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Developing a Method to Optimize Automated Quality Control in Parts Manufacturing using Systems Engineering

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Abstract

In order to run a successful company today and to be able to face the constant competitive pressure, the quality of the end product in particular, but also the proper quality of the individual processes in the company have to be ensured. Many companies are therefore certified with the standardized quality norm ISO 9001. This standard focuses on customer and supplier relationships, on the involvement of employees on every level, from managers to shop floor workers, and on the continuous improvement of the processes in the company. Although the norm approaches Total Quality Management (TQM) since the last years, they are not identical. However, TQM tries to take a step further by incorporate not only process related workers. Instead TQM improves the quality continuously by involving everyone, including human resources, marketing and accounting. In addition, TQM is also responsible for the company's vision, policies, strategies and tactics.

In addition to the high pressure of producing excellent quality, the complexity of the products rises, especially due to the increase in variance. Systems Engineering offers a systematic approach to manage the complexity. Through systematic thinking, complex systems can be divided into subsystems that can be viewed more easily. The interfaces and relationships between individual subsystems can be investigated. Therefore, it is easier to understand the overall problem and to develop many different solutions to overcome it. The main procedure model of Systems Engineering consists of four components, which are connected to a meaningful whole. The first component is the principle "from rough to detail". Thereby, the system is examined in more detail with each step. The second component is the principle of variant creation. The third component, is the principle of structuring the project into project phases. The fourth component is the problem-solving cycle. This component determines the situation, participates in the search for solutions in cooperation with the creation of variants and helps with the selection of the solution.

In course of this thesis, the principles of Systems Engineering were used to identify different solutions to optimize the automated quality control in a component manufacturing system. The practical part was done in cooperation with Miba HydraMechanica Corp. The methodology for the optimization process was divided into nine phases. The first five project phases were carried out in accordance to the "from rough to detail" principle. These phases address the requirements of the automated quality machine, the appropriate inspection procedure, the modules of the program and the implementation. These phases were supported by the use of further Systems Engineering components, the problem-solving cycle and the principle of variants. The last four phases are test phases and were performed using the bottom-up principle, to ensure compatibility of the individual models. The test phases started with simulation tests on the computer up to real testing phases on the automated quality control system and was concluded with the user acceptance testing phase. Each test phase was verified with the corresponding development phase. Finally, the entire process was validated in the last step. Because of this structural approach and the methods provided by Systems Engineering, it was possible to analyze the overall problem situation and to identify solutions on several levels. Ultimately, it was possible to satisfy all requirements of the company and to improve the quality control significantly.

Kurzfassung

Um heute ein erfolgreiches Unternehmen zu führen und dem ständigen Wettbewerbsdruck standhalten zu können, muss vor allem die Qualität des Endprodukts, aber auch die Qualität der einzelnen Prozesse im Unternehmen sichergestellt sein. Viele Unternehmen sind daher nach der standardisierten Qualitätsnorm ISO 9001 zertifiziert. Im Mittelpunkt dieser Norm stehen die Kunden- und Lieferantenbeziehungen, die Einbeziehung der Mitarbeiter auf allen Ebenen, vom Manager bis zum Arbeiter, und die kontinuierliche Verbesserung der Prozesse im Unternehmen. Obwohl die Norm seit den letzten Jahren das Total Quality Management (TQM) anstrebt, sind sie nicht identisch. TQM versucht, einen Schritt weiter zu gehen, indem es nicht nur prozessbezogene Mitarbeiter einbezieht, sondern die Qualität kontinuierlich durch die Einbeziehung aller Beteiligten, einschließlich Personal, Marketing und Buchhaltung verbessert. Darüber hinaus ist TQM auch für die Vision, Richtlinien, Strategien und Taktiken des Unternehmens verantwortlich.

Neben dem enormen Druck, exzellente Qualität zu produzieren, steigt die Komplexität der Produkte kontinuierlich, insbesondere durch die Zunahme der Varianz. Systems Engineering bietet einen systematischen Ansatz zur Bewältigung der Komplexität. Durch systematisches Denken können komplexe Systeme in Subsysteme unterteilt werden, die leichter zu betrachten sind. Daher ist es einfacher, das Gesamtproblem zu verstehen und viele verschiedene Lösungen zu entwickeln. Das Hauptverfahrensmodell Systems Engineering nach Hall-BWI besteht aus vier Komponenten, die zu einem sinnvollen Ganzen verbunden sind. Die erste Komponente ist das Prinzip "vom Groben zum Detail". Die zweite Komponente ist das Prinzip der Variantenerstellung.Die dritte Komponente, ist das Prinzip der Strukturierung des Projekts in Projektphasen. Die vierte Komponente ist der Problemlösungszyklus. Diese Komponente eruiert die Situation, beteiligt sich an der Suche nach Lösungen in Zusammenarbeit mit der Erstellung von Varianten und hilft bei der Auswahl der Lösung.

