 main findings measurements batch (regular) assembly times

In the table several bits of information are given and whereas some might speak for themselves, others do not. The number of activities refers to the different sections of the total time, this can be assembly, set-up, etc. that follow one another. For example the string of activities is: set-up, assembly, picking materials, assembly, clean up. Then the number of activities would be 5. Then the different fractions of time; NNVA (Necessary but Not Value Adding) and VA (Value Adding). These categories differentiate between the customer value of different activities. Making this distinction is a widespread practice in Lean manufacturing (Bicheno & Holweg, 2016). In this case all activities that do not involve direct assembly are regarded as Necessary but Not Value Adding, this includes counting and orienting when those activities are done separately. The last column that needs some explaining is the assembly strategy. Every production employee has a separate approach to counting, orienting and stacking the LFEs. Some will first count and orient the LFEs before stacking them, while others might count and orient while stacking. In this column any additional activities that are included in the assembly activity are mentioned. Pure assembly means that neither counting nor orienting was done during the assembly activity. This column is not relevant for the M-packages, the LFEs do not get counted or oriented in this case.

The table provides several insights. The larger packages that are still counted by hand have the highest average time and the largest fraction of NNVA. While the 50K (out of the package types that were measured) takes on average the longest, the 20K takes the cake when it comes to time spent on NNVA activities. About 63.6% of the time spent on the 20K packages consists out of counting and orienting (the other 5% is spent on set-up, cleaning and picking materials). As might be expected the smaller packages have a lower fraction of time spent on NNVA activities. Due to the small number of LFEs that are necessary, there is not much counting to be done. Additionally since these packages use so little materials there is not much need to replenish those during assembly, usually the LFEs picked during set-up are more than enough to make the desired number of packages.

Most employees have the same assembly strategy for the larger packages since they contain such a large number of LFEs that need to be counted by hand. The LFEs for these packages are first counted and oriented (pure assembly) by almost all production personnel. The 10K on the other hand is done differently depending on who is assembling the packages, in this case counting, orienting and stacking was done simultaneously. This entails that both the counting and orienting is included in the VA time instead of the NNVA, which explains why the fraction of NNVA time is so low.

According to the analysis based on added value, the most time to be won is in the counting and orienting steps (and perhaps some of the set-up and cleaning time) of the larger, hand counted, packages. If the time spent on these steps could be reduced or if these steps could be eliminated, more time would be available to spend on other tasks in production.

2.4 The rejects

In this section the reject rate will be discussed. First a general overview of the reject rate will be given, then it will be investigated what is causing the rejects and finally what costs are tied to these rejects. All data on the rejects is gathered in TGP1.

2.4.1 General reject rate

To determine an overall reject rate data was needed on the occurrence of rejects. There wasn't any historical data on rejected LFE packages as those rejects usually do not get documented. Therefore data had to be collected in production department TGP1. The production personnel would collect all LFE package rejects which were retrieved every 3 weeks to be documented for this research. The data on rejects in this paragraph is based on the rejects collected in week 7 till 15. After week 15 the rejects were still monitored for this research, however due to the initiative of the production personnel and some miscommunication not all rejects were collected. Hence, this data is not used in the determination of the general reject rate in the analysis of the current situation.

When looking at the total production and the total collected number of rejects in the 9 week period, an overall reject rate of 4.01% can be observed. However when looking at the different three week periods it becomes apparent that there are some variations between the periods. As can be seen in Table 2-2. Periods 1 and 2 are practically equal when it comes to reject rate, even though the production and number of rejects are quite different. Period 3 had the largest production output but the lowest reject rate of all periods.

Period	Reject Rate
Period 1; week 7 till 9	4.75%
Period 2; week 10 till 12	4.76%
Period 3; week 13 till 15	2.51%
Total; week 7 till 15	4.01%

Table 2-2 Reject rate of several periods

There are several explanations for the reduced reject rate of period three. First off, it is quite possible that not all rejects were collected. The collection of rejects only happened once every three weeks and it had been going on for a while at that point, (a part of) the production personnel might have forgotten to carefully collect all rejects as requested. Secondly, it seemed that as time moved on and rejects were collected, that more package types were tried a second time (in a new body) after being noticed in calibration. Lastly, it would not be very surprising that out of habit some rejects have been reworked, scrapped or otherwise displaced.

The variation in the reject rate might also be a “natural” occurrence. It could correspond with the production personnel that made the packages that were used in that particular week. However due to the lack of traceability with LFE packages this cannot be determined.

Another particularly interesting bit of information that can be extrapolated from the collected reject data is the reject rate of the 20K packages (the reject rate of the other packages can be found in appendix H). These were the package with one of the highest assembly times and greatest percentage of necessary but not value adding time. Again looking at the whole nine week period an overall reject rate of 13.70% can be determined for the 20K. Significant variations in reject rate can be observed when looking at the three separate periods, as seen in Table 2-3. In this case period two had the lowest production output with 20K packages, yet had the highest number of rejects and thus the highest reject rate. As said without the ability to trace the packages it is difficult to determine why there is such a spike in 20K rejects.

Period	Reject Rate (20K)
Period 1; week 7 till 9	12.42%
Period 2; week 10 till 12	24.44%
Period 3; week 13 till 15	6.10%
Total; week 7 till 15	13.70%

Table 2-3 Reject rate of 20K packages of several periods

2.4.2 Issues causing rejects

Rejects are often identified during the calibration of the flowmeter, it will become apparent that there is a deviation most likely caused by the LFE package. However they can’t tell during or after the calibration what is exactly wrong with the LFE package. Therefore more research was necessary, a total of X LFE packages have been disassembled to figure out what causes them to be rejects. The found short-comings, if there were any, will be analysed by the means of a Pareto analysis.

The Pareto rule basically states, in this case, that 20% of the causes create 80% of the rejects. These percentages are not completely set in stone but give an indication. By looking at the occurrence of the defects that cause a LFE package to be rejected, it can be seen whether it is indeed true that only a few causes are responsible for the majority of the rejects. Should this be the case, then the Pareto analysis prescribes that these causes should be given priority, in the problem-solving process, over the other causes.

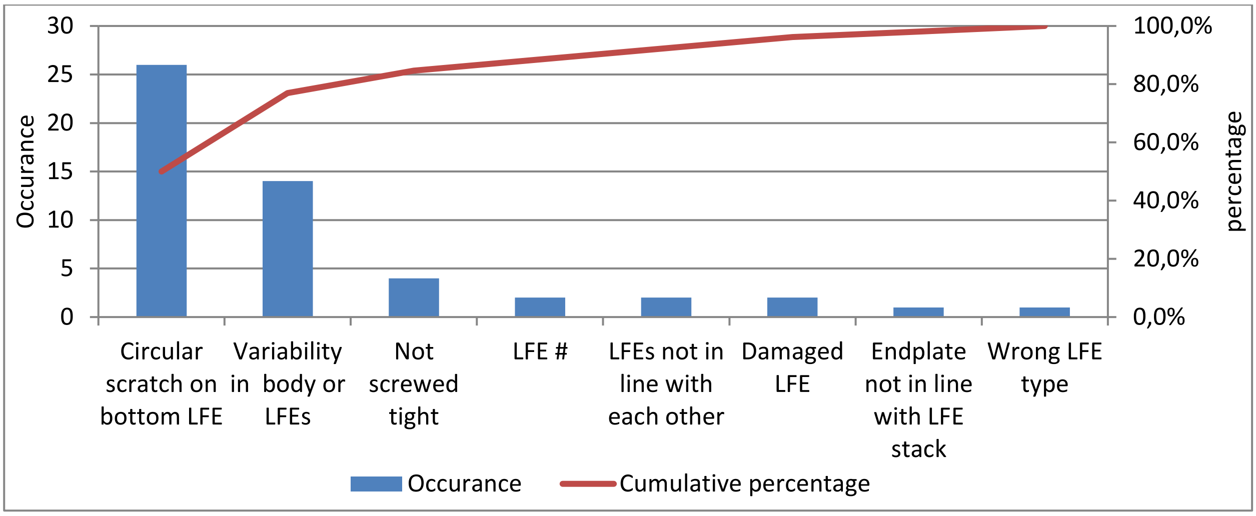


Figure 2-8 Pareto analysis reject causes

After disassembling 52 different rejected LFE packages several defects where found. Surprisingly the predictable defects (wrong orientation and wrong number of LFEs) hardly occurred. The (possible) defect that occurred by far the most was a peculiar damaged LFE (a circular scratch) which had not been encountered or thought of before. This, and the other defects, are included in the Pareto analysis found in Figure 2-8.

In the chart is can be seen that the circular scratch occurred in 50% of the disassembled LFE packages. This scratch occurred only in the spindle packages on the LFE that was adjacent to the cover of the spindle package. Often a slight difference could also be observed on the surface of the spindle corresponding with the location of the scratch on the LFE. It is not certain whether this scratch is the cause for rejecting the package, it is however likely and the scratch is most certainly not supposed to be there. These findings have also been reported to the Quality engineers of TGP1.

The Quality engineers did some investigating and concluded that the circular scratch does not influence whether a package will be a reject or not. They collected a few of the damaged LFEs and observed them under a microscope to see if the scratch would interfere with the grooves of the LFE. This was not the case as can be seen in Figure 2-9. Therefore the rejects with a circular scratch where likely caused by variability in the LFEs themselves, the bodies they were mounted in or a combination of the two, as will be further discussed below Figure 2-9.

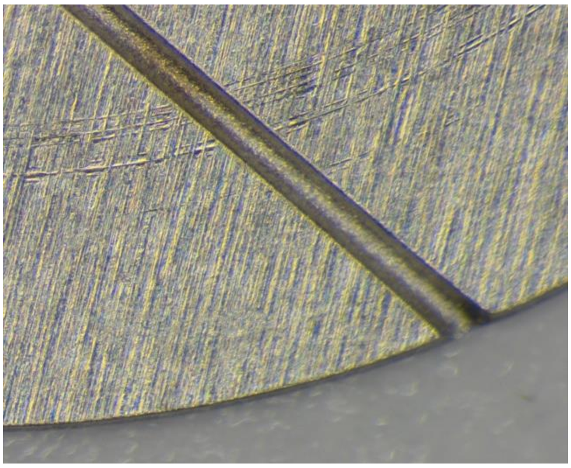


Figure 2-9 Close up of the circular scratch on a LFE

It also occurred that the rejected package seemingly had nothing wrong with it; the materials seemed undamaged, the number and orientation of LFEs was correct and everything was screwed tightly. That nothing can be observed does not necessarily mean that there is nothing wrong with it. It is known that due to the production process of the LFEs a part of the produced LFEs is above specifications (a larger flow capacity) and below (less flow capacity). The flow canals of LFEs are produced by the means of chemical etching. Because the etching liquid is sprayed from the sides onto the sheet containing the LFEs the etching liquid is fresher on the outer rim of the sheet. This causes the LFEs on the outer rim of the sheet to have deeper canals then the LFEs in the middle of the sheet where the etching liquid is not as easily refreshed. Therefore the LFEs on the outer rim of the sheet have a higher flow capacity than the ones in the middle as depicted in Figure 2-10.

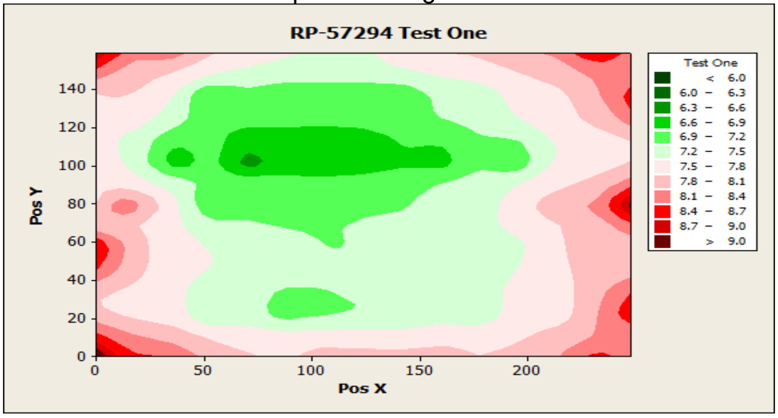


Figure 2-10 flow distribution of a batch (sheet) of LFEs

When the LFEs with a higher flow capacity are mixed with the lower ones, the overall package might be up to specifications. However should all the LFEs with a higher flow capacity be put in one package, the package will also have a higher flow capacity than specified. The same story goes for LFEs with a lower flow capacity. It is possible that the LFE packages that have been rejected without an obvious cause are plagued by this variation caused by the production process of the LFEs. In Bronkhorst there is a project running in the supplier engineering department concerning this variation.

Another explanation for the rejection of seemingly good LFE packages is that the packages are indeed within specifications. There can also be some variation within the body where these LFE packages are installed. The combination of variation in the body and variation in the LFE package can cause one package to be a reject due to one body, while being a perfect fit for another body.

The circular scratch and the seemingly not defective packages are responsible for 77% of the rejects. Showing that indeed a small amount of the causes can create the majority of the rejects. While all issues should be addressed eventually, these two issues should be given priority for as far as possible.

2.5 The costs

Of course time and quality would not be an issue if there would not be any money involved. Therefore to gain even more insight in the magnitude of the issues that plague this assembly process the costs should be analysed. In the first paragraph the regular costs of assembling LFE packages is looked at, in this situation it is assumed that the process runs flawless. Then in the following paragraph the costs of rejects will be looked at. Lastly the labour costs and the rejects will be combined to give a more complete view of the total costs and the potential savings.

2.5.1 The regular costs

The costs of assembling the LFE packages can be roughly divided in material and labour costs. The costs for tools and (running) the flow bench are neglected, they are assumed to be fixed costs.

Material costs

The materials for the LFE packages do not come cheap, as might be expected for relatively tiny metal precision parts. The LFEs in particular can push the costs up, especially when used in greater numbers. The cost of LFEs varies between €0.21 - €0.95 per LFE. The other materials used in a package are the same for each type of package within the same category. Just as with the assembly times the effect of the number of LFEs in a package becomes apparent when looking at the material costs per package. In Figure 2-11 the total material costs of the spindle packages is shown. Again a rise can be observed with a drop every time a new type of LFE is used. This transition is seen after 100 and 1K0 similar with the assembly times. For a more detailed graph, containing the specific costs per package, see appendix I.