Der praktische Teil der Arbeit wurde in Zusammenarbeit mit der Miba HydraMechanica Corp. durchgeführt. Die Methodik für den Optimierungsprozess wurde in neun Phasen unterteilt. Die ersten fünf Projektphasen wurden nach dem Prinzip "vom Groben zum Detail" durchgeführt. In diesen Phasen werden die Anforderungen an die automatisierte Qualitätskontrolle, wie das entsprechende Prüfverfahren, die Module des Programmes und die Implementierung behandelt. Unterstützt wurden diese Phasen durch den Einsatz weiterer Komponenten des Systems Engineering, den Problemlösungszyklus und das Prinzip der Variantenbildung. Die letzten vier Phasen sind Testphasen und wurden nach dem Bottom-up-Prinzip durchgeführt. Die Testphasen begannen mit Simulationstests am Computer bis hin zu realen Testphasen an der automatisierten Qualitätskontrolle und wurden mit der Phase der Benutzerakzeptanzprüfung abgeschlossen. Jede Testphase wurde mit der entsprechenden Entwicklungsphase verifiziert. Schließlich wurde der gesamte Prozess im letzten Schritt validiert. Durch diesen strukturellen Ansatz und die vom Systems Engineering bereitgestellten Methoden, war es möglich, die gesamte Problemsituation zu analysieren und Lösungen auf mehreren Ebenen zu identifizieren. Letztendlich war es möglich, alle Anforderungen des Unternehmens zu erfüllen und die Qualitätskontrolle deutlich zu verbessern.

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Abbreviations

CCD	Charge Coupled Device
CMOS	Complimentary Metal-Oxid-Semiconductor
DIN	Deutsches Institut für Normung (*German Institute of Standardization*)
EN	European Norm
Incose	International Council of Systems Engineering
IO	In Order
ISO	International Organization of Standardization
NIO	Not In Order
OEM	Original Equipmant Manufacturer
QM	Quality Management
SE	Systems Engineering
TQM	Total Quality Management
XT	Extreme Tailoring

1 Introduction

The quality of products and services is a key factor in managing a successful company today. Experiences show that especially companies of German-speaking regions that operate on the world market, attach great importance to quality. The principles of Quality Management (QM) in those companies, are not only followed by the management, but also by the employees. QM has become indispensable for many companies. Without excellent QM, which leads to high product quality, some companies would no longer survive on the world market. The increasing globalisation of markets leads to the loss of protective geographical advantages. This applies in particular to high-wage countries. In these countries, cost pressure is increasing enormously. One way of differentiating from the competitors in low-wage countries is due to a high quality of the product. Another important factor is rising customer expectations. A functional product alone is often inappropriate. The aspects concerning reliability, easy handling and good service are of essential importance. Demands on customers' environmental friendliness and energy efficiency are increasing more frequently. QM therefore does not only refer to the final quality of the product, but also to the quality of the processes in the company. Due to the increasing number of variants, the complexity of products are rising drastically. At the same time, the complexity of development projects also increases. This is aggravated by the circumstances, that the development of an individual project includes input from other countries. This means, for example, that a software is developed in India, necessary components are purchased from China or can be produced in Eastern Europe. Only the systematic use of quality methods makes it possible that such complex constellation can be realized and therefore the demanded quality of the customer can be generated. (Brüggemann and Bremer, 2011)

The topic of complexity does not only impact QM, but also Systems Engineering (SE). Furthermore, it is mentioned again, that intelligent technical systems require new approaches in the development, which arise from the interdisciplinary nature and complexity of different products and production systems. The more complex the products, the greater the demands on the performance of the methodology. Systems Engineering seems to be the suitable solution, because it is a comprehensive approach of different disciplines for the development of multidisciplinary systems. It addresses not only the development of the system, but also the associated project. In German-speaking countries, the distribution of SE is strongly sector-dependent. SE is firmly established in the aerospace industry. In the automotive industry, SE is now seen as an enabler. It is becoming increasingly important and is being driven forward by OEMs (Original Equipment Manufacturer). (Gausemeier et al., 2013)

1.1 Research Questions of the Thesis

This thesis addresses the following research questions:

a) How can SE be used to improve QM in Parts Manufacturing?

b) What are the reasons that lead to or require Process Optimization? What benefits can companies generate by implementing appropriate Quality Assurance measures? Do methods exist that allow a systematic approach for optimization and also address the quality requirements of the process in a focused way?

1.2 Structure of the Thesis

The purpose of this work is on the one hand to discuss the research questions mentioned above and on the other hand to find a suitable methodology for a systematic approach to optimize an automated quality control system. The focus should be on the high quality requirements of the process. This methodology is explained on the basis of a practical case. The first three chapters after the introduction are dedicated to the theoretical part, the remaining chapters to the practical part of the work. Chapter 2 explains two different QM systems, ISO 9001:2015 and Total QM. Both are presented briefly and the most important components are explained. Finally, the costs caused by poor quality are shortly discussed. Chapter 3 is dedicated to SE. First, general terms on the subject of SE are explained, such as System Thinking or System Complexity. Then the four components of SE are explained (From Rough to Detail, Principle of Variation, Problem Solving Cycle, Principles of the Structure of Project Phases) and the connections of the components are explained. Finally, further process models are discussed and compared in terms of advantages and disadvantages. Building on this, chapter 4 combines the topics of SE and QM (research question a) and shows that these are already used together in practice. Chapter 5 describes the introduction of the practical case study. The company that provided the project for the optimization of an automated quality machine is briefly presented here. First, the initial situation is described. Subsequently, the production process of friction plates is explained in this chapter. It is explained which types of friction plates are produced and what the current quality requirements for these plates are. Finally the quality of the friction plates is determined by the automated quality control. This machine should assess the quality of the parts accordingly to the described quality requirements and sort them correctly into good and bad parts. For this purpose, a methodology is to be developed with which the automated quality machine can be optimized. The following chapter 6 describes the methodology for optimizing the automated quality control under consideration of the quality requirements of the machine. Therefore a V-Model is used in combination with SE components. It consists of nine phases. The first five phases are processed according to the "from rough to detail" principle. This means that each phase goes one step further into detail. In some phases, further components from