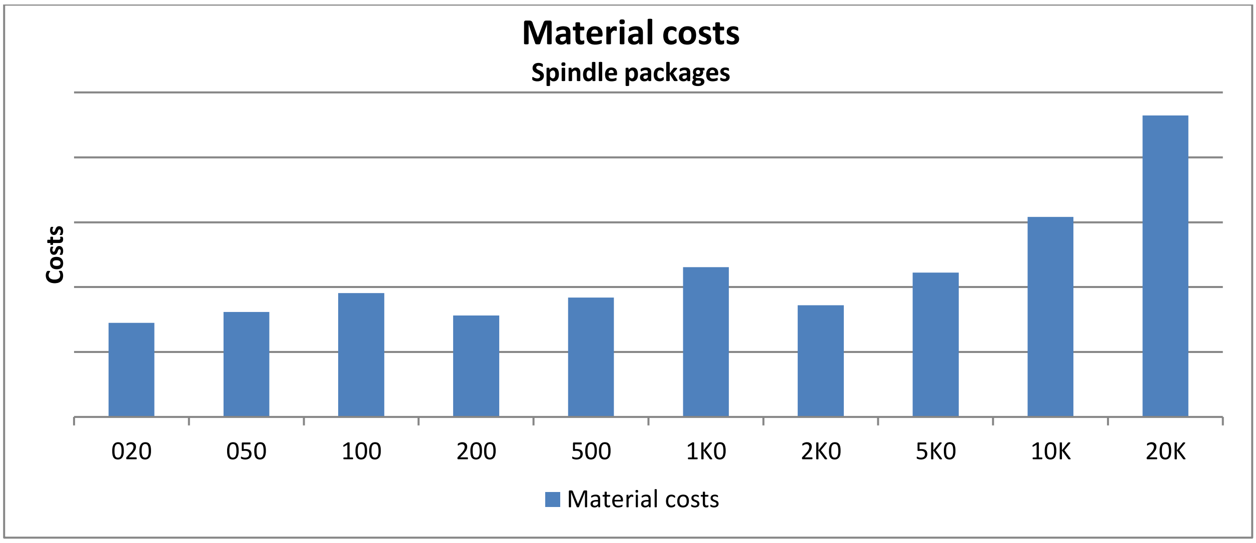


Figure 2-11 Material costs per LFE package type

Labour costs
Since this process is done completely manually there are also quite some man-hours for the company to pay. The labour cost can vary quite a bit depending on several factors. It is assumed that only production personnel with the function of (ass.) instrument maker 1 assemble the LFE packages. This function sits in salary scale F, within Bronkhorst this scale has 10 regular steps and two additional steps which can be used for outstanding performance. The two additional steps are disregarded in calculations. The average time in function of these (ass.) instrument makers is about ten years, however there is a clear division between the instrument makers in the years in function. About half of the instrument makers have been with Bronkhorst for approximately twenty years, the other half for less than two years. It's usually the latter halve that assembles the LFE packages. To calculate labour costs calculation method E from the RVO (Rijksdienst voor Ondernemend Nederland) is used (Rijksdienst voor Ondernemend Nederland, 2019).It is assumed that the direct labour costs for the company adds 32% to the gross salary of the employee. For the indirect costs an additional 15% of the total is added. All this information results in the following labour costs as described in Table 2-4.

Function years in F-scale	Gross monthly salary	Direct labour cost	Total labour cost	Total labour cost per hour
0	€ 2,280	€ 2,964.39	€ 3,409.05	€ 20.70
1	€ 2,333	€ 3,033.48	€ 3,488.50	€ 21.19
2	€ 2,383	€ 3,097.90	€ 3,562.59	€ 21.64
3	€ 2,435	€ 3,165.50	€ 3,640.33	€ 22.11
4	€ 2,485	€ 3,230.50	€ 3,715.08	€ 22.56
5	€ 2,536	€ 3,297.22	€ 3,791.81	€ 23.03
6	€ 2,587	€ 3,363.61	€ 3,868.15	€ 23.49
7	€ 2,666	€ 3,466.11	€ 3,986.03	€ 24.21
8	€ 2,737	€ 3,558.45	€ 4,092.22	€ 24.85
9	€ 2,786	€ 3,621.35	€ 4,164.55	€ 25.29
10	€ 2,848	€ 3,702.16	€ 4,257.48	€ 25.86

Table 2-4 Labour costs of instrument makers

For the labour cost per package type the single timed assembly times will be used, with four different employees per type and the presence of all types is seems the most suitable. In Table 2-5 the labour cost per package type is given for step 2 and 10 of the F-scale. For a complete overview of all steps and their corresponding labour cost per package see appendix J. Additionally, because Bronkhorst often calculates the costs of labour with an hourly rate of €50 this is also included in the table as a worst case scenario.

Type	assembly time	Years in function 2	Years in function 10(+)	Bronkhorst rate (€50)
020	00:33.1	€ 0.20	€ 0.24	€ 0.46
050	00:41.7	€ 0.25	€ 0.30	€ 0.58
100	01:03.6	€ 0.38	€ 0.46	€ 0.88
200	00:36.8	€ 0.22	€ 0.26	€ 0.51
500	00:55.8	€ 0.34	€ 0.40	€ 0.77
1K0	01:21.6	€ 0.49	€ 0.59	€ 1.13
2K0	00:40.1	€ 0.24	€ 0.29	€ 0.56
5K0	01:06.2	€ 0.40	€ 0.48	€ 0.92
10K	01:56.4	€ 0.70	€ 0.84	€ 1.62
20K	03:34.8	€ 1.29	€ 1.54	€ 2.98
50K	05:21.6	€ 1.93	€ 2.31	€ 4.47
70K	06:58.3	€ 2.51	€ 3.00	€ 5.81
M10	03:05.0	€ 1.11	€ 1.33	€ 2.57
M20	02:52.9	€ 1.04	€ 1.24	€ 2.40
M50	04:39.7	€ 1.68	€ 2.01	€ 3.88
1M0	05:09.5	€ 1.86	€ 2.22	€ 4.30

Table 2-5 Labour costs per package type

Considering the output of flow meters of TGP1 in 2018, which can be found in Appendix K. The labour cost incurred by LFE package assembly alone, using the F-scale labour costs, without considering the possibility of rejects, is between €27,037 - €32,311. If the total assembly times could be reduced with 15% these cost would have been €22,982 – €27,464.

When using the Bronkhorst standard labour rate, again without considering the possibility of rejects, the total cost is approximately €62,486.13. If the total assembly times could be reduced by 15% (the target stated in the goal of this project) the total labour costs would be €53,113.21.

2.5.2 The quality (rejection) costs

In the previous paragraph it was assumed that the assembly of LFE packages runs flawless, this is of course an ideal situation and not the case. As was seen in section 2.4 where the rejects have gotten a closer look. In this paragraph the costs that are involved with the rejects are discussed. To give this section more structure the four cost categories as described by the TQM (Total Quality Management) method are used (Slack, Brandon-Jones, & Johnston, 2013). The categories that will be discussed are: Prevention costs, appraisal costs, internal failure costs and external failure costs. The internal failure costs will be quantified for as far as possible.

Prevention costs

“*Prevention costs are those costs incurred in trying to prevent problems, failures and errors from occurring in the first place*.” (Slack et al., 2013, p. 551). In the process of assembling the LFE packages themselves there is not much error or failure prevention, the tools are labelled and for the spindle packages there is a mould to aid in the assembly. However there is a prevention process before the assembly concerning the LFEs. When a new batch of LFEs comes in, samples are taken from this batch and measured to see if they adhere to the set specifications concerning the flow capacity. If the results of these measurements are unsatisfactory the batch of LFEs will not be used in production and the supplier will be contacted. The LFE test-unit used to take the measurements costs €3945,76, see also appendix L. According to the supplier engineer it takes roughly two hours to do measurements on one batch. The measurements that are done at Bronkhorst are also done at the supplier. There is project in the supplier engineering department concerning issues with LFEs (as mentioned in paragraph 2.4.2), in this project it will also be investigated if the measurements at Bronkhorst can be eliminated.

Appraisal costs

"*Appraisal costs are those costs associated with controlling quality to check to see if problems or errors have occurred during and after the creation of the service or product*." (Slack et al., 2013, p. 551). All flow meters undergo an end test to see that everything is in order. If there are issues with the product it will most likely be found in the end test, once found they can be resolved. If there are issues that cannot be easily resolved or if during/after production faulty materials or sub-assemblies (for example a LFE package) are encountered they are registered in the PAR system. The PAR system contains reported defects of materials, sub-assemblies and products. If there are an unusual amount of PARs on the same subject then it will be further investigated.

Internal failure costs

"*Internal failure costs are failure costs associated with errors which are dealt with inside the operation.* " (Slack et al., 2013, p. 552). These costs include, in the case of the LFE packages, the scrap, rework and lost time. According to the rejection process as described in paragraph 2.2.2 LFE packages will first get reworked before they get (partially) scrapped. There is no set schedule to do rework in production, they usually collect the rejects and when the amount seems sufficient (usually every two weeks) one of the instrument makers will spend a day worth of work on reworking the LFE packages. That would mean that each rework session costs, conservatively calculated, between €173.12 - €206.88 in labour costs. When using the Bronkhorst labour rate this would even be €400. Considering that a rework session takes place every two weeks, 26 times a year this would add up to conservatively €4,500.11 - €5,377.87 and using the Bronkhorst rate €10,400.00 During rework parts that are beyond saving are scrapped and replaced, adding cost for the new materials as well as scrap costs for the materials that are not useable anymore. If the reworked package still does not adhere to the set specifications it is usually scrapped in its entirety. The material costs for the whole package, the time spent on initially assembling and reworking it are then practically thrown in a bin. Additionally the time spent by the instrument maker on these rejects could have been spent on another part of the flowmeter. Processes that have perhaps more value added time than the LFE package assembly process (see also paragraph 2.3.2).

External failure costs

"*External failure costs are those which are associated with an error going out of the operation to a customer*". (Slack et al., 2013, p. 552). Most of the times if there is a defect due to the LFE package it gets noticed in either the calibration or end test phase of production. It does not happen often that a failure occurs at a customer due to the LFE package. However that it does not happen often does not mean it never happens. There has been an incident at one of the customers back in 2015, the issues with the faulty flowmeter were due to a LFE package having a too high flow capacity. This fault in the LFE package was retraced to the LFEs used in it. The supplier of the LFEs was made aware of this defect (and that it occurred at one of Bronkhorsts customers). They undertook several steps to improve quality control in the production of LFEs.

2.5.3 The complete picture

By combining most of the findings of the previous chapters it can be calculated how much is spend in total on LFE packages and how much there could be potentially saved. These calculations will be done in a conservative way, using the labour cost based on the salary scale, and also according to the Bronkhorst hourly labour cost rate of €50. All calculations will follow the same assumptions.

Assumptions labour costs

For the labour cost per package the single timed assembly times are used, since there is data present for each package type. The fraction of necessary but non value adding will be determined by grouping LFE packages with similar characteristics in a category with one NNVA percentage. The percentages will be based on the batch (regular) assembly times data and can be found in Table 2-6. To determine the amount of rejects the overall reject rate of 4.01% will be used uniformly over all packages types.

Category	LFE package types	NNVA fraction of time
Small (<10 LFEs), manually counted	020, 050, 200, 2K0	20%
Medium (10<x<35 LFEs),	100, 500, 1K0, 5K0, 10K	30%

manually counted		
Large (>35 LFEs), manually counted	20K, 50K, 70K	55%
M-packages	M10, M20, M50, 1M0	15%

Table 2-6 NNVA fraction of time per category

Overall labour cost (2018)

In Table 2-7 the total labour costs incurred by the LFE package assembly process can be found. This includes the regular production of 2018, the estimated number of rejects in 2018 (4.01% of regular production) and the rework costs of a year.

F-scale	hourly rate	Total labour cost including rejects	Total labour cost NNVA time (including rejects)	Total labour cost rejects
0	€ 20.70	€ 31,216.33	€ 14,350.18	€ 5,343.66
1	€ 21.19	€ 31,943.83	€ 14,684.62	€ 5,468.20
2	€ 21.64	€ 32,622.27	€ 14,996.50	€ 5,584.33
3	€ 22.11	€ 33,334.10	€ 15,323.72	€ 5,706.18
4	€ 22.56	€ 34,018.58	€ 15,638.38	€ 5,823.35
5	€ 23.03	€ 34,721.20	€ 15,961.38	€ 5,943.63
6	€ 23.49	€ 35,420.30	€ 16,282.75	€ 6,063.30
7	€ 24.21	€ 36,499.67	€ 16,778.94	€ 6,248.07
8	€ 24.85	€ 37,472.08	€ 17,225.96	€ 6,414.53
9	€ 25.29	€ 38,134.38	€ 17,530.42	€ 6,527.90
10	€ 25.86	€ 38,985.31	€ 17,921.59	€ 6,673.57
Bronkhorst rate	€ 50.00	€ 75,391.82	€ 34,657.71	€ 12,905.69

Table 2-7 Overall labour cost including rework costs (2018)

The total labour costs associated with the necessary but non value adding time ranges from a conservative €17,921.59 on the top of the F-scale to a whopping €34,657.71 when using the standard rate Bronkhorst uses. In essence these costs could be eliminated and form the total savings potential of the labour costs associated with the LFE package assembly.

Assumptions material costs

The rejects are disassembled and materials that still seem useable will get cleaned and eventually find their way back into production again. However it is policy to always scrap the top and bottom couple of LFEs, so there is always some scrap. Since it is not known how much of the materials get scrapped, the scrap cost will be calculated for a variety of percentages. The number of rejects are determined by using the found reject rate of 4% and the production output of TGP1.

Material costs (2018)

In Table 2-8 the total material costs incurred by the production of LFE packages in the TGP1 production department are shown. The total material costs are based on the production output of TGP1 and the material cost per package type as found in the company's ERP system. The estimated scrap costs are included and shown separate from the total material costs in Table 2-9.

Type	Material cost excluding scrap	Material cost including 5% scrap	Material cost including 10% scrap	Material cost including 15% scrap	Material cost including 20% scrap	Material cost including 25% scrap	Material cost including 50% scrap
020	€5,314.32	€5,324.98	€5,335.63	€5,346.29	€5,356.94	€5,367.60	€5,420.87
050	€6,528.63	€6,541.72	€6,554.81	€6,567.90	€6,580.99	€6,594.08	€6,659.53
100	€10,285.35	€10,305.97	€10,326.59	€10,347.22	€10,367.84	€10,388.46	€10,491.57
200	€11,597.06	€11,620.31	€11,643.56	€11,666.82	€11,690.07	€11,713.32	€11,829.58

500	€23,434.50	€23,481.49	€23,528.47	€23,575.46	€23,622.44	€23,669.43	€23,904.36
1K0	€29,267.70	€29,326.38	€29,385.06	€29,443.75	€29,502.43	€29,561.11	€29,854.52
2K0	€22,282.68	€22,327.36	€22,372.03	€22,416.71	€22,461.39	€22,506.06	€22,729.45
5K0	€23,907.24	€23,955.17	€24,003.11	€24,051.04	€24,098.98	€24,146.91	€24,386.58
10K	€37,338.43	€37,413.29	€37,488.16	€37,563.02	€37,637.88	€37,712.75	€38,087.07
20K	€59,559.30	€59,678.72	€59,798.13	€59,917.55	€60,036.97	€60,156.38	€60,753.46
50K	€93,435.48	€93,622.82	€93,810.16	€93,997.49	€94,184.83	€94,372.17	€95,308.86
70K	€20,377.70	€20,418.56	€20,459.41	€20,500.27	€20,541.13	€20,581.99	€20,786.27
M10	€101,652.10	€101,855.91	€102,059.72	€102,263.54	€102,467.35	€102,671.16	€103,690.22
M20	€193,920.32	€194,309.13	€194,697.94	€195,086.75	€195,475.56	€195,864.37	€197,808.42
M50	€232,093.19	€232,558.54	€233,023.88	€233,489.23	€233,954.58	€234,419.92	€236,746.66
1M0	€305,753.00	€306,366.03	€306,979.07	€307,592.10	€308,205.14	€308,818.17	€311,883.35
Total	€1,176,747.00	€1,179,106.38	€1,181,465.76	€1,183,825.13	€1,186,184.51	€1,188,543.89	€1,200,340.78

Table 2-8 Total material costs (2018)

The saving potential is in the scrap costs, those are the extra costs that add to the grand total but do not add value in any way, shape or form.

Type	**scrap factor 5%**	**scrap factor 10%**	**scrap factor 15%**	**scrap factor 20%**	**scrap factor 25%**	**scrap factor 50%**	**scrap factor 75%**
020	€ 10.66	€ 21.31	€ 31.97	€ 42.62	€ 53.28	€ 106.55	€ 159.83
050	€ 13.09	€ 26.18	€ 39.27	€ 52.36	€ 65.45	€ 130.90	€ 196.35
100	€ 20.62	€ 41.24	€ 61.87	€ 82.49	€ 103.11	€ 206.22	€ 309.33
200	€ 23.25	€ 46.50	€ 69.76	€ 93.01	€ 116.26	€ 232.52	€ 348.78
500	€ 46.99	€ 93.97	€ 140.96	€ 187.94	€ 234.93	€ 469.86	€ 704.79
1K0	€ 58.68	€ 117.36	€ 176.05	€ 234.73	€ 293.41	€ 586.82	€ 880.23
2K0	€ 44.68	€ 89.35	€ 134.03	€ 178.71	€ 223.38	€ 446.77	€ 670.15
5K0	€ 47.93	€ 95.87	€ 143.80	€ 191.74	€ 239.67	€ 479.34	€ 719.01
10K	€ 74.86	€ 149.73	€ 224.59	€ 299.45	€ 374.32	€ 748.64	€ 1,122.95
20K	€ 119.42	€ 238.83	€ 358.25	€ 477.67	€ 597.08	€ 1,194.16	€ 1,791.25
50K	€ 187.34	€ 374.68	€ 562.01	€ 749.35	€ 936.69	€ 1,873.38	€ 2,810.07
70K	€ 40.86	€ 81.71	€ 122.57	€ 163.43	€ 204.29	€ 408.57	€ 612.86
M10	€ 203.81	€ 407.62	€ 611.44	€ 815.25	€ 1,019.06	€ 2,038.12	€ 3,057.19
M20	€ 388.81	€ 777.62	€ 1,166.43	€ 1,555.24	€ 1,944.05	€ 3,888.10	€ 5,832.15
M50	€ 465.35	€ 930.69	€ 1,396.04	€ 1,861.39	€ 2,326.73	€ 4,653.47	€ 6,980.20
1M0	€ 613.03	€ 1,226.07	€ 1,839.10	€ 2,452.14	€ 3,065.17	€ 6,130.35	€ 9,195.52
Total	€ 2,359.38	€ 4,718.76	€ 7,078.13	€ 9,437.51	€ 11,796.89	€ 23,593.78	€ 35,390.67

Table 2-9 Estimated scrap costs (2018)

Depending on how much of the materials actually do get scrapped the savings could be significant. The target set in this project is to halve the current reject rate, reaching the targeted 2% reject rate or perhaps even a reject rate below 2%. If the target of 2% is reached it could save between €1,179.69 - €17,695.34.

2.6 The impact on employees

Bronkhorst cares about her employees, which is emphasized by a recent project “Bronkhorst builds” in which the managerial layer of Bronkhorst defined 5 values that define Bronkhorst. One of these values is that employees need to feel good about what they are doing, that they get joy form their work. One of the other values was care for one another. When looking at the different aspects of the LFE assembly process, these values do not seem applicable.

Emotional aspect

The assembly of LFE packages is often regarded as the least interesting and least enjoyable task in production. The task is often given to new production personnel or an employee that recently messed something up in another part of production. Nobody will complain about having to do this task, yet no one will say they looked forward to it. It is one of those tasks you just have to get it over with. What employees will complain about is the length of time they have to do this task, some employees will be busy assembling LFE packages for half a day or even a whole day. None of the employees seemed particularly sad about the possibility of fully automating this process.

Physical aspect

As said some employees will spend half a day or a whole day assembling the LFE packages. The assembly of LFE packages is done in a flow bench, a workspace that continuously blows air over the surface area to prevent contamination from dust. People often get dry eyes after sitting at a flow bench for a certain amount of time. It is not the most comfortable place to be working.

Perhaps even more important however is the nature of movements involved in assembling a LFE package. The movements made are basically the same couple of movements over and over again. According to the definition of repetitive movements by the Ministry of Social Affairs and Employment the assembly of LFE packages falls under this category (Ministerie van Sociale Zaken en Werkgelegenheid, 2019). The movements are repeated within 90 seconds and are done for more than 2 hours a day. Adding to the risk of injury due to repetitive movements is the fact that it is a precision task. Therefore the assembly of LFE packages has a significant chance to cause RSI (repetitive strain injury). In the law it is stated that processes should be designed or adapted to limit the dangers to the physical wellbeing of the employee (Grave et al., 1997). In case of the LFE package assembly process there is definitely room for improvement.

2.7 Conclusion

The number of LFEs and subsequently LFE packages production has steadily increased over the years, with the exception of 2018 where the number of purchased LFEs grew with 92% to a grand total of 3.2 million LFEs. Half of these LFEs were processed by production department TGP1 where most data was collected for further analysis of the assembly process. The analysis focused on the time spent on assembly, the quality of the process and subsequently the costs associated with the assembly process.

As might be expected the assembly times are greatly dependant on the number of LFEs that have to be manually counted, the greater the number of LFEs in the package the longer assembly takes. This excludes the M-packages, since those get measured not counted. When looking at the level of experience an employee has in assembling the LFE packages it is clear that the more experienced employees have a more methodical strategy to assembling the packages. This makes them slightly slower on the smaller packages, but benefits them greatly on the larger ones. Due to their experience they are also capable of assembling the M-packages a bit quicker, they make better estimates of the size an M-package should be. The time of day also seems to be a factor influencing the assembly times of LFE packages, in the morning the assembly times are roughly 21% faster than in the afternoon. However it must be said that the data was somewhat limited and that it is not sufficient to draw any hard conclusions on the time of day. When the focus from single package assembly times shifted to regular production it became apparent just how much time was actually lost in the necessary but not value adding activities, especially the counting and orienting of the LFEs. In the most extreme case 63.6% of the assembly time was spent on just counting and orienting the LFEs. There is time to be won in this assembly process.

The rejection process of the LFE packages had (and still has) quite some mystery to it. There is no documentation available on how the process should go and when asked every employee in the production department gives a different answer. Even though the process of rejecting a LFE package might be unclear it was definitely clear that there were plenty of rejects to go around. An overall reject rate of 4% could be determined from rejects that were collected over the span of nine weeks. Noticeably the 20K package again managed to stand out among the other packages with an observed reject rate of 13.7% in the same nine week period. The reasons for rejecting the packages were as much surprising as it was insightful. The suspicions that the number of LFEs or the orientation of the LFEs might be the cause turned out to be completely wrong. Those defects hardly occurred. The defects that did occur frequently and were identified as main causes by the Pareto analysis were a circular scratch on the bottom LFE of spindle packages and the seemingly fine packages. The seemingly fine packages had no visible defect, however it is known that due to variation in the flow capacity of the individual LFEs the LFE packages might not be up to specifications. Additionally the body in which the LFE package is mounted can also have variations, making some combinations of LFE package and body stand out during the calibration or end test. The rejection rate is double of the targeted rejection rate of 2% and the variation in several parts seems to have significantly contributed to that percentage. Tackling the circular scratch that occurs in the spindle packages might be the way to reduce the reject rate on the short term.

When analysing the costs associated with the production of LFE packages it can be seen that a significant amount of the total costs consists of the materials, approximately 83.5% - 97.3%. The materials that are uniform to the packages within a package type are a given and form a constant cost. The variable within the material costs are the number (and type) of LFEs. The materials are practically a given for the LFE packages and due to the specialist nature of the parts and the product it is eventually used in there is not much opportunity for savings on materials. The scrap costs do provide potential for savings between €2,359.38 - €35,390.67 depending on the percentage of scrapped materials. The labour forms roughly 2.7% - 16.5% of the total costs associated with the LFE packages. As stated in there is quite some time spend on necessary but non value adding activities (up to 68.66%), if this could be reduced or eliminated the labour costs could be reduced by approximately €17,921.59 - €34,657.71 (based on 2018). The assembly of LFE packages fall sunder a function that sits in salary scale F. There are salary scales below F, there could be potential for formulating a new function within production for these kind of assembly process.

Apart from the functional and financial shortcomings of the process there are also some concerns about the well-being of the employees who are assigned the task of assembling the LFE packages. Bronkhorst believes it to be important to enjoy your work, none of the instrument makers seem to particularly enjoy the assembling of LFE packages. The assembly is done in a flow bench, which continuously blows air towards the employee creating dry eyes. The assembly of LFE packages is a precision task that consists out of multiple repeated movements, there is a serious potential for RSI if this task is performed for several hours.

In short; the pressure on the production departments has increased over the years. The assembly times consist, especially for the larger packages, out of a lot of necessary but non value adding activities. There are several factors like experience, the time of day and the assembly strategy that influence the speed of the assembly process. The process of rejecting a LFE package is unclear, the LFE packages lack traceability and have a reject rate that is double the targeted reject rate (4% vs 2%). The LFE packages are plagued by variation, both in their own flow capacity as well as the variation in the body they are mounted in. Additionally the spindle packages have an issue with scratched LFEs. Scrap and rework increase costs and with lack of traceability it might increase even more. Putting older (more years in function) employees on the assembly of LFE packages increases costs (per package) significantly. For an overview of findings see Figure 2-12.

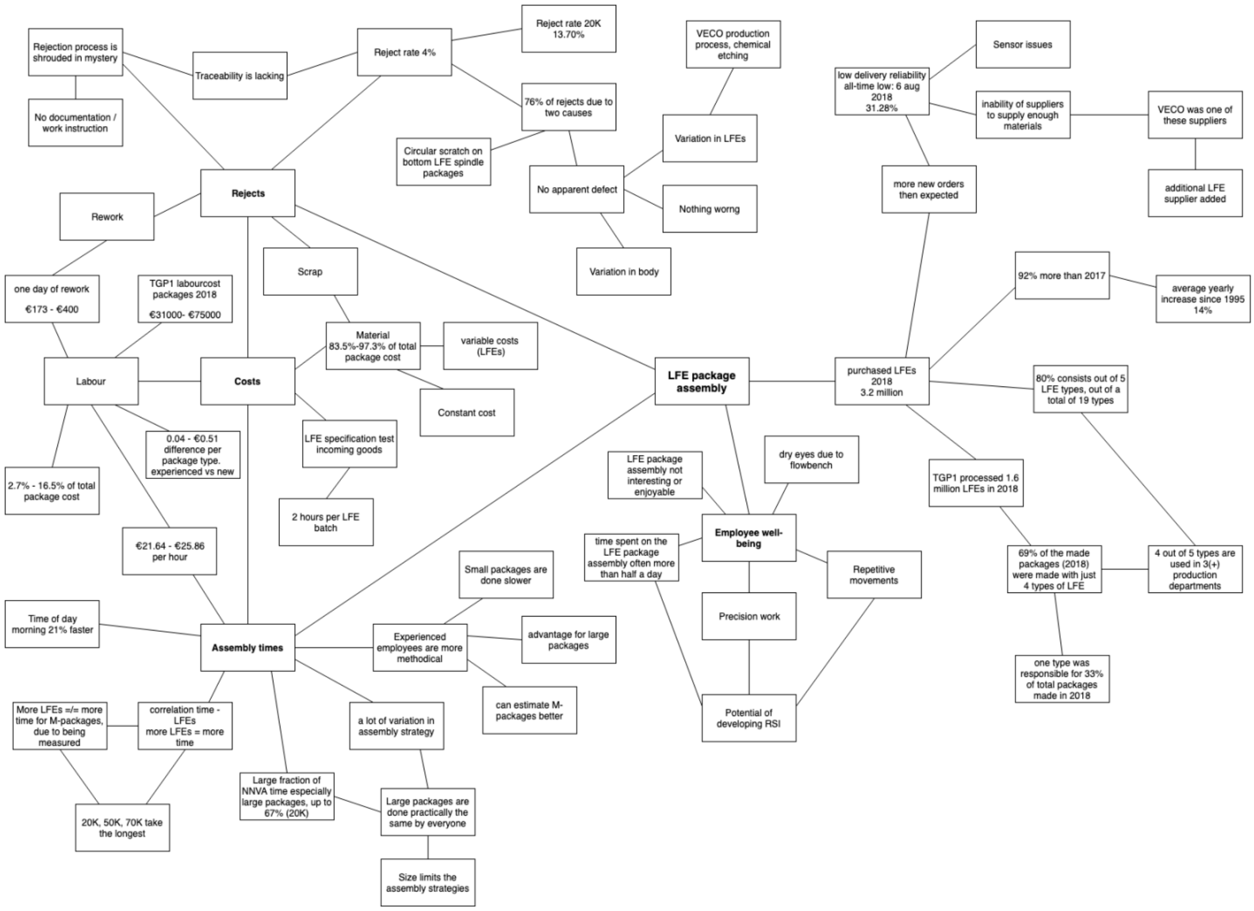


Figure 2-12 Findings cluster

3 Creation of alternative process designs

Now that the analysis of the current assembly process is complete and its strong points, shortcomings and limits are known, alternatives can be proposed and worked out in detail. The LFE package assembly process is an integral part of Bronkhorst production and thus many people will come in contact with it. There are bound to be ideas within the company on how to tackle the redesign of the assembly process, these will be discussed first. Then, for the second section in this chapter, the literature will be consulted for alternative process designs and methods to improve the current process. In both sections there will be a division between alternatives based on their estimated time to implement (considering the required process changes and capital investment); short-term, medium-term and long-term.

3.1 “Bronkhorst” thoughts on alternatives

As said in the introduction of this chapter a lot of people have ties to the assembly process of LFE packages since it is an integral part of most Bronkhorst products. The ideas that were collected came from all layers of the company, from the supply chain manger to the instrument makers that actually assemble the packages. Most ideas are described in this section, some ideas that had a lot of similarities have been combined.

3.1.1 Short term improvements

Short term improvements should be implementable within a timespan of roughly three months. These improvements will not alter the process drastically, more likely they will mostly be quality of life improvements.

Counting machine for the LFEs

Suggested by one of the instrument makers of production department TGP1. He figured that if banks can count coins to a specific number with a machine it should also be possible with the LFEs. This idea would help reduce the necessary but non value adding time that is now found to be plentiful in the current process. Ideally it would be a machine that could be used uniformly for all LFE types processed by the particular production department where it is deployed. The instrument maker would empty a (couple of) bag(s) of the correct LFEs into the machine, type in the number he or she needs and the machine would dispense that number. The machine should come with the option to either quickly change the LFEs stored in it or it should have a way to differentiate between the different types of LFEs. This machine would reduce the necessary but non value adding time by eliminating the need to count the LFEs, saving on the labour costs. There, most likely, will not be an “off the shelf” counting machine suitable for LFEs. So there will be some costs developing this particular tool. Instead of giving an official engineer this task, the developing of a counting machine could also be considered as a project for MBO (or HBO) mechanical engineering students.

3.1.2 Medium-term improvements

Medium-term improvements should be implementable within a time span of 3-6 months. These improvements might alter the current process substantially, removing or altering an integral sub-process within the process. The process however will remain recognizable as an adaptation of the current process.

Supplying LFEs on a rod

Suggested by several people within the company, ranging from supplier engineers to the production personnel. By supplying the LFEs, pre-oriented on a rod, the need for orienting would be eliminated. This would reduce some of the necessary but non value adding time that is currently plaguing the LFE package assembly process. Of course the supplier will have extra operations to perform, which will increase the cost of the LFEs. The supplier of the LFEs has already mentioned to be willing and able to supply the LFEs in such a way. Additionally if the supplier would stack the LFEs directly from the plate they were etched on, they could evenly distribute the LFEs from the plate over the packages. This would make it less likely for LFEs with either a low or a high flow capacity to all end up in the same package. This would limit the variability in LFE packages (§2.4.2). This improvement could be combined with the idea to supply the LFEs in numbers corresponding to the number of LFEs found in several package types.