SE are used, such as the "problem-solving cycle" or the "principle of variant creation". The last phase is the implementation, before the "bottom-up" principle is started. Here each phase of the top-down (=from rough to detail) process is tested and verified. If a test phase is not positively verified, the opposite phase of the V-Model must be entered in order to eliminate the error. The V-Model is concluded with the user acceptance test phase. Meetings, training courses, the transfer of documentation and the handover of the optimized automated quality machine take place here. The thesis in chapter 7 finishes with the result of the optimization and a brief outlook on possible further developments. In this chapter, the research questions from Block b) are also discussed.

2 Quality Management

This chapter refers to quality standards and systems that are widely used in companies. Among them is the quality standard DIN EN ISO 9001:20015, which is no legal obligation, but certification is possible according to this standard and stands for more quality towards customers and suppliers. The second form of Quality Management discussed in this chapter is Total Quality Management (TQM). In addition, the individual costs caused by the topic of quality are discussed further.

2.1 DIN EN ISO 9001:2015

This chapter provides an overview of the intentions and rough structure of the DIN EN ISO 9001 standard and explains why standardization of QM systems makes sense. Furthermore, the basic principles and the structure of the norm is explained on the basis of the process model.

ISO 9001:2015 "Quality Management Systems - Requirements" is the central standard of the ISO 9000 ff. series of standards and contains a minimum standard of requirements according to which the company's QM system is to be designed. This enables the company to meet the quality requirements of its customers. ISO 9001:2015 is the relevant quality standard for the certification of the QM system. (Harmeier, 2016)

The norm DIN EN ISO 9001 is intended to ensure that a company manufactures products or provides good services in the right quality. In order to make this quality-oriented action of the company measurable and comparable, an attempt was made to create an uniform standard norm. Due to the desired standardization, it is difficult to find a suitable standard for every company. ISO 9001 applies to small businesses as well as to large companies. The variety of applications goes from classical production, to services as well as to a wide range of industries from printing to medical practices. For this reason, the norm remains very general in some standards. Mostly there are only descriptions about the regulations and no details explained for the implementation. This applies especially for companies who manufactures products or provides services, as these differ greatly from company to company. And because companies differ strongly from each other, also the QM systems, which are described in manuals or other documents, should differ from each other.

The use of a QM should not be subdivided into the norm chapters, but should be individually arranged after the self-conception of the individual company. A uniform structure of a manual according to the norm is neither intended nor desired. (Brugger-Gebhardt, 2016)

2.1.1 Seven Principles of Quality Management

The definition of a principle is a fundamental theory or rule, which have a big influence on the method on how something is achieved. The principle of the QM can be used as a basis for performance increases of a company. Those principles are not prioritized in the following, due to the fact that the priority can vary from company to company. Even inside the company, the priority of the principles can change over time.

Customer Focus

The main focus of the principle customer focus in QM is to meet the customer's requirements as well to exceed customer's expectations. To achieve a sustainable success in a company it is one of the most important tasks to earn the trust of the customer. Every aspect of a customer interaction gives the opportunity to add value to the customer relationship. Also, the understanding of the customers actual needs and the needs in the future is essential for a sustainable success.

Leadership

Leaders on all levels create purposes, directions and conditions, which are used by the employees to achieve the quality objectives. The establishment with purpose, orientation and also the engagement from employees offer the company the ability to coordinate strategies, guidelines and resources to achieve their goals.

Engagement of People

It is very important to have competent, committed and qualified employees on all company levels to improve value-added capabilities. In order to manage an organization as effective and efficient as possible it is crucial to respect and involve every employee. The recognition, improvement and empowerment of competence also increases the commitment of an employee and therefore it helps to keep up the quality goals.

Process Approach

The QM system exists of interconnected processes. Therefore, more effectiveness and efficiency can be achieved if consistent, predictable activities are described as connected processes, which can be controlled as a coherent system. The understanding of how the goals are achieved in the systems, enables the company to optimize services and systems.

Improvement

The principle of an improvement describes the focus on the continuously enhancement of the process in a company. The continuous improvement is essential to keep up the high level of performances as well as to react accordingly to internal and external changes and create new possibilities.

Evidence-based Decision Making

In case of the decision making, it is more convenient to base the decisions on facts from analyses than on instinct or rush. To find the right decision can be tricky. It can be a complex process with a lot of uncertainties, because mostly there are more than one variant with different sources and inputs, which can be subjective as well. Therefore, it is really important to understand all cause-and - effect relations with their possible, unintended risks. In order to bring more confidence and objectivity to decision making, facts, evidence and data analysis are necessary.