Supplying the LFEs in the numbers needed for the packages
Suggested by several people within the company, ranging from supplier engineers to the production personnel. Usually mentioned in one breath with the idea to supply the LFEs pre-oriented on a rod. By supplying the LFEs in the correct number for the packages the need for counting would be eliminated and with it a large portion of the necessary but non value adding time. However since there are several packages, with differing needs for the number of LFEs, which use the same LFE type it could prove difficult to supply the exact amount for every package type. A solution could be to only supply the LFEs in the number of the largest package that is made with that type of LFE. The smaller packages would then be made with a small portion of the supplied number, while the largest package would be made instantly by using a freshly supplied bag/rod of LFEs. This would eliminate the largest portion of necessary but non value adding time, while keeping the simplicity of one way of supplying LFEs per LFE type. Of course the supplier will have extra operations to perform, which will increase the cost of the LFEs.

3.1.3 Long-term improvements
Long-term improvements should be implementable within a time span of 6 months to 2 years. These improvements will likely replace most of the current process. The changes proposed for the long-term are quite drastic.

3D-printing LFE packages
Suggested by one of the process engineers. Instead of assembling multiple different components into a LFE package to get the right flow capacity, a different component could be designed with the same function as the LFE package. This component would be made by the means of 3D-printing using a porous material. The size and the type of material used would determine the flow capacity. The benefits of this method would be that it removes the entire need of the LFE package assembly process, it could make LFE “packages” overnight and it would save on delicate metal precision parts. This also means that the variability that is currently plaguing the LFEs (§2.4.2) would no longer matter. It remains to be seen if it is feasible (for all package types), both in the financial sense of feasibility and in the sense of whether it is actually possible to get the exact right flow capacity using 3D-printing in combination with a porous material.

Altering the etching process of the supplier
The variation of flow capacity in the LFEs is caused by the process of chemical etching, as explained in paragraph §2.4.2. This variation seems to be the main cause for rejecting LFE packages. Instead of working around the variation by mixing the LFEs the variation itself could be tackled by altering the etching process which is currently the cause of the variation. However, this could prove difficult (and expensive) as it is a process of the supplier and not a process owned by Bronkhorst.

Automating the assembly process by the means of a cobot
Suggested by most of the process engineers. In the design of the new production cell (as mentioned in §1.1.2) a cobot is included. This “collaborative robot” is supposed to automate the calibration and end test of a flowmeter, but there is definite interest to see if a cobot could fulfil other duties like (partially) assembling the LFE packages. The cobot could be performing the entire assembly of LFE packages or for only the counting, orienting and stacking of the LFEs. If the cobot would take on the entire assembly of LFE packages it would be no longer needed for an instrument maker to spend time on the LFE packages, he/she could pick up different (more value adding) tasks instead. If the cobot was limited to the counting, orienting and stacking of LFEs then it would eliminate most of the necessary but non value adding time. This would save up to 46% of the total labour costs associated with the assembly of LFE packages (§2.5.3). Additionally by (partially) automating the assembly process of the LFE packages the process might be less sensitive for rejects. However a second cobot would need to be purchased, possibly a different one than the one responsible for calibration. The cobot for the LFE package assembly process would need to be further researched.

Outsourcing the assembly process
Suggested by several people in the company. The assembly of LFE package is a relatively simple task that does not need the prior knowledge from any specific education. It merely requires some explaining on what tools to use and to handle the material with care. The instrument makers that are currently involved in assembling the LFE packages are capable of doing more challenging tasks in production. It might therefore make sense to remove the LFE package assembly task from the people who can spend their time on more valuable tasks. The assembly would however still have to take place, this might be

accomplished by outsourcing this particular task at a different company. This would free up the instrument makers to pick up other tasks, however it remains to be seen if it is cost effective.

Alternatively, since the assembly process is relatively simple, a slightly different approach could prove interesting. One of Bronkhorsts goals is to be a social organization, this is shown for example by their eagerness to find suppliers close to the head office to stimulate the local economy and the events they sponsor in the community. Instead of outsourcing the process to a "regular" company they could also consider the option of a social workplace. A social workplace employs people with a greater distance to the labour market (for example people with a physical or psychological handicap). By outsourcing the assembly of LFE packages to a social workplace would mean that the instrument makers can pick up other tasks, that the labour costs associated with the assembly will be lower and that Bronkhorst would be more invested in the social side of business.

Moving the assembly process to the supplier of LFEs
Suggested by several people in the company. Even though technically this would also be considered outsourcing it is described separately because outsourcing the assembly process at the company that produces the LFEs is a particular situation. The reasoning behind this idea is relatively simple; if the supplier can supply the LFEs stacked, oriented and counted they could perhaps also do the final step of screwing it all together. It would free up the instrument makers, but whether it is cost effective and if Bronkhorst would want such an integral part to be (almost) totally in hands of one supplier remains to be seen.

3.2 Literature study on alternatives

Bronkhorst is most likely not the first company to struggle with a manual assembly process that is not running quite as efficient as it could be. There is bound to be information, methods and ideas to be found in existing literature that might prove useful in this situation. In the literature study there will be special focus on Lean methods since this is a company endorsed method. However other literature will not be neglected, methods and ideas not directly linked with Lean but seemingly useful will be used.

Lean
As stated in the introduction Lean is an already used and promoted methodology within the company. Since it is mainly the quality of the process that is focused on in the stated goal of this project it makes sense to have a look at the framework for Lean quality as described by (Bicheno & Holweg, 2016, p. 235). In this framework quality is divided into three aspects; complexity, variation and mistakes. Each aspect has its own Lean tools to improve with either the focus on the product or the process, as can also be seen in Figure 3-1.

	Product	Process
Complexity	GT, DFM, DFSS, QCC tools, Kano Model	DFM, Layout, SOPS, 5S, SMED, Mapping
Variation	Six Sigma, Shainin tools	Six Sigma, visibility, SPC, TPM, 7 quality tools, 5S, SOPS, Shainin tools, Successive inspection
Mistakes	Pokayoke	Pokayoke, 5S, SOPS, visibility

Figure 3-1 Lean quality framework (Bicheno & Holweg, 2016, p. 235)

Since complexity is not one of the issues plaguing the LFE package assembly process, the corresponding row in the Lean quality framework is disregarded. The most interesting category for this project is the second, containing the aspect of variation. The analysis of the rejects showed that variation could be the main culprit when it comes to causing rejects (§2.4.2). The aspect of mistakes might not be as interesting as the analysis also showed that the predicted mistakes rarely occur. However the company is still concerned about the possibility of mistakes, so this row will not be entirely disregarded. Not all tools named in the framework will be applicable or useful for the LFE package assembly. The most promising and/or implementable tools will be explored in the paragraphs below together with other tools and ideas found in other literature.

3.2.1 Short-term improvements

Short term improvements should be implementable within a timespan of roughly three months. These improvements will not alter the process drastically, more likely they will mostly be quality of life improvements.

5S (Sort, Straighten, Sweep, Standardise & Sustain)

According to Slack "*the 5Ss can be thought of as a simple housekeeping methodology to organize work areas*"(2013, p. 484). This methodology entails keeping the working space clean, all tools and materials put in their respective places which can be easily reached and eliminating all that is not necessary in the workspace. However Bicheno & Holweg (2016) argue that by viewing 5S as a clean-up there is a risk that 5S is seen as trivial. According to Bicheno & Holweg (2016) the real objectives of 5S should be: to reduce waste, to reduce variation and to improve productivity.

5S is already used to some extent but could be further improved and implemented. Currently the execution of 5S in the production department (TGP1) seems to follow the housekeeping perspective as described by (Slack et al., 2013). There are regular clean-ups of the entire department and all materials and tools have a designated place. When looking at the specific Ss as described by (Bicheno & Holweg, 2016) there seems to be room for improvement in 3 of the 5 Ss. Scan, Standardise and Sustain all have aspects that are seemingly not quite implemented yet in the production department. Scan and Sustain are closely related in this case. Scan refers to the diligence of the employees, once they spot something out of place or another abnormality they should put it where it belongs and find the cause of the abnormality. Sustain basically means to keep everyone continuously participating in the 5S activities. Between the regular clean-ups it can be observed that the workspaces, specifically the flow benches used in the assembly of LFE packages, are often in a bit of a messy state. There will be (faulty) materials on the workspace and the tool drawer will be disorganized and occasionally missing a tool. Scan and Sustain could be improved if the employees would also keep 5S in mind during regular days and not only during the clean-up.

While Scan and Sustain could improve a bit, there are seemingly more benefits when considering the third S that could be improved; Standardise. "*Standardising also includes measuring, recording, training and work balance. Here, visual management becomes the norm.*" according to Bicheno & Holweg (2016, p. 138). Slack (2013, p. 712) defines visual management as follows: "*An approach to making the current and planned state of an operation or process transparent to everyone*." This should include, among others, information on schedules, standard work, quality and maintenance. Not all of this information is easily available, let alone visually available in the production department. This information could help in monitoring the processes, specifically the LFE package assembly, which in turn could prove useful in controlling and improving the processes.

SOP & Self Inspection & Successive Inspection

A standard operating procedure (SOP) describes, in a concise and simple manner, how a job should be done. Currently it can be observed that nearly every employee has his/her own way to assemble the LFE packages (as mentioned in §2.3.2). This in itself is variation in the process. The current work instructions are now mainly used to check how many LFEs go into a specific package type and what additional materials are needed. It often takes a little while for them to locate the information on the work instruction sheet. By replacing the current instruction sheets whit a SOP they could remove the variation in the process and make the information that is most looked for more apparent on the sheet.

Additionally inspection steps could be included in the SOP. One of the employees that was observed while making LFE packages first counted all LFEs and then he would stack them. During the stacking, even though he already counted the LFEs, he counted them again as a way to make sure he got the exact number. This self-inspection could be useful to also include in the SOP, since the company is worried about wrongly counted LFE packages. Additionally successive inspection could be used in the step following the assembly of LFE packages. A quick visual inspection might ensure that packages with slight damage or contamination are not installed in a body, but are immediately put in the container for packages that are to be reworked. As Bicheno & Holweg (2016, p. 237) put it: "*These types of judgement inspection are worthy of consideration because they provide immediate or short-term feedback and (in case of successive checks) are capable of a high degree of reliability.*".

3.2.2 Medium-term improvements

Medium-term improvements should be implementable within a time span of 3-6 months. These improvements might alter the current process substantially, removing or altering an integral sub-process within the process. The process however will remain recognizable as an adaptation of the current process.

Six Sigma

Often named in one breath with Lean, but whereas Lean focuses mainly on mistakes and complexity, Six Sigma focuses mainly on variation. "*The main purpose is to identify and eradicate sources of undesired variation.*" (Bicheno & Holweg, 2016, p. 241). Six Sigma is based on statistics, focused on the reduction of variation (and its accompanying financial gain) and is done by the means of projects rather than continuous improvement.

"*The Six Sigma approach uses a number of related measures to assess the performance of operations processes*" (Slack et al., 2013, p. 593). It does so by looking at the DPMO (Defects Per Million Opportunities), which can be converted to a Sigma level. The DPMO is calculated as followed:

$$DPMO = [Number\ of\ defects/(Number\ of\ measurements\ taken * Number\ of\ units\ produced)] * 1000000$$

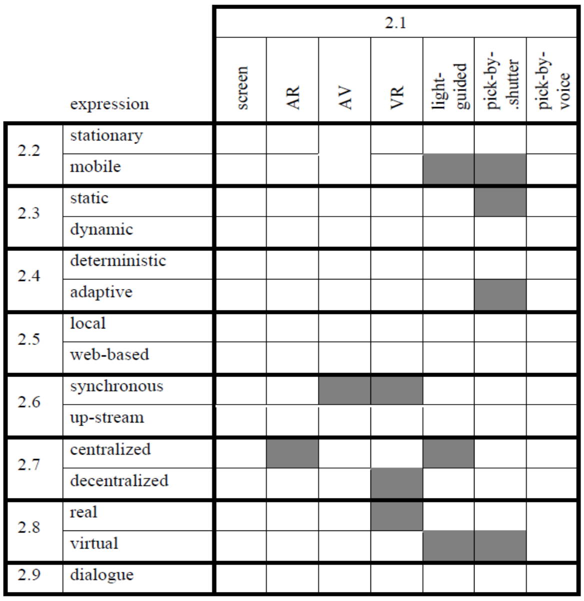
Equation 3-1 DPMO formula as described by Bicheno (2016, p. 243)

The Sigma level of the LFE package assembly process could be determined with the gathered data on rejects in weeks 7 till 15 (Appendix H). A total of 227 rejects were collected by gathering them at three separate dates, the total production in weeks 7 till 15 was 5735 LFE packages. This yields a DPMO of 13194 which corresponds with a Sigma level between 3.7 and 3.8. The goal set by Six Sigma is in the name, a Sigma level of 6.0 is the eventual goal in this methodology. To reach this goal projects are done to reduce variability and improve processes. These projects are (almost) always done using the DMAIC (Define, Measure, Analyse, Implement and Control) improvement cycle. Often these projects use tools of other methodologies to improve the actual process, which is also a reason why Lean and Six Sigma often are named together.

Some of the older employees in the production department mentioned that in the past 10-20 years there have been people running projects on the LFE package assembly. However all those projects seem to have died silent deaths. The first few steps of the DMAIC cycle might have been completed, but then the implementation phase seems to not be followed through. If the variation in the LFE package assembly is to be lowered, then the projects with that very goal should be followed through.

WIS (Worker Information System)

A WIS (worker information system) is a tool to deliver needed information to employees. This tool can range from the old school paper based work instruction to the futuristic use of VR (virtual reality). A WIS should support an employee in dealing with the diversity of information that is needed in the production environment (Lušić, Fischer, Bönig, Hornfeck, & Franke, 2016). There are already ideas within Bronkhorst of implementing two varieties of WISs in the new production cell, a screen and a pick to light system. However, since the new production facility (where the new production cell will be used) is still a few years away a WIS might prove useful in the current production facility as well. Especially when considering that currently only paper based instructions are used for the assembly of LFE packages. Lušić (2016) provided guidelines for choosing WIS systems based on their characteristics and on boundary conditions set by the company. These guidelines and restrictions inherent to the nature of the WISs are summarized by the matrix that (Lušić et al., 2016) created (see Figure 3-2).



	expression	2.1 screen	AR	AV	VR	light-guided	pick-by-.shutter	pick-by-voice
2.2	stationary							
	mobile							
2.3	static							
	dynamic							
2.4	deterministic							
	adaptive							
2.5	local							
	web-based							
2.6	synchronous							
	up-stream							
2.7	centralized							
	decentralized							
2.8	real							
	virtual							
2.9	dialogue							

Figure 3-2 ***"Example for combination restrictions generated by today's practical point of view."*** **(Lušić et al., 2016, p. 1116)**

When looking at the LFE package assembly process and the expressions as stated in the matrix and further defined in the paper by Lušić (2016), the needs of an information system for this process can be further defined in the terms of those expressions. The task of assembling the LFE packages is done only in flow benches, there is no need during the process to move to a different workstation, therefore a stationary WIS would be more sensible than a mobile one. The information that is crucial for the LFE assembly process is mainly the correct number of LFEs and what type of materials to use. This is the information that is most often looked for. The actual operations of the assembly process are known by heart, the employees hardly ever use the work instruction to look up processes. Due to the simplistic nature of the information the provision of information is most suited to be done in a static manner. Since the assembly of LFE packages consists of consecutive steps, with no possibility of altering the order of steps to be taken, deterministic worker guidance will be most suitable. The information which is provided to the employees is from within the company, a local network would thus be sufficient for the LFE assembly process. The provision of information should be synchronous with the assembly, this should be possible due to the simplistic nature of the information and is should help in preventing additional non-value added time that can be caused by an upstream provision of information (Lušić et al., 2016). Workplace specific WIS seems more convenient than a central WIS for multiple workstations, as it does not require the employee to walk over to the central WIS and since the employees from different workstations could be working on different package types. In the case of LFE package assembly it would make little sense to provide the information in a virtual manner, the use of CAD-models (Computer-Aided Design) to observe LFE package in more detail does not help the assembly in any way. The option to dialogue with the WIS might prove useful. This would allow for the collection of specific kinds of data, for example the registration of rejects.

When considering the expressions as stated in Figure 3-2 and the manner in which the LFE assembly process can be characterized by them, a few options for WISs can be eliminated by the restrictions set by Lušić (2016). The "pick by shutter", "augmented virtuality" and "virtual reality" are eliminated due to these restrictions. Taking the production environment in consideration, with all its different sounds like music and electrical screwdrivers, a pick-by-voice system also does not seem very convenient. The three options that remain are screens, augmented reality and a pick-by-light system. The use of augmented reality requires a great effort from the IT department to set up the system. The IT department of Bronkhorst is already busy with regular operations and other projects, additionally the knowledge necessary to implement such a system might not available within the company. Therefore it might be interesting to investigate the option of outsourcing the set-up of such a system. Even if the set-up of such a system could be pulled of it remains to be seen how much more helpful it would be relative to the other two options. The pick-by-light system could prove useful, the current work instruction are often quickly consulted for the type of materials needed. With a pick-by-light system it would be obvious within a blink of an eye. However a pick-to-light system does not convey the information on the assembly process itself or, more importantly, the number of required LFEs that are necessary for a specific LFE package type.

The pick-to-light system could be complemented with screens. The screens could display the information regarding the process and the number of required LFEs.

The benefits of using a WIS, in this case that would be the combination of screens and a pick-by-light system, are perhaps not directly counteracting any quality issues, but could provide some aid in monitoring quality issues. If the system is open for dialogue any defective parts could be registered without leaving the workstation. Additionally a log could be kept of the production of LFE packages, with times, number of assembled packages, who assembled them, etc. This would provide far more insight into the workings and performance of the process than is currently possible. This insight could help control the process in the future.

3.2.3 Long-term improvements

Long-term improvements should be implementable within a time span of 6 months to 2 years. These improvements will mostly replace the entire process. The changes proposed for the long-term are quite drastic.

Automating by the means of a cobot/robot or mechanical solution

The LFE package assembly process could be (partially) automated by the means of a cobot. Cobot is short for “collaborative robot”; a robot that works alongside humans. A cobot should provide the benefits of automation without losing the advantages that a human operator brings. “*The human-robot integrated production systems combine the creativity, intelligence, knowledge, flexibility and skill of humans with the electronics and physical power, speed and accuracy of a machine. The approach enables an assembly system to produce complex on-demand products at reduced costs*.” (Malik & Bilberg, 2017, p. 1152). By (partially) automating the LFE package assembly the time spent by production employees on assembling the LFE packages could be significantly reduced. Additionally, if the counting, orienting and stacking is done by a robot, then the company might feel more reassured that the majority of the rejects are not caused by human oversight. Furthermore, the implementation of a cobot (or a robot or mechanical solution) might reduce, the currently needed, repetitive movements and subsequently reduce to risk of injuries associated with those movements (Botti, Mora, & Regattieri, 2017).

When implementing a cobot there should be some consideration on how automated the process should be. Over the past decades lean principles have been combined with automation technologies to come up with simpler and less over engineered solutions (Malik & Bilberg, 2017). This Lean automation, as one could call it was defined by Dulchlnos as followed: ““*Lean automation is a technique which applies the right amount of automation to a given task. It stresses robust, reliable components and minimizes overly complicated solutions.”* (Dulchlnos & Massaro, 2005). To get some idea of the degree of automation that would be well suited for the LFE package assembly process, the following figure (Figure 3-3) as used by Malik & Bilberg (2017) might prove insightful.

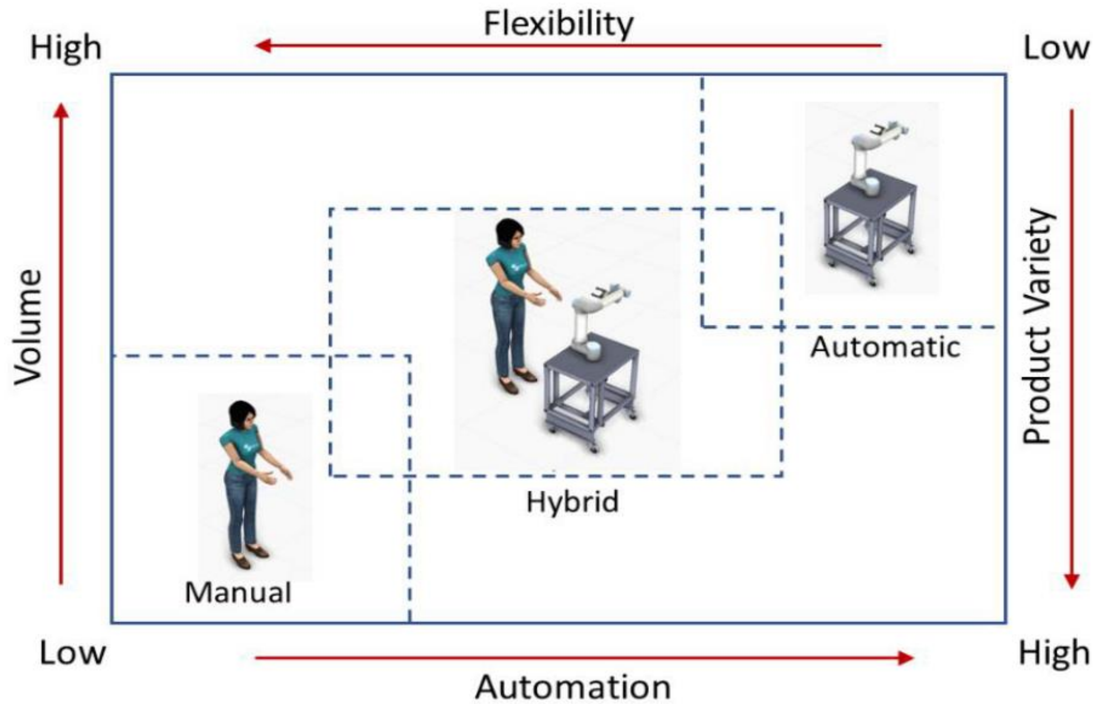


Figure 3-3 "*Flexibility and automation*" (Malik & Bilberg, 2017, p. 1153)

In the figure it can be observed that the degree of automation influences the flexibility of the process, the more automated the process is, the less flexible it will be. The same goes for the production volume and the product variety, if there is a great variety of products to be produced the volume of the production output will be lower. Considering the characteristics of the LFE package assembly process, it could be placed in this figure. The assembly process (in TGP1) is responsible for the assembly of 16 different types of LFE packages. Those 16 different types can however be categorised by their assembly process in 3 categories (as described in §2.2.1). Therefore the product variety could be considered medium with a slight preference to high. The flowmeters, in which the LFE packages are installed, are produced based on client orders, since a lot of the flowmeter are made to the specifications of the client there are no flowmeters made in advance. The production volume could be considered to be moderately low. This would place the LFE package assembly in the hybrid category with a slight preference towards to manual corner in the figure. Of course as goals might change concerning the variety of products and the volume in which they are to be produced (there some predictions that TGP1 will go from producing 750 flowmeters in a week to 2000 flowmeters in a week), the placement in the figure, and with it the degree of automation, might shift.

General conclusion literature

When considering the current process and the improvements/alternatives proposed by the literature there are certain trends that can be identified. First of all the need for insight and control of the process, this is an important aspect in most of the, by the literature, suggested improvements and alternatives; 5S, SOP & self/successive-inspection, WIS and to some extent Six Sigma. Second, the actual undertaking of action; not all (Six Sigma) projects are followed through and the implementation of 5S seems to be done in a minimalistic manner. Lastly, when it comes to the long-term, automation seems the way to go. However the degree of automation depends on whether the company wants to automate the process as it is now, or according to future goals that are still very much open for change.

4 Assessment of alternatives

In the previous chapter several improvements and alternative process designs have been identified. These findings need to be assessed on their usefulness to the company. First of all an assessment method will have to be chosen that supports the use of multiple criteria. Then the criteria will be defined according to the findings of held interviews and the goals set in this project. Finally the assessment method and the criteria will be used to assess the most promising solutions.

4.1 Assessment method

There are a plethora of multi criteria decision making methods (MCDM). While some methods are more used than others, it can't be said that on method is better than the other. This became apparent when looking at several topics on the choice of MCDM on Researchgate (Salabun, 2013) (Homayounfar, 2018). The type of project and the personal preference of the researcher seem to be the main factor for choosing a multi criteria decision making method. For this project the AHP (Analytical Hierarchy Process) method is chosen for the determination of the criteria weights. This is one of the most commonly used MCDMs. For the ranking of the alternatives the VIKOR method is chosen, while relatively simple it does provide a ranking of the alternatives with potentially multiple viable solutions.

AHP (Analytical Hierarchy Process)

The AHP method weighs the criteria against one another to determine their weights. Other methods often rank, vote or freely assign weights to criteria. After comparing the criteria and having determined the preferences, the method also contains a check whether the comparisons and preferences were logical and consistent. Because AHP is used to determine the weights and not for the eventual assessment, it is only done for the main criteria, not for all the elements below a criteria. The steps to completing the AHP are as follows (Al-harbi, 2001, p. 20):

1) Define the problem and determine its goal
2) Structure the hierarchy from the top (the objectives from a decision-maker's viewpoint) through the intermediate levels (criteria on which the subsequent levels depend) to the lowest level which usually contains the list of alternatives
3) Construct a pair-wise comparison matrix (size n x n) (n is the number of different criteria) for the criteria by using the relative scale measurement
4) There are n(n-1)/ judgements required to develop the matrix in step 3. Reciprocals are automatically assigned in each pair-wise comparison
5) Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy
6) Finally the consistency ratio (CR) must be determined. The CR is acceptable if it does not exceed 0.10

VIKOR (Vlse Kriterijumska Optimizacija I Kompromisno Resenje)

VIKOR is an abbreviation for the Serbian sentence "multi criteria optimization and compromise solution". "*It is a multi criteria decision making method developed in 1990 by Serafim Opricovic to solve decision problems with conflicting criteria. This method ranks alternatives and determines the compromise solution that is the closest to the "ideal".*". (Yazdani & Graeml, 2014, p. 57)The steps to completing the VIKOR are as followed (Opricovic, 2004):

1) Find the best and the worst value of the beneficial and non-beneficial criteria
2) Calculate the utility measure and the regret measure
3) Compute the optimal values for the utility measure and the regret measure
4) Determine the value of Q_i and rank the alternatives by the values of Q_i
5) Check the two conditions; C1: "acceptable advantage" & C2: "acceptable stability in decision making"

4.2 The criteria

To determine the criteria which the alternatives will be assessed on, interviews were held (see appendix N for the transcripts). These interviews were done with the prime members of the TGP1 department and the team leader of the process engineering department. In the interview the interviewee was asked what demands and wishes he had for the LFE assembly process. The interviews were kept short (10-15 minutes per person) to accommodate the working schedules of the interviewees and to ensure the interviews would be to the point. Additionally the criteria will also be based on the set goals in this project. This includes both the aspect of quality and time.

Some of the demands made in the interview were directly related to a specific possible solutions/alternative, these will be addressed separately from the criteria used to assess all methods. Those demands become useful if the specific solution is chosen in the assessment and an implementation plan is in order. The costs were not deemed as important enough by any of the interviewees to be included in the criteria, this attribute of the alternatives will be discussed in an eventual implementation plan. The only indication of a budget is that the investment should be earned back within three years, this came across as a guideline rather than a hard rule.

4.2.1 Criteria for the assessment of alternatives

From the held interviews and the objectives of this project the following criteria where determined. Each criterion will be shortly explained and the scale of grading will be given which will be used to score the different alternatives.

Labour/man-hours

The most named demand in the interviews and an aspect of this projects goal. The LFE package assembly process takes quite a bit of time, of which a significant amount is necessary but non value adding. From the interviews it became apparent that the less man-hours the process takes the better it is. At the least the counting and orienting of the majority of the large packages (20K, 50K and/or 70K) should be eliminated, as far as one of the Q-engineers is concerned. The scoring of this criterion can be found in Table 4-1. A score can be between two defined scores, in that case a 0.5 will be added to the lower score. This is a beneficial criterion, the higher scores are more desired than lower scores.

Score	0	1	2	3	4	5
Description	The man-hours will increase	The man-hours will remain the same	The NNVA time (excl. setup and clean-up) of at least 2 of the 3 larger packages (20K, 50K, 70K) is eliminated	The NNVA time (excl. set-up and clean-up) is eliminated for at least one package per LFE type	The NNVA time (excl. set-up and clean-up) of all packages is eliminated	The NNVA time is eliminated for all packages and there are less man-hours necessary for the “pure” assembly

Table 4-1 Scoring table of the criteria “Labour/man-hours”

Job satisfaction

Named by the most prominent of the interviewees and supported by the production personnel that participated in the measurements done for the analysis (chapter 2). The assembly of LFE packages is not one of the tasks that is particularly enjoyed, additionally it consists out of mostly repetitive movements increasing the risk of RSI. Currently there is also a companywide project that, among others, emphasises the joy and meaning employees should get from their work. The job satisfaction could be increased by reducing the time the production personnel needs to spent on the assembly, by limiting the time in the flow bench or by limiting the repetitive movements. The scoring of this criterion can be found in Table 4-2. This is a beneficial criterion, the higher scores are more desired than lower scores.

Score	0	1	2	3	4	5
Description	The time spent on assembly increases *OR* The amount of repetitive	The process does not alter in regards to assembly time or repetitive movements	The time spent on assembly is reduced (by the NNVA time of 2 of the larger packages)	The time spent on assembly is reduced (by the NNVA time all packages) *OR*	The time spent on assembly only consist out of pure assembly (no counting or	The entire assembly process has no longer need of regular human interference

	movements increases	*OR* The amount of repetitive movements is reduced by 1 of these process steps: counting, orienting, assembly	The amount of repetitive movements is reduced by 2 of these process steps: counting, orienting, assembly	orienting)

Table 4-2 Scoring table of the criteria “Job satisfaction”

Degree of automation

Most interviewees showed interest in an automated solution, both partial and complete automation are welcomed. Although the further in the future the alternative is implemented the higher the degree of automation should be. The scoring of this criterion can be found in Table 4-3. This is a beneficial criterion, the higher scores are more desired than lower scores.