Relationship Management

One of the main points of a sustainable success of a company are the relations to others, for example to their suppliers. Those third parties influence the performances of a company. If the company successfully cares and manages these relationships, sustainable success is more likely to be achieved and performance optimized. Especially the relationship to the suppliers and partners are essential. (ISO, 2015)

2.1.2 Process Orientation

In 2000, ISO 9001 devoted itself for the first time to the approach of process-oriented QM. In the current revision (2015), the requirements for process-oriented QM were tightened. A central feature of it is the orientation of service provision towards process systematization and a department-oriented approach. Important for this is the documentation of the processes. To this end, the organization must be divided into core and performance processes as well as management and support processes. The first step here is identification, management and monitoring. In this context, the focus must not only be on the processes themselves, but above all on their interactions and interfaces. Through this approach, the process orientation demands and promotes a stronger engagement with operational processes and responsibilities. The organization is made more comprehensible and therefore facilitates the clarity and comprehensibility of the process structures. The employees identify their place within the processes relevant for themselves as well as within the entire value chain. (Hinsch, 2014)

Advantages of Process Orientation

- No randomly good results, instead the result is as good as planned.
- The important high-risk processes are known and can be observed in particular
- Process effectiveness and efficiency
- Reliable performance
- Transparency
- Lower costs, shorter work cycles, more economical use of resources
- Improved, reliable and predictable results
- Better knowledge of the interaction of processes
- Promotion of employee motivation and clear assignment of responsibilities

In order to achieve these goals with the QM system, a functioning process management is required. (Brugger-Gebhardt, 2016)

2.1.3 Process Management

Process management includes planning, controlling, implementing, monitoring, measuring and improving processes. The mapping or description of processes is the basis for process management. By the use of written representations the company gets a better overview of the process characteristics and the processes. This is to ensure that good products are not created by chance, instead the products are created exactly as they were planned. If this succeeds, it is called a "controlled" process. There are two different types of process management. **Process effectiveness** is the ability of the process to achieve the desired result. It is necessary to deliver reliably good products or services and to satisfy the customer. The **process performance** is the achieved result in relation to used resources or inputs. The efficiency of a process must be constantly monitored so that the company is able to produce good products at a reasonable price in the long term and therefore be competitive.

However, processes should not be described and managed for their own sake. The focus should always be on improving the process effectiveness and efficiency, which can or cannot be achieved with good process management. Therefore, the way of process management depends strongly on the visions and missions, the industry and the diversity of the respective company. The detail of the process description and management depends heavily on the size of the company. The greater the company the more detailed level will be used and also more division of labour takes place. (Brugger-Gebhardt, 2016)

2.2 Total Quality Management

Since 2000 the ISO 9001 Quality Norm tries to take steps towards the TQM, but they are not identical. The ISO 9001 deals with selected QM systems for design, development, production or services. TQM instead deals with every aspect of the company in every level. These includes among others human resources, finances and marketing. The TQM is also responsible for the visions of the company, guidelines, as well as strategies and tactics.

TQM is defined as a business approach that seeks to maximize the competitiveness of an organization by continuously improving the quality of its processes, products, services, people and environments. (Goetsch and Davis, 2014)

> *“1. Quality—is to continuously satisfy customers’ expectations. 2. Total quality—is to achieve quality at low cost. 3. Total Quality Management—is to achieve total quality through everybody’s participation."* (J.Dahlgaard et al., 2007)

2.2.1 The Five Principles of Total Quality Management

In this section, the five principles of TQM are explained in more detail. The five principles are shown in the pyramid of TQM in Figure 1.

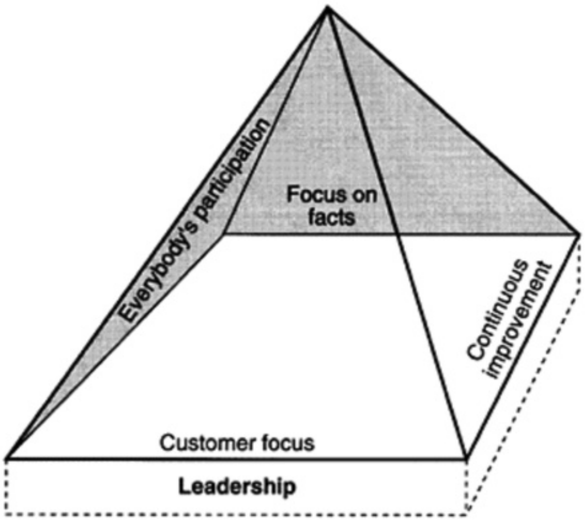


Figure 1: Pyramid of Total Quality Management (J.Dahlgaard et al., 2007)

a) **Leadership:** "Total Quality" can only be achieved, if there is an active participation of the management. One important task for every management is to define the quality objectives, guidelines and plans according to the four sides of the TQM pyramid. This is so important, that the top management should proof those defined quality features to ensure at all costs that they correspond to the pyramid and change them in case they do not fit. It is equally important to make sure that those objectives and guidelines are meaningful and understood by the employees.

b) **Customer Focus:** The principle focus on customers does not only deal with external customers, it deals with internal customers as well. It is very important to keep an eye on the internal customer and supplier relationship. Therefore, employees are a part of the processes in a company. This leads inevitably to a dependency between the employees and quality. Thereby a continuous improvement at lower costs can only be done with committed and satisfied employees. In addition, obstacles which limit the commitment or satisfaction of the employees must be removed. Another very important point in this principle is to create external customer satisfaction. Therefore, it is not enough just to meet the expectations of the customer, because it removes "only" the dissatisfaction. In this step it is essential to add value quality, in that case the customer will be surprised and satisfied with the product.