Score	0	1	2	3	4
Description	No form of automation present in the process	Counting of the LFEs is done automatically OR Orienting of LFEs is done automatically	Counting and orienting are done automatically	Counting, orienting and stacking are done automatically	The entire assembly is done automatically

Table 4-3 Scoring table of the criteria “Degree of automation”

Quality

Not always explicitly mentioned as a demand, wish or otherwise by the interviewees. Interestingly the team leader process engineering focused more on the quality aspect while the representatives of the TGP1 production department were focusing on the time aspect. The quality aspect is however a large part of the goal set in this project (reducing the reject rate from 4% to 2%). The greatest quality issue that was identified is the variation found in the LFEs. The degree in which this problem is tackled will determine the quality score. The scoring of this criterion can be found in Table 4-4. This is a beneficial criterion, the higher scores are more desired than lower scores.

Score	0	1	2
Description	Variation in LFEs is not addressed	Variation in LFEs is taken into account	The variation in the LFEs themselves is addressed

Table 4-4 Scoring table of the criteria “Quality”

Space

A subject that is not particularly important to the interviewees. In the current production facility an alternative should not take up more space than is currently used for the LFE assembly. For the long term alternatives space is not (yet) an issue as the entirely new production facility still has to be designed. There is a common consensus that a compact solution would be more ideal than a large one, especially when the production of LFE packages remains within the production line of TGP1. The scoring of this criterion can be found in Table 4-5. This is a beneficial criterion, the higher scores are more desired than lower scores.

Score	0	1	2
Description	Takes up more space than the current workspace allocated to the LFE package assembly process	Takes up equal space as the current workspace allocated to the LFE package assembly process	Takes up less space than the current workspace allocated to the LFE package assembly process

Table 4-5 Scoring table of the criteria “Space”

4.2.2 Demands and wishes for specific alternatives

As said in the introduction of this chapter, there were not only general demands and wishes but also very specific ones for certain alternatives, should those alternatives be chosen. These demands and wishes are described below.

Flexibility (future proofing) in LFE numbers

In case of an alternative supplying method or automation the pre-set number of LFEs in the different packages types should be adaptable. It could be that in the future the number of LFEs per package type changes, the supplier must be able to cope with such a change and an automated machine should be reprogrammable to those new numbers.

Traceability

If the LFEs are supplied in a different manner (e.g. on a rod) the packaging could be supplemented with a QR-code which can identify the type of LFEs and the batch they came from. This would tie in with another project on the traceability of materials.

Material certificate

If the manner in which LFEs are supplied is altered then it would be nice to ensure the material certificates are included. Currently this is not the case. Potentially this could be combined with the ideas on traceability as described above.

Dust free

If the LFEs are going to be supplied in an alternative manner, it is important that the cleanliness of these materials is maintained. This is not just a wish but a condition for the materials.

4.3 Assessment of alternatives

As described in section 4.1, the weights for the criteria used in the assessment are determined by using the AHP method. These weights are determined prior to the assessments of the different alternatives/improvements. After the weights have been determined the assessments are done for the alternative/improvements in each of the different categories of implementation length.

4.3.1 Weight of the criteria

The first step of the AHP is to develop a hierarchical structure. Even though the weights for the criteria will be the same for each different time span, each time span will have its own hierarchical structure. This is mainly done for the legibility of the figures. The hierarchical structure for the short-term improvements is shown in Figure 4-1. The other two hierarchical structures (medium-term and long-term) can be found in Appendix O.

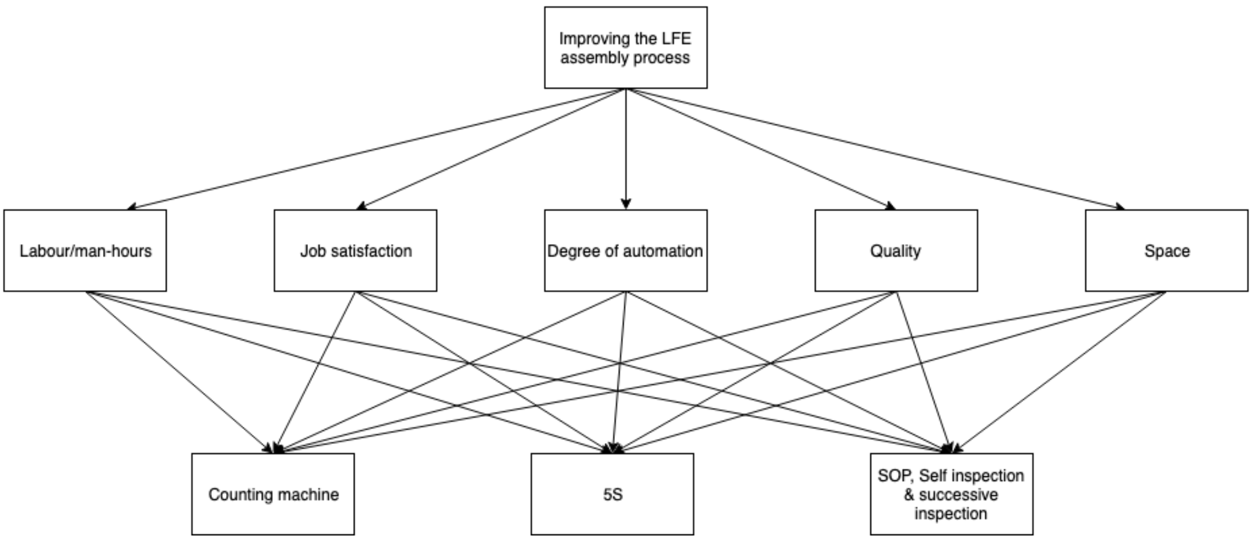


Figure 4-1 Hierarchical structure of short-term improvements

The second step of AHP is to create a pair-wise matrix by using the relative scale measurement as shown in Figure 4-2.

Numerical rating	Verbal judgments of preferences
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred
2	Equally to moderately
1	Equally preferred

Figure 4-2 Pair-wise comparison scale for AHP preferences {reference Al-Harbi p.20}

The comparisons are based on the preferences that were made clear during the interviews, other interactions with the prime members of TGP1 and the process engineering department and the insights gained in the first phases of the project. The pair-wise matrix (Table 4-6) should be read as followed; how important is the criteria in the left column with respect to the criteria in the top row. On the bottom row the values in the columns are added to one another, this helps in the next step with normalizing the matrix.

	Labour/man-hours	**Job satisfaction**	**Degree of automation**	**Quality**	**Space**
Labour/man-hours	1	5	6	5	9
Job satisfaction	0.20	1	3	2	7
Degree of automation	0.17	0.33	1	0.25	3
Quality	0.20	0.50	4	1	7
Space	0.11	0.14	0.33	0.14	1
SUM	1.68	6.97	14.20	8.39	29

Table 4-6 Pair-wise matrix

By normalizing the pair-wise matrix the criteria weights can be obtained. The normalized matrix with the weights included can be found in the following table (Table 4-7).

	Labour/man-hours	**Job satisfaction**	**Degree of automation**	**Quality**	**Space**	**Criteria weight**
Labour/man-hours	0.5952	0.7174	0.4187	0.5959	0.3333	*0.5321*
Job satisfaction	0.1190	0.1435	0.2094	0.2384	0.2593	*0.1939*
Degree of automation	0.1012	0.0473	0.0698	0.0298	0.1111	*0.0718*
Quality	0.1190	0.0717	0.2791	0.1192	0.2593	*0.1697*
Space	0.0655	0.0201	0.0230	0.0167	0.0370	*0.0325*

Table 4-7 Normalized pair-wise matrix, including the obtained criteria weights

Now the weights need to be checked for consistency, this is done by calculating the λ_{max} which is done with the help of the criteria weights and the regular pair-wise matrix. In this case the λ_{max} has a value of 5.357. This value is used to calculate the consistency index (C.I.), following the following formula (Equation 4-1), where *n* is the number of criteria:

$$C.I. = \frac{\lambda\text{max} - \text{n}}{n - 1}$$

Equation 4-1 Consistency index formula

The consistency index has a value of 0.089. This value together with the random index (R.I.) (as depicted in Figure 4-3) is used to find the consistency ratio, following Equation 4-2.

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Figure 4-3 Average random consistency (R.I.) (Al-harbi, 2001)

$$Consistency\ Ratio = \frac{C.I.}{R.I.}$$

Equation 4-2 Consistency ratio formula

The consistency ratio has, in this case, a value of 0.0798. Which makes the matrix consistent enough, as the value should not exceed 0.10 (Al-harbi, 2001). Thus the weights as found in Table 4-7 can be used in the further assessment of alternatives.

4.3.2 Assessment short-term improvements

For the VIKOR assessment the different alternatives first need to be scored on the different criteria, these scores can be found in Table 4-8 together with the best and worst scores of each criteria. Since short-term improvements/alternatives are often small alterations or additions to the process, the scores will be naturally on the lower side of the spectrum.

	Labour/man-hours	Job satisfaction	Degree of automation	Quality	Space
Criteria weights	*0.5321*	*0.1939*	*0.0718*	*0.1697*	*0.0325*
Counting machine	1.5	2	1	0	1
5S	1	1	0	0	1
SOP, self-inspection & successive inspection	1	1	0	0	1
Best (X_j^+)	*1.5*	*2*	*1*	*0*	*1*
Worst (X_j^-)	*1*	*1*	*0*	*0*	*1*

Table 4-8 Criteria scores for the short-term improvements

All criteria are beneficial, meaning that a higher score is preferred over a lower score. For each criterion the best (X_i^+) and the worst (X_i^-) score need to be identified, these scores can also be found in Table 4-8. With the best and worst scores per criteria identified the utility (S_i) and regret (R_i) measures can be determined using the following two equations (Equation 4-3 & Equation 4-4) (Opricovic, 2004, p. 447):

$$S_i = \sum_{j}^{n} (W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-})$$

Equation 4-3 Utility measure

$$R_i = \max_j (W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-})$$

Equation 4-4 Regret measure

Using these two equations gives the following table (Table 4-9).

	Labour/man-hours	Job satisfaction	Degree of automation	Quality	Space	S_i	R_i
Criteria weights	*0.5321*	*0.1939*	*0.0718*	*0.1697*	*0.0325*	*N.A.*	*N.A.*
Counting machine	0	0	0	0	0	0	0
5S	0.5321	0.1939	0.0718	0	0	0.7978	0.5321
SOP, self-inspection & successive inspection	0.5321	0.1939	0.0718	0	0	0.7978	0.5321

Table 4-9 Utility and regret measures

To determine the ranking of the improvements/alternatives Q_i must be calculated, to do so the maximum (S^- and R^-) and minimum (S^* and R^*) of both S_i and R_i are needed. Additionally v (the weight of maximum group utility) is needed, the standard value for v is 0.5. To calculate Q_i the following equation (Equation 4-5) is used (Opricovic, 2004, p. 448).

$$Q_i = v * \frac{S_i - S^*}{S^- - S^*} + (1 - v) * \frac{R_i - R^*}{R^- - R^*}$$

Equation 4-5 equation to determine the value of Q_i

The following ranking can be identified when evaluating the value of Q_i. The counting machine gets the highest rank followed by the other two alternatives who tied in second place.

	S_i	R_i	Q_i	Rank based on Q_i
Counting machine	0	0	0	1
5S	0.7978	0.5321	1	2
SOP, self-inspection & successive inspection	0.7978	0.5321	1	2

Table 4-10 Ranking of short-term improvements based on Q_i value

Now that the ranking is known the two conditions can be checked (the acceptable advantage and the acceptable stability in decision making). The first condition (the acceptable advantage) follows the following equation (Equation 4-6) (Opricovic, 2004, p. 448):

$$Q(A^2) - Q(A^1) \geq DQ$$
$$DQ = \frac{1}{j - 1}$$

Equation 4-6 Acceptable advantage

In this equation $Q(A^2)$ is the Q-value of the alternative that has the second rank, similarly $Q(A^1)$ is the Q-value of the first ranked alternative. This condition is met in this case as the value of $Q(A^2) - Q(A^1) = 1$ is greater than the value of $DQ = 0.5$

The second condition (the acceptable stability in decision making) states that the best ranked alternative should also have the best rank in either S_i, R_i or both. In this case it has the best value in both S_i and R_i and therefore also meets this condition. Since both conditions are met only the alternative that is ranked first (counting machine) is proposed to be the solution for the short-term.

Conclusion
The counting machine has the highest rank of the three short-term improvements, with 5S and SOP tied on the second place. Because both conditions (the acceptable advantage and the acceptable stability in decision making) have been met, the counting machine is the only solution proposed.

4.3.3 Assessment medium-term improvements
For the VIKOR assessment the different alternatives first need to be scored on the different criteria, these scores can be found in Table 4-11, together with the best and worst scores of each criteria.

	Labour/man-hours	Job satisfaction	Degree of automation	Quality	Space
Criteria weights	*0.5321*	*0.1939*	*0.0718*	*0.1697*	*0.0325*
Supplying LFEs on a rod	1.5	2	1*	1	1
Supplying LFEs in the required numbers	1.5	2	1*	0	1
Supplying LFEs on a rod and in the required number for the larger packages	2.5	3	2.5*	1	1
Supplying LFEs on a rod and in the required numbers for all packages	4	4	3*	1	1
Six Sigma	1	1	0	0	1
WIS (Worker Information System)	1	1	0.5	0	1
Best (X_j^+)	*4*	*4*	*3*	*1*	*1*
Worst (X_j^-)	*1*	*1*	*0*	*0*	*1*

Table 4-11 Criteria scores for the medium-term improvements

(*) The counting, orienting and stacking of LFEs done by the supplier are assumed to be automatic, as it is also the case for the LFEs used in the M-packages. All criteria are beneficial, meaning that a higher score is preferred over a lower score. For each criterion the best (X_i^+) and the worst (X_i^-) score need to be identified, these scores can also be found in Table. With the best and worst scores per criteria identified the utility (S_i) and regret (R_i) measures can be determined using the same two equations (Equation 4-7 & Equation 4-8) as in §4.3.2 (Opricovic, 2004, p. 447):

$$S_i = \sum_{j}^{n} (W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-})$$

Equation 4-7 Utility measure

$$R_i = \max_j (W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-})$$

Equation 4-8 Regret measure

Using these two equations gives the following table (Table 4-12):

	Labour/man-hours	Job satisfaction	Degree of automation	Quality	Space	S_i	R_i
Criteria	*0.5321*	*0.1939*	*0.0718*	*0.1697*	*0.0325*	*N.A.*	*N.A.*

weights							
Supplying LFEs on a rod	0.4434	0.1293	0.0479	0.0000	0.0000	0.6206	0.4434
Supplying LFEs in the required numbers	0.4434	0.1293	0.0479	0.1697	0.0000	0.7903	0.4434
Supplying LFEs on a rod and in the required number for the larger packages	0.2661	0.0646	0.0120	0.0000	0.0000	0.3427	0.2661
Supplying LFEs on a rod and in the required numbers for all packages	0.0000	0.0000	0.0000	0.0000	0.0000	*0.0000*	*0.0000*
Six Sigma	0.5321	0.1939	0.0718	0.1697	0.0000	*0.9675*	*0.5321*
WIS (Worker Information System)	0.5321	0.1939	0.0598	0.1697	0.0000	0.9555	*0.5321*

Table 4-12 Utility and regret measures medium-term alternatives

To determine the ranking of the improvements/alternatives Q_i must be calculated, to do so the maximum (S^- and R^-) and minimum (S^* and R^*) of both S_i and R_i are needed. Additionally v (the weight of maximum group utility) is needed, its standard value for v is 0.5. To calculate Q_i the same equation (Equation 4-9) is used as in §4.3.2 (Opricovic, 2004, p. 448).

$$Q_i = v * \frac{S_i - S^*}{S^- - S^*} + (1 - v) * \frac{R_i - R^*}{R^- - R^*}$$

Equation 4-9 Equation to determine the value of Q_i

The following ranking (Table 4-13) can be identified when evaluating the value of Q_i. Supplying the LFEs on a rod, in the required numbers for all packages, has the highest rank followed by supplying them that way for only the larger packages.

	S_i	R_i	Q_i	Rank based on Q_i
Supplying LFEs on a rod	0.6206	0.4434	0.7374	3
Supplying LFEs in the required numbers	0.7903	0.4434	0.8251	4
Supplying LFEs on a rod and in the required number for the larger packages	0.3427	0.2661	0.4271	2
Supplying LFEs on a rod and in the required numbers for all packages	0.0000	0.0000	0	1

Six Sigma	0.9675	0.5321	1	6
WIS (Worker Information System)	0.9555	0.5321	0.9938	5

Table 4-13 Ranking of medium-term improvements based on Q_i value

Now that the ranking is known the two conditions can be checked (the acceptable advantage and the acceptable stability in decision making). The first condition (the acceptable advantage) follows the same equation as in §4.3.2 (Equation 4-10) (Opricovic, 2004, p. 448):

$$Q(A^2) - Q(A^1) \geq DQ$$
$$DQ = \frac{1}{j-1}$$

Equation 4-10 Acceptable advantage

In this equation *$Q(A^2)$* is the Q-value of the alternative that has the second rank, similarly *$Q(A^1)$* is the Q-value of the first ranked alternative. This condition is met in this case as the value of *$Q(A^2) - Q(A^1) = 0.4271$* is greater than the value of *$DQ = 0.2$*

The second condition (the acceptable stability in decision making) states that the best ranked alternative should also have the best rank in either S_i, R_i or both. In this case it has the best value in both S_i and R_i and therefore also meets this condition. Since both conditions are met only the alternative that is ranked first (supplying the LFEs oriented and in the right number for all packages) is proposed to be the solution for the medium-term.

Conclusion

The highest ranking solution is to supply the LFEs on a rod in the required numbers for all packages. Followed by supplying them that exact way only for the larger packages. Since both conditions (the acceptable advantage and the acceptable stability in decision making) are met, only the highest ranking solution (supplying the LFEs on a rod in the required numbers) is proposed.

4.3.4 Assessment long-term alternatives

For the VIKOR assessment the different alternatives first need to be scored on the different criteria, these scores can be found in Table 4-14, together with the best and worst scores of each criteria.

	Labour/man-hours	**Job satisfaction**	**Degree of automation**	**Quality**	**Space**
Criteria weights	*0.5321*	*0.1939*	*0.0718*	*0.1697*	*0.0325*
3D-printing packages	5	4.5	4	2	1
Altering the etching process of the supplier	1	1	0	2	1
Partially automating with a cobot or mechanical solution	4	3	3	0	0
Outsourcing	5	5	0	0	2
Full automation	5	5	4	0	1
Best (X_j^+)	*5*	*5*	*4*	*2*	*2*

Worst (X_j^-)	1	1	0	0	0

Table 4-14 Criteria scores for the long-term alternatives

All criteria are beneficial, meaning that a higher score is preferred over a lower score. For each criteria the best (X_i^+) and the worst (X_i^-) score need to be identified, these scores can also be found in Table 4-14. With the best and worst scores per criteria identified the utility (S_i) and regret (R_i) measures can be determined using the same two equations (Equation 4-11 & Equation 4-12) as in §4.3.2 & § 4.3.3 (Opricovic, 2004, p. 447):

$$S_i = \sum_{j}^{n}(W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-})$$

Equation 4-11 Utility measure

$$R_i = \max_j(W_j * \frac{X_i^+ - X_{ij}}{X_i^+ - X_i^-})$$

Equation 4-12 Regret measure

Using these two equations gives the following table (Table 4-15):

	Labour/man-hours	Job satisfaction	Degree of automation	Quality	Space	S_i	R_i
Criteria weights	0.5321	0.1939	0.0718	0.1697	0.0325	N.A.	N.A.
3D-printing packages	0.0000	0.0242	0.0000	0.0000	0.0163	0.0405	0.0242
Altering the etching process of the supplier	0.5321	0.1939	0.0718	0.0000	0.0163	0.8141	0.5321
Partially automating with a cobot or mechanical solution	0.1330	0.0970	0.0180	0.1697	0.0325	0.4501	0.1697
Outsourcing	0.0000	0.0000	0.0718	0.1697	0.0000	0.2415	0.1697
Full automation	0.0000	0.0000	0.0000	0.1697	0.0163	0.1860	0.1697

Table 4-15 Utility and regret measures long-term alternatives

To determine the ranking of the improvements/alternatives Q_i must be calculated, to do so the maximum (S^- and R^-) and minimum (S^* and R^*) of both S_i and R_i are needed. Additionally v (the weight of maximum group utility) is needed, its standard value for v is 0.5. To calculate Q_i the same equation (Equation 4-13) is used as in §4.3.2 and §4.3.3 (Opricovic, 2004, p. 448).

$$Q_i = v * \frac{S_i - S^*}{S^- - S^*} + (1 - v) * \frac{R_i - R^*}{R^- - R^*}$$

Equation 4-13 Equation to determine the value of Q_i

The following ranking (Table 4-16) can be identified when evaluating the value of Q_i. 3D-printing the LFE packages has the highest ranking, followed by full automation.

	S_i	R_i	Q_i	Rank based on Q_i
3D-printing packages	0.0405	0.0242	0	1
Altering the etching process of the supplier	0.8141	0.5321	1	5

Partially automating with a cobot or mechanical solution	0.4501	0.1697	0.407984	4
Outsourcing	0.2415	0.1697	0.273137	3
Full automation	0.1860	0.1697	0.237232	2

Table 4-16 Ranking of long-term alternatives based on Q_i value

Now that the ranking is known the two conditions can be checked (the acceptable advantage and the acceptable stability in decision making). The first condition (the acceptable advantage) follows the same equation as in §4.3.2 and §4.3.3 (Equation 4-14) (Opricovic, 2004, p. 448):

$$Q(A^2) - Q(A^1) \geq DQ$$
$$DQ = \frac{1}{j-1}$$

Equation 4-14 Acceptable advantage

In this equation *$Q(A^2)$* is the Q-value of the alternative that has the second rank, similarly *$Q(A^1)$* is the Q-value of the first ranked alternative. This condition is not met in this case as the value of *$Q(A^2)$ - $Q(A^1)$ = 0.2372* is smaller than the value of *DQ = 0.25.*

The second condition (the acceptable stability in decision making) states that the best ranked alternative should also have the best rank in either S_i, R_i or both. In this case it has the best value in both S_i and R_i and therefore meets this condition.

Since the first condition was not met, multiple solutions will be proposed based on the following equation:

$$Q\left(a^{(M)}\right) - Q(a^1) < DQ \qquad for\ maximum\ M$$

Equation 4-15 Equation to determine solutions in case condition 1 was not met

$Q(A^3)$ - $Q(A^1)$ = 0.2731 is larger than the value of *DQ = 0.25.* Thus the first (3D-printing the packages) and second (Full automation) ranked alternatives are proposed as solutions.

Conclusion
The highest ranking alternative is 3D-printing the LFE packages, closely followed by full automation. The first condition (the acceptable advantage) was not met, causing both the first (3D-printing the LFE packages) and second (full automation) ranked alternative to be proposed as solutions.

4.3.5 Conclusion
The weights acquired by the AHP method in combination with the VIKOR method were used to assess the different improvements and alternatives of different timeframes. For the short-term there was one improvement that was proposed by the VIKOR assessment; a counting machine. Similarly the medium-term also had one proposed solution; supplying the LFEs oriented and in the right number for all packages. The assessment for the long-term was less decisive proposing two viable solutions; 3D-printing the LFE packages and fully automating the assembly of LFE packages. In the next chapter the findings of the assessment will be further discussed.

5 Choice of alternative

Now that the assessment of the alternatives is done, the results can be considered. The proposed solutions will be discussed. Once a general course of action is determined, the course of action for one of the proposed solutions will be discussed before it is elaborated upon in more detail by the means of an implementation plan. Before the implementation plan is proposed there will be a short discussion about the contents of a proper implementation plan.

5.1 The proposed solutions

The alternatives and improvements were divided based on the expected time to implement, for the short-term improvements the counting machine was proposed as the solution. While it would be a very helpful addition to the LFE package assembly process, it would also be made obsolete as soon as the medium-term solution (supplying the LFEs on a rod in the required numbers) is implemented. This makes the counting machine seemingly less interesting, however there is still merit in the idea of a counting machine.

For example, Bronkhorst hosts many (graduate) interns, of (mainly) technical study programmes from all educational layers. The design and creation of a counting machine could prove to be a nice assignment for either a MBO or HBO student (depending on the details of the counting machine) for example from mechanical engineering. It would cost a company about €3,438.50 (total labour cost) to host a student (HBO) for five months and for such an assignment students are often allowed to purchase some materials that are needed. For a counting machine, assuming it has to be working tool and not just a prototype/mock-up, the material costs could be up to €2,500 depending on the already available materials within the company and the intended complexity of the machine. The insights provided by these assignments could aid in further automating the process in the future, as was one solution proposed for the long-term. Additionally the medium-term solution that was proposed might not be implemented right away. It is not unthinkable that the alterations in the manner of supplying the LFEs are done in several phases, especially since most of the LFEs are not only used by TGP, but also in different numbers by other production departments. In the meantime a counting machine might prove useful before and during some of the phases of implementing this new supplying method.

The solutions proposed for the long-term, 3D-printing LFE packages and full automation, are still very vague, especially the 3D-printing of LFE packages. It can be said that either of these option would be a viable solution in the future, however the specifics will still have to be researched. What machine would be suitable, what kind of specifications would it need to have, is it going to be a custom machine, etc. The fact that automation (be it 3D-printing or not) is the way forward is clear, how it exactly will be executed needs to be researched by an engineer with (more) experience in the technical details, perhaps one with a mechanical engineering background. Depending on whether this research is done by a student or an engineer the approximate costs for five months of research are respectively €3,438.50 or €41,166.66 (based on the €50 an hour rate that Bronkhorst uses). The results from the research will determine the price of the eventual solution.

As the long-term solutions need more research to uncover the details and the short-term solutions usefulness might fluctuate depending on the implementation of the medium-term solution, the implementation plan will be made for the medium-term solution, supplying the LFEs on a rod in the required numbers. But first some additional considerations for the solution will be discussed.

5.2 The medium-term solution; supplying the LFEs on a rod (in the required number)

As mentioned earlier in the report, there have been a lot of initiatives over the years to improve the LFE package assembly process, none of which yielded an implementation of any kind. From the interactions with the production personnel during both the analysis and the interviews it has become clear that they do not have confidence anymore in that the process will be improved. The prime members of TGP1 have been suggesting a different way to supply the LFEs for a long period of time, it is by no means a new idea. However these ideas, just like those projects never yielded any tangible results and died silent deaths. It is therefore important, that the implementation of the solution is visible, so the production personnel can see it is worked on and not forsaken or forgotten as many other projects were.

Therefore it might make sense to implement the different manner of supplying in multiple phases. Supplying the required number of LFEs pre stacked and oriented for all package types (also those of other departments) might be too big of a change to implement in a relatively short period. There are several ways to first partially implement the different supplying method. There are multiple types of packages made with one type of LFE in several production departments. Department TGP1 makes the largest packages of those LFE types included in this research. The LFEs could first off be supplied in only the number of the largest package. Alternatively the LFEs could be supplied in a standard number on a rod, this way the counting will still take some time but the orientation would already be taken care of. The latter was also suggested by the prime members of TGP1, as they are very eager to see some form of improvement.

The main concern in implementing the solution in phases is the flexibility of the supplier concerning the numbers put on a rod. If this is not easily adapted a change from a standard number to specific numbers might prove difficult and consequently costly. This flexibility will also come in play when in the (distant) future the process is fully automated. It is not yet known how the machine would need the LFEs to be supplied to it, but be it on a rod or in bags it will be needed in great numbers. Additionally it might occur that the number for specific packages changes. This needs to be considered in making the new agreements with the supplier.

A nice addition that might be added when the manner of supplying is going to change is some traceability. There is a project within Bronkhorst to make materials more traceable by the means of QR codes. This could also be done with the LFEs, the new packaging material could be fitted with a QR code containing the information on which batch these LFEs came from and for example the material certificates. One thing that has to be kept in mind when altering the method of supplying is that the materials need to be clean (ergo dust and grime free).

In short

The production personnel needs to see an improvement in the process, however small it might be, to gain some confidence that this time there will be no empty promises of improvement. To do so it might make sense to do the implementation in several phases. It however needs to be assured, through the phases and beyond, that the number of LFEs on a rod remains flexible to facilitate changes. It would be a nice addition to this solution when traceability can be added to the new packaging method, using QR codes on the packaging material to convey information about the batch and the material certificate. With the changes to the supplying method, the cleanliness of the LFEs has to be watched, since the parts will need their cleanliness to be ensured.

5.3 The aspects of the implementation plan

There are no guidelines within Bronkhorst for the writing of implementation plans, there was also no literature found that recommended a format for an implementation plan. Therefore an implementation plan will be written using general components often found in implementation plans. Additionally some inspiration will be taken from (Slevin & Pinto, 1987) to expand on the general components.

General components

An implementation plan generally describes the time, people and resources that are necessary. Since a supplier is involved and the most radical changes are mostly at the supplier side, all three of these aspects cannot be expressed in a very detailed manner. The Bronkhorst side of affairs should prove to be more detailed. The aspect of time will be represented by a planning/schedule. The aspect of people will be represented by a task list with the corresponding people responsible for those tasks and by the people affected by the implementation. Lastly, the aspect of resources will be represented by a cost analysis.

Pinto & Slevin

Pinto & Slevin (1987) identified 10 factors deemed important to successful project implementation. Some more applicable than others in this case, but definitely worth a look. The 10 factors can be found in Figure 5-1.

1. *Project Mission*—Initial clearly defined goals and general directions.
2. *Top Management Support*—Willingness of top management to provide the necessary resources and authority/power for project success.
3. *Project Schedule/Plan*—A detailed specification of the individual actions steps for project implementation.
4. *Client Consultation*—Communication, consultation, and active listening to all impacted parties.
5. *Personnel*—Recruitment, selection, and training of the necessary personnel for the project team.
6. *Technical Tasks*—Availability of the required technology and expertise to accomplish the specific technical action steps.
7. *Client Acceptance*—The act of "selling" the final project to its ultimate intended users.
8. *Monitoring and Feedback*—Timely provision of comprehensive control information at each stage in the implementation process.
9. *Communication*—The provision of an appropriate network and necessary data to all key actors in the project implementation.
10. *Troubleshooting*—Ability to handle unexpected crises and deviations from plan.

Figure 5-1 Factors of project implementation (Slevin & Pinto, 1987, p. 174)

The first factor, project mission, can most definitely be incorporated in the implementation plan. A clearly defined goal will aid in the understanding of the implementation plan if the reader chose not to read the thesis prior to the implementation plan.

The second factor, top management support, will indeed be necessary for the implementation of the new supplier agreements. However their support will not be explicitly mentioned in the eventual implementation plan.