c) **Focus on Facts:** For the Realization of TQM, a system for a continued measuring of quality factors is needed. It is important, to determine the actual situation, before changing anything. In the principle focus on facts in TQM are three different kinds of measurements described. The first one is the satisfaction of the external customer, the second one the satisfaction of the internal customer and the third one is other quality measurements from the internal processes of the company. (J.Dahlgaard et al., 2007)

d) **Continuous Improvements (Kaizen):** Kaizen is the philosophy of continuous improvement in all areas with the involvement of all people (Brüggemann and Bremer, 2011). The principle of quality improvement in TQM can be divided into internal and external quality improvement. The goal of internal quality improvements is, to lean the internal processes, which means to avoid issues and problems to increase costs. The aim of external quality improvement is to get customers satisfied and therefore gain a bigger market share and higher earnings. Both kind of improvements are closely linked to the questions of the yearly audit for quality. But not only the top management should deal with those questions, also every employee should address the issue. Every employee should be allowed to actively answer those questions, by suggesting quality improvements. Both types of quality improvements, which should not be seen separately, lead to higher profits. Only bad quality is costly.

e) **Everybody's Participation:** TQM is process orientated. Therefore not only external customers are part of the process, also internal customers (e.g. employees). The requirements and expectations of those customers must be identified. The next step is to make a plan about how to fulfill the requirements and expectation. Therefore a feedback from the customers is necessary to collect every issue and experience of the processes. This feedback is a prerequisite for the constant improvement of those processes, as well as for products. To make sure, that the feedback is effective, everyone should participate. Management plays an important role as a role model here. The presence of the company management at the annual quality audits promotes the active participation of employees. (J.Dahlgaard et al., 2007)

2.3 Quality-Related Costs

The "Cost of Poor Quality" is a well-known discussion topic for everyone who is engaged with TQM or ISO 9001. If products or services don't fulfil the customer's desired requirements, a non-conformity is generated. This can lead to costs for bad quality. (Chiarini, 2012)

There are two different quality cost models, a traditional and a modern one. Due to the fact that the modern two-part quality cost model meets the requirements from nowadays businesses, this model is chosen to be described further. Modern QM systems aim at the implementation of a "zero-defect strategy". According to today's understanding of quality, fault-free products are the result of error-free and reliable processes. This is accompanied by the understanding that good quality in the company is achieved through consistent implementation of measures to avoid errors (e.g. process improvements, quality planning), not through more testing. Today, quality is defined in a customer-oriented way as "conformity with the requirements". Newer quality cost models take this understanding of quality into account and subdivide the quality costs as cost of conformance and cost of compliance. The error avoidance costs and the planned inspection costs are added to the costs of conformance. The defect costs and the unplanned inspection costs are added to the costs of non conformance. (Brüggemann and Bremer, 2011)

Cost of Compliance

The cost of compliance includes all costs incurred to ensure that the product meets the customer's requirements, i.e. the quality. These are the costs to "do things right". The costs of conformity include all expenses in the context of error prevention and planned inspections, including:

- Costs for applications of QM techniques, such as audits and quality planning,
- Costs for quality related training and education,
- Costs for testing and monitoring activities, such as incoming goods inspections or test equipment costs.

The costs of compliance are generally known, predictable and unavoidable. They serve to ensure the conformity of the product with customer requirements. As the customer rewards this compliance with his requirements (quality) by purchasing the product or even paying a higher product price, activities to increase compliance are regarded as value-adding measures.

Cost of Non-Conformance

The costs of non-conformance or the costs of the variance include all costs that are triggered by defects and their corrective actions. These are costs incurred by doing "things wrong" because the product does not meet the quality requirements. The costs of non-compliance include defect costs and unplanned inspection costs incurred in the form of:

- Scrap or rework,
- Quantity variances,
- Problem and cause research for quality problems,
- Additional unplanned inspection costs (for example, inspections for defective lots),
- Warranty, recall actions or producer liability,
- Impairments and sales deductions.

The costs of non-conformity are thus costs incurred in connection with defective product quality and inefficient production or business processes. They also represent a waste of company resources and therefore a reduction in added value (e.g. scrap production). The costs of compliance are avoidable, cannot be planned and can therefore only be estimated. (Brüggemann and Bremer, 2011)

3 Systems Engineering

This chapter deals primarily with the definition of system, system complexity and system thinking for the better understanding of the term Systems Engineering (SE). Chapter 3.4 deals with the process model of SE, which is divided into four components. The following chapter 3.5 explains the individual correlations of these four parts. In addition, other process models are discussed. On the one hand, two further models are explained which fall under the plan driven methods chapter 3.6, namely the Waterfall Model and the V- Model. Contrary to this, two agile methods chapter 3.7 are presented, the Spiral Model and Scrum.

3.1 Definition of Systems Engineering

> *"Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem."* (Incose, 2004)

A **system** is a collection of interrelated parts, which in one sense forms a whole. A system consists of **elements** which can be described as **parts and components**. These elements have different characteristics and functions. A characteristic of a physical element would be for example the size or colour while the function describes the purpose of the use inside the system. Elements can be viewed also as a system itself, and then they are called subsystem. All elements of a system are connected through different relations. This is also called the **structure of the system**. The structures can vary in their forms, such as for example hierarchical structure, star structure, structure with feedback and many more. A **system of systems (SoS)** is described by two attributes. Every SoS can be independent from the overall system, can function on its own or with other systems together.

It has therefore an own purpose which can be fulfilled independently. The second aspect is that every single system of those SoS can be acquired and developed primarily independently. (Haberfellner et al., 2012)

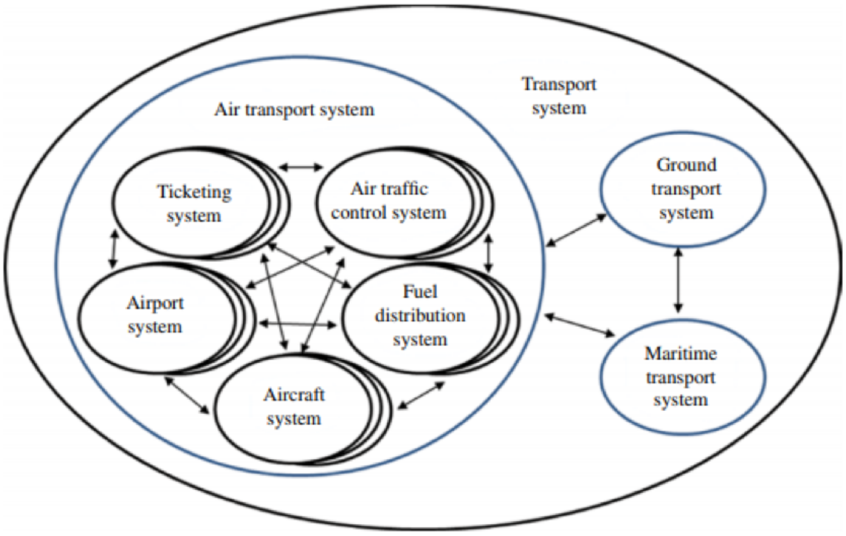


Figure 2: Example of a System of Systems (Incose, 2015)

In Figure 2 is an example shown for a system of systems. In this example the air transport system illustrates the SoS. This air transport system works independently and fulfils its own purposes. Furthermore it has a relation to the ground transport system and also to the maritime transport system. (Incose, 2015)

3.2 System Complexity

Every different type of a system can be classified by its complexity. It is described in a two dimensional diagram with the axes of variability/dynamic and variety/diversity as shown in Figure 3.

Variety/diversity

The variety is given by the number of elements in a defined system. The diversity is described by the heterogeneity of those elements. The simplest case of a system would be just one element with a homogeneous characteristic. If the number of elements increase and the elements get heterogeneous the system becomes more and more complicated.

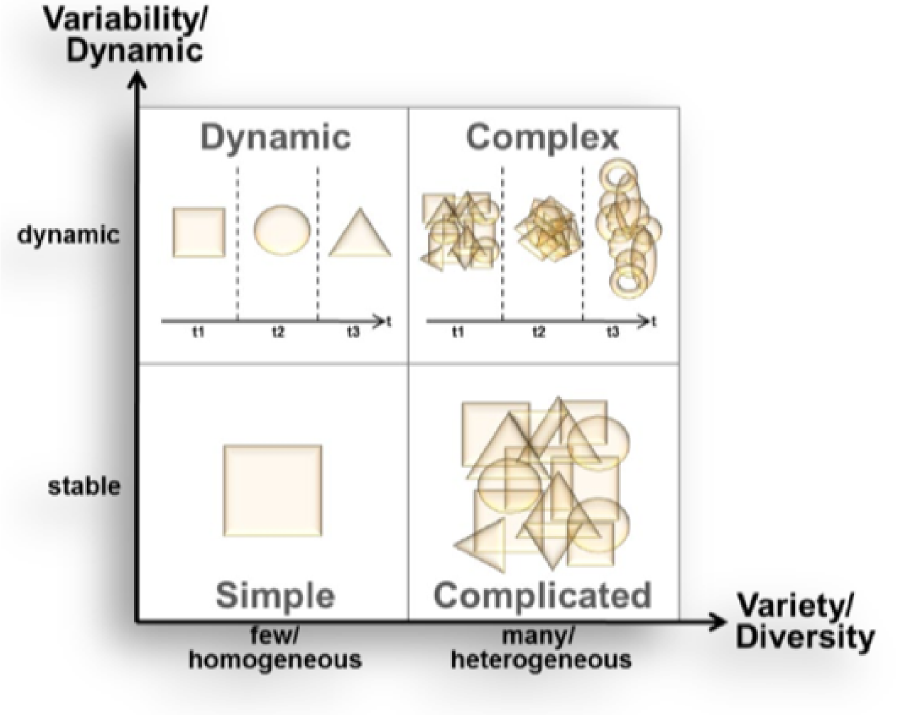


Figure 3: Different Types of Systems (Memecon, 2011)

Variability/dynamic

The variability describes the behaviour of the system over time (short or long term) and distinguishes between stable and dynamic. A stable system is easier to investigate in detail for a long term, because the system does not change. Despite on the other hand a dynamic system requires a need - orientated and fast concept. (Memecon, 2011) Depending on the level of variety and variability four types of systems can be distinguished as it is stated in the following paragraphs.

Simple System

A simple system contains a few elements, which are rigid and permanent connected. Those elements have a weak relation to each other. The entity of the simple system can be described as explicit, in special cases even with mathematic-analytic methods.

Dynamic System

A dynamic system is characterized by the time and mostly by its nonlinear changes between the relations of the elements regarded to the art of interaction and structure. The number of elements and also the number of interactions between the elements are comparatively low. But never the less to quantify or predict the system it is still very difficult because of the influences from the dynamic behaviour.

Complicated System

A complicated system is characterized trough the great number of elements with heterogeneous features and static connections. Compared to the simple system the complicated system cannot be described explicit, because of the large system size. That applies also to the description for the behaviour of the system, which can mostly be described by a computer simulation only.

Complex System

A complex system is described by its high number of heterogeneous elements and dynamic connections. This is the most difficult system to describe or understand, because of its huge different interactions between the single elements. SE tries to reduce the complexity of the system by modelling them into simple systems if possible. (Haberfellner et al., 2012)

3.3 System Thinking

> „*Systems Thinking is a way of thinking used to address complex and uncertain real-world problems. It recognises that the world is a set of highly interconnected technical and social entities which are hierarchically organised producing emergent behaviour.*
> “ (Incose, 2010)

System thinking is a needful tool for SE, because it delivers key factors for an intellectual foundation to the SE. There are several benefits of system thinking. On the one hand it integrates people, process, performance, purpose with their system related surroundings. And on the other hand

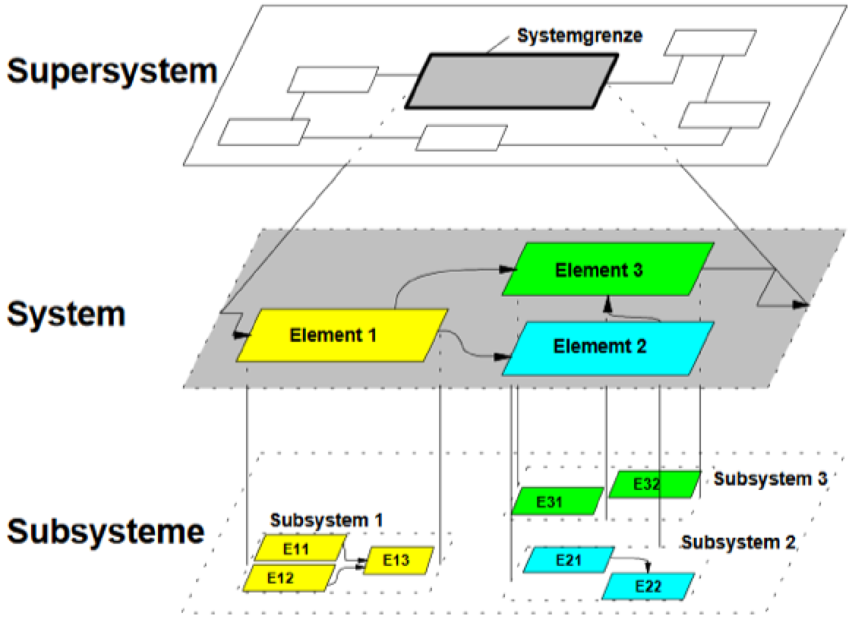


Figure 4: Incremental downbreaking from a Supersystem into a Subsystem (Spahni, 2000)

system thinking gives a way to understand complex difficulties without excluding the impact of unintended consequences. System thinking is also about coordinating teams, disciplines and specialism to exceed great performances. (Incose, 2010)

System thinking encourages the thinking in an orderly way. It should be applied when complex phenomena are encountered, which can be understood or analyzed as systems. The idea of system thinking should also help to identify cause-effect chains or weak points easier. Single elements of a system can be understood better than a big quantity of elements. Therefore, system thinking divides the system into smaller subsystem to gain the better understanding of those subsystems as shown in Figure 4. (Spahni, 2000)

This breaking down of a system into smaller subsystems is called hierarchical system thinking. The first step is to structure the overall system roughly into comprehensible and deliberately limited subsystems. Those subsystems have an essential relationship to the overall system. In order to be able to neglect detailed consideration aspects for the time being, the subsystems are displayed as black boxes. A black box is called a phenomenon with an unknown inner structure, which is without meaning for that time being. Only if this level does not provide sufficient meaningful results anymore, a deeper level will be reached. In the next level those black boxes will be analysed and understood. This is enabled by the current question regarding which level is needed for certain analyses, without losing sight of the entire context. The principle of hierarchical systems can be described as a "zoom-objective". According to the desired output it can be more detailed by “zooming in” or more an overview by "zooming out". (Haberfellner et al., 2012)

3.4 Systems Engineering Process Model according to Hall-BWI

According to SE, a process model is a general procedural guideline that can be used for the redesign or modification of systems. If the point of view is placed on the project and the project is regarded as a system, the procedure which is used for the realization of the project can be described as a procedure model.

A holistic process model

- helps with the successive integration and networking of the components of a system,
- supports the recognition of problem situations and the identification of critical and elements
- simplifies the communication of the employees involved and supports project management.

A process model consists of several basic components which are combined to form a whole. The individual components are explained in more detail below.

3.4.1 "From Rough to Detail"

The "From rough to detailed" component of the process model indicates that it is considered advisable to first define the general objectives for the overall system and a general solution framework. The degree of concretization and detail is only gradually increased in the course of the design of the solution concept. (Böhm, 2005)

The initial analysis of the starting situation should not unnecessarily complicate the problem area through detailed surveys. At the beginning, the problem area should be roughly structured and the interfaces to its environment clearly defined. Only then will the problem area be expanded and addressed in more detail through a step-by-step approach. The procedure from "rough to detailed" is also known as the top-down principle. The opposite would be the bottom up principle. In this case the starting point is the detailed approach and the whole results comes from the addition of the individual measures. This principle is applied under specific circumstances, such as to create an improvement in an already functioning solution. Another field of application of the bottom up principle can be found in agile process models. An agile system constitute in general a permanently changing situation with regard to the process. In this case the bottom up principle divide the the situations in small development increments and sort them accordingly to their priority, which can be constantly reconsidered. (Haberfellner et al., 2012)

3.4.2 "Principle of Variation"

Another important component of the SE procedure model is thinking in variants. The principle behind this is that each problem can always be confronted with several possible solutions. When designing a system, you should never choose the first variant without asking for alternatives. If a system or process with different functionalities exists at the same time, this is called a variant. Basically the different variant formations are divided into variants and detail variants. Principle variants already differentiate from each other in the basic idea. Detail variants, on the other hand, are based on the same basic principle, but their detailed elaboration is different. When using the top-down principle, a suitable level of detail must be found that allows an assessment of the consequences of decisions for a variant. In addition, the variants can be differentiated with regard to their design methodology. Thus, they can be formed by the composition of different modules to a solution (composition principle) or also the inheritance of characteristics and the modification of other characteristics (inheritance principle). The principle of variation is an "indispensable component of good planning" and should be used in particular when several unknown conditions can influence the effectiveness of a solution. If the creation of variants is dispensed with, there is an increased risk of having chosen the wrong solution and only recognizing this at the end of the planning phase. In the worst case this can lead to the stop of the project. (Kloth, 2009)

3.4.3 "Principle of the Structure of Project Phases"

This further component concretizes the structuring into project phases and complements the general considerations which have already been made from the first two components. This component should enable a step-by-step, overview able planning-decision- and concretization process. This is divided into partial sequences. The number of project phases depends on the type, scope and significance of the project. In the case of a smaller project, it is usually possible to complete this project with a smaller number of phases without any disadvantages. The individual phases are designated in very different ways depending on the company, sector and task. In this context, it is secondary to arrive at a common denominator. However, it is important that the complexity of a problem and the risk of a wrong decision can be reduced through the targeted division into individual planning and implementation phases. There are basically three main phases. The first main phase is development. This includes the preliminary study, the main study and the detailed study. The second main phase consists of system construction and system integration. The third phase, the use phase, deals with the use of the system and the initiation of its redesign. (Böhm, 2005)

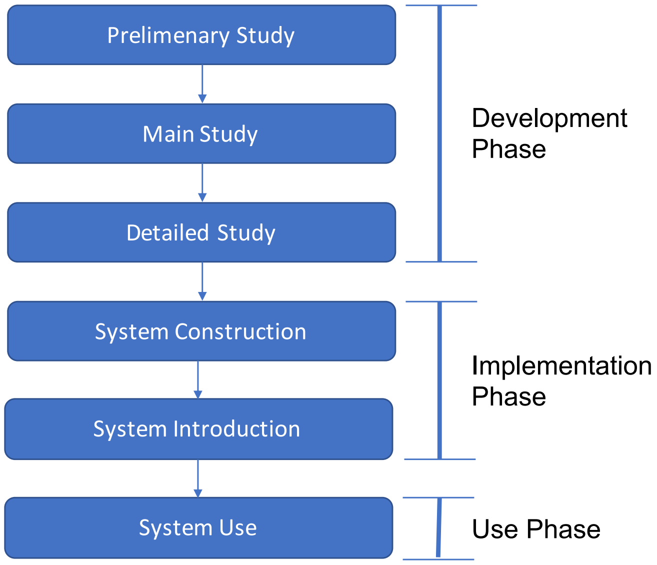


Figure 5: The Structure of Project Phases (cf. Schönsleben, 2015)

Preliminary Study

The purpose of the preliminary study is to clarify the following with reasonable effort

- how broad the scope of analysis should be defined (= the delimitation of the system)
- whether the correct problem is addressed
- how the problem area is influenced by possible mechanisms
- whether there is a need for a new or revised system at all and to what extent and of what kind
- the scope of a new or modified solution
- basically which solution principles would be feasible
- what requirements the solutions should meet
- which solution principle is the most promising, whereby the relevant assessment criteria should be worked out in the preliminary study (Böhm, 2005)
- whether an existing solution should be upgraded based on an existing system architecture or if a new architecture is necessary

By combining the principle of the project phases with the principle of variant formation, the problem is identified in the preliminary study and the possible solution variants are formulated. In addition, the decision basis for the selection of the most promising variant is chosen here. A preliminary study is therefore more than just an analysis of the current situation, as various solutions are already being elaborated. In the preliminary study it is also important to take proper account of the environment and its interactions. The preliminary study offers two huge advantages. On the one hand, it clarifies the task of the project so that there are no more ambiguities. On the other hand, the preliminary study quickly reveals whether a project of this kind is feasible at all. For this reason, a project can be terminated prematurely, which in turn saves a lot of costs, because this could be determined with little planning effort. If the project is continued after the preliminary study, however, it does not mean that it will be carried out to the end. The project can still be abandoned due to better insights into the problem relations in the main study or detailed study. (Haberfellner et al., 2012)

Main Study

The purpose of the main study is to refine the preliminary study. In particular, the chosen solution principles should be refined. In this phase, overall concepts