The third factor, project schedule/plan, overlaps with the general aspect of time discussed in the previous paragraph and will thus be included.

The fourth factor, client consultation, is an important one. The need for communication will be taken into account in the implementation plan, as it is particularly important to communicate any progress to the members of the production departments.

The fifth factor, personnel, as it is described in the figure is not quite applicable, the implementation of an alternative method of supplying the LFEs does not need new personnel or new skills for existing personnel. The supplier engineers are quite capable and the change of supplying method has been long awaited by the production personnel.

The sixth factor, technical tasks, sits on the suppliers' side of affairs. This will be lightly touched upon in the implementation plan as the supplier already mentioned they are capable to supply the LFEs in such a way.

The seventh factor, client acceptance, closely relates to the fourth factor. The eventual intended beneficiary of the new supplying method is the production department. They will be kept in the loop during implementation and as they have requested these types of changes themselves, there will be no need to "sell" this new method to them.

The eight factor, monitoring and feedback, is part of the communication, however this also includes the communication with the supplier.

The ninth factor, communication, by (Slevin & Pinto, 1987) described as "*the provision of an appropriate network and necessary data*.." will be lightly touched upon in the implementation plan.

The tenth and final factor, troubleshooting, will be taken into account, especially when the implementation will happen in phases. Both the supplier and the production department might run into an issue, it is important that these issues are addressed quickly and adequately before people start to work around the issue. To conclude; Out of the ten factors, factors 1, 3, 4, 8 & 10 will be included in the implementation plan.

5.4 The implementation plan

In this paragraph a short, summarized version of the implementation plan will be shown. The complete implementation plan can be found in appendix P.

Mission statement

The goal is for the supplier to supply certain types of LFEs on a rod in the numbers required for the LFE packages.

People involved

Process engineering, the initiator of the project. Responsible for initiating the project, they'll monitor the implementation, analyse the results and design the tooling necessary for the new supplying method.
Supplier engineering, the executing force of the project. Responsible for all communication with the supplier, the new agreements made with the supplier and the communication of these agreements with the other parties involved.
The supplier, the external executing force of the project. Responsible for altering their packaging method, so they can supply the LFEs as the new method describes.
Production department TGP1, the main beneficiary of the project. Responsible for providing the lion's share of feedback on the new supplying method once implemented and reporting any issues that might occur.
Production departments OEM & Cleanroom, also get some benefits from a new supplying method. They are also responsible for providing feedback and reporting issues if they occur.

Costs & Benefits

Of course there are costs and benefits associated with a new supply method, these are described in Table 5-1. The last entry of the table can be combined with the first three entries, by evenly spreading the LFEs of the plate over the rods the variability should be countered. This will result in less rejects and thus less time spent on rework.

Supplying method	Costs	Financial benefits	Other benefits
Standard number on a rod	Initial costs of approximately 270 rods +5% of the regular purchasing price	9% savings in labour time	+Show of goodwill towards TGP
Packages with the most NNVA time on a rod	Initial costs of approximately 2580 rods +7.5% of regular purchasing price	37% savings in labour time	+ Show of goodwill towards TGP + Reduced chance on RSI-like injuries + Job satisfaction
All required numbers on a rod	Initial costs of approximately 3540 rods +12.5% of regular purchasing price	46% savings in labour time	+ Show of goodwill towards TGP + Reduced chance on RSI like injuries + Job satisfaction
* LFEs are evenly divided from the plate to the rods	+25% of regular purchasing price	9% - 46% savings in regular labour time 77% in rework labour time	+Might make future research into the variability of bodies and sensors easier

Table 5-1 costs and benefits of implementing a new supplying method

Schedule

The implementation of e new supply method was deemed a medium-term solution, meaning that is should be implementable within approximately six months. The schedule to implement such a change is shown in Table 5-2.

Month	Tasks	Responsible departments
1	• Inform the “other” production departments • Create concept tooling (rods) • Discuss options and potential costs with the supplier • Communicate the suppliers options with production and process engineering	Process engineering Supplier engineering
2	• Communicate suppliers options with production and process engineering • Agree on specifics of supplying method • Communicate chosen method to the supplier	Supplier engineering Production departments (TGP, OEM & Cleanroom) Process engineering
3	• Implement necessary changes to support the new method	The supplier
4	• Implement necessary changes to support the new method • “Activate” new supplying method • Depletion of old stock	The supplier Supplier engineering Production departments (TGP, OEM & Cleanroom)
5	• Depletion of old stock • Feedback on the new supplying method	Production departments (TGP, OEM & Cleanroom)
6	• Feedback on the new supplying method • Evaluation	Production departments (TGP, OEM & Cleanroom) Process engineering Supplier engineering

Table 5-2 Schedule for the implementation of a new supplying method

6 Conclusions and recommendations

This is the final chapter of this report. The findings will be briefly discussed in the conclusion section, followed by the recommendations for further research and actions to be undertaken with the addition of several considerations.

6.1 Conclusions

The LFE package assembly process is not running as efficient as it could. The process is plagued by a significant amount of non-value added time (§2.3.2) and variation in the materials, causing rejects (§2.4.2). Additionally the production employees are exposed to questionable risks concerning repetitive movements and generally do not seem to enjoy this task (§2.6).

There were plenty of ideas within the company on how to potentially improve the process (§3.1) and literature gave some additional insights (§3.2). The collected improvements and alternatives where assessed with the VIKOR method (§4.1) using criteria obtained from interviews (§4.2.1) and weighed by the AHP method. After the assessments, solutions were proposed for the short-, medium- and long-term. A counting machine for the short-term (§4.3.2), a different supplying method for the medium-term (§4.3.3) and full automation (potentially 3D-printing) for the long-term (§4.3.4).

Since the long-term solutions still need a fair bit of research, the counting machine would be relatively quickly obsolete and the counting machine does not (potentially) address the variation of the LFEs it was chosen to pursue the medium-term alternative (§5.1.1); supplying the LFEs on rods in the required numbers. This solution will save up to 46% of the time currently spent on assembling the LFE packages, might tackle some of the variation found in the LFEs, will reduce the risks on RSI and likely increase job satisfaction(§5.1.4).

The goal initially set in this project was as follows: “*The thesis will aim to provide the company with an alternative process design for the assembly of the LFE packages. This alternative design should halve the current reject rate, preferably getting the reject rate as close to the target of 2% as possible, and reduce assembly times by 15%.”* (§1.4). Whereas in the beginning the rejects were thought to be caused by wrongly counted or oriented LFEs, during the project it became apparent that these issues where practically non-existent. The real trouble seemingly lies with the variation in the LFEs (§2.4.2) and how this variation interacts with the variation of the body where the LFE package is installed in. Making the reject issue significantly more complex.

The potential time savings turned out to be much greater than first thought. When setting the goal 15% initially seemed a reasonable target, when analysing the process further the time that is necessary but non value adding showed a large savings potential of up to 68% in case of the 20K package (§2.3.2). Most ideas on how to improve the process from within the company were focussed on time rather than quality. Of all the alternatives, both form literature (§3.2) as from within the company (§3.1), only three potentially addressed the quality issue. One of those three alternatives is for the long-term and still needs quite some research (3D-printing), another where the feasibility is questionable to say the least (changing the etching process at the supplier) and one that seems doable (changing the manner in which the LFEs are supplied). The latter was, after assessing the alternatives (§4), chosen to be worked out in more detail in an implementation plan (§5.1.4).

Depending on the suppliers’ capability to tackle the variation, for example by methodically pushing the LFEs out of the metal sheet to spread them evenly, the chosen solution might reduce the rejection rate. Even if the LFE packages become less varied, the combination with certain bodies and sensors might still cause issues. However, the production department sneakingly already started to take this interacting variation in consideration. When a LFE package is taken out of a body due to an abnormality in the calibration it will first be tried in another body before being marked as a reject. This has seemingly already reduced the reject rate. By supplying the LFEs in the required number for at least the packages per LFE type with the largest necessary but non value adding the time spent on assembling LFE packages could already be reduced by 37% (§5.1.4).

While it remains to be seen if the variation can be sufficiently tackled to reach the goal of a maximum reject rate of 2%, the aspect of time as set in the goal can be accomplished rather easily. The time savings could be as high as 46%.

6.2 Recommendations

In this section recommendations will be done concerning additional research, actions to be taken and considerations for the company. Each recommendation will be assigned to one of these categories and will be shortly explained.

6.2.1 Actions

This project was concluded by an implementation plan for a possible solution. Of course an implementation plan requires action to be actually executed. The advised actions can be found in this paragraph with a short explanation.

Implementation of alternative supplying method

The findings of this thesis accumulated to an implementation plan for a new supply method for the LFEs. It is advised that this new supplying method is implemented in possibly several phases. With the most important phase being the implementation of the new method for the largest necessary but non value adding time packages. By implementing this new method the goal for the reduction of assembly times should be reached, whether the quality issue will be mostly solved remains to be seen.

Implementation of any solution/improvement

Should the new supplying method not be pursued then it would be advisable to take another course of action. The improvement of the LFE assembly process has been stagnant for many years, at one point something has to happen to it, however small it might be, to get it moving forwards again. This could be in the form of a counting machine, limiting the assembly to the morning or another improvement.

6.2.2 Research

During the thesis several questions were raised by certain findings, however due to the nature of a bachelor thesis there was no time to properly research them. In this paragraph these questions/findings will be raised again, so they can be answered in the future.

Further research into automation of the LFE assembly process, done by someone with a mechanical engineering (or similar) background

The options on full automation should be further explored. It is clear that automation is the way to go, however the exact specifics remain to be researched. This research should include the option of 3D-printig the LFE packages, as this would also (partially) automate the process. This research would be most suited for someone with a background in mechanical engineering or similar to mechanical engineering. They could make a list of technical requirements and review the different possibilities.

Further research into the interaction between the variations in LFEs, bodies and sensors.

The largest issue with the quality of LFE packages turned out to be the variation in the flow capacity of the LFEs. It is assumed that this variation interacts with variation in the bodies and potentially the sensors. It is not yet known how much the variation in bodies and sensor affects the reject rate of LFE packages. That they are related is known, as is shown by the fact that a LFE package might be rejected in one body but accepted in another. Further research into the variation of all those parts might prove insightful and could uncover similar problems with the bodies and sensors to the problems the LFEs are currently experiencing.

Further research in the differences between morning and afternoon assembly

During the analysis of the assembly times, measurements were done to determine the individual assembly times of different LFE packages. These measurements where partially done in the morning and partially in the afternoon. From the results it could be derived that assembly in the morning is around 21% faster than in the afternoon. However, the measurements were not done with the same people in the morning as in the afternoon and the number of measurements were limited. The results however are too promising to ignore, therefore it is proposed that more research is done on the assembly times in the morning and afternoon.

6.2.3 Considerations

To conclude this section of recommendations, a few considerations will be given. These considerations will be shortly explained.

Job satisfaction & RSI risks

The assembly of LFE packages is not an enjoyable task, it is done in a flow bench and consists out of many repetitive movements. The flow bench continuously blows air towards the instrument maker, often causing dry eyes and headaches. The repetitive movements, the length of time that is spent on the task and the fact that it is a precision task all increase the risk of developing RSI. Considering that there is an initiative in the company where two out of the five key concepts are "taking care of one another" and "joy & meaning", it is worth to have another look at the assembly process and to what it could mean for this project.

Visibility of a solution

There apparently have been multiple projects over the years concerning the LFE package assembly, none of which yielded visible results for the production personnel. They have lost trust that there will be something done and have become sceptical. It would be beneficial for them to see the progress of the implementation of a solution. It would restore trust and perhaps even (re)create some goodwill.

Al-harbi, K. M. A. (2001). Application of the AHP in project management. *International Journal of Project Management*, *19*, 19–27.

Bicheno, J., & Holweg, M. (2016). *The lean toolbox* (5th ed.). Buckingham: PICSIE Books.

Botti, L., Mora, C., & Regattieri, A. (2017). Integrating ergonomics and lean manufacturing principles in a hybrid assembly line. *Computers & Industrial Engineering*, *111*, 481–491. Retrieved from http://10.0.3.248/j.cie.2017.05.011

Dulchlnos, J., & Massaro, P. (2005). The time is right for labs to embrace the principles of industrial automation. *Drug World Discovery, Winter-Issue*, *2006*, 25–28.

Grave, F. H. G. de, Ritzen, J. M. M., Dijkstal, H. F., Jorritsma-Lebbink, A., Sorgdrager, W., Gmelich Meijling, J. C., & Kok, W. (1997). Arbeidsomstandighedenbesluit. Retrieved from https://wetten.overheid.nl/BWBR0008498/2019-01-01/#Hoofdstuk5_Afdeling1_Artikel5.2

Homayounfar, F. (2018). Does anyone know about the difference between Topsis and Vikor methods? Retrieved June 23, 2019, from https://www.researchgate.net/post/Does_anyone_know_about_the_difference_between_Topsis_and_Vikor_methods

Lušić, M., Fischer, C., Bönig, J., Hornfeck, R., & Franke, J. (2016). Worker Information Systems: State of the Art and Guideline for Selection under Consideration of Company Specific Boundary Conditions. In T. R. (Ed.), *48th CIRP International Conference on Manufacturing Systems, CIRP CMS 2015* (Vol. 41, pp. 1113–1118). https://doi.org/10.1016/j.procir.2015.12.003

Malik, A. A., & Bilberg, A. (2017). Framework to implement collaborative robots in manual assembly: A lean automation approach. In K. B. (Ed.), *28th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2017* (pp. 1151–1160). https://doi.org/10.2507/28th.daaam.proceedings.160

Ministerie van Sociale Zaken en Werkgelegenheid. (2019). Repeterende handelingen. Retrieved June 23, 2019, from https://www.arboportaal.nl/onderwerpen/repeterende-handelingen

Opricovic, S. (2004). Compromise solution by MCDM methods : A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*, *156*, 445–455. https://doi.org/10.1016/S0377-2217(03)00020-1

Oxford University Press. (2019). Oxford dictionaries. Retrieved from https://en.oxforddictionaries.com/definition/inefficiency

Rijksdienst voor Ondernemend Nederland. (2019). Loon en overheadkosten. Retrieved June 23, 2019, from https://www.rvo.nl/onderwerpen/agrarisch-ondernemen/visserij/eu-fonds-voor-maritieme-zaken-en-visserij/subsidiespelregels/subsidie-aanvragen/subsidiabele-kosten/loon-en

Salabun, W. (2013). Which MCDM methods are yours favorites and why? Retrieved June 23, 2019, from https://www.researchgate.net/post/Which_MCDM_methods_are_yours_favorites_and_why

Slack, N., Brandon-Jones, A., & Johnston, R. (2013). *Operations Management* (7th editio). Pearson.

Slevin, D., & Pinto, J. (1987). *20 . Critical Success Factors in Effective Project implementation*.

Yazdani, M., & Graeml, F. R. (2014). VIKOR and its applications: a state-of-the-art survey. *International Journal of Strategic Decision Sciences (IJSDS*, (October), 56–83. https://doi.org/10.4018/ijsds.2014040105

ANALYSING AND OPTIMIZING THE ASSEMBLY PROCESS OF LFE PACKAGES AT BRONKHORST HIGH-TECH B.V.

A research project conducted in the process engineering department of Bronkhorst High-Tech. The finalization of the bachelor Industrial Engineering and Management.

This report contains an analysis of the LFE package assembly process, assesses several different improvements and alternatives and gives advice on how to improve the assembly process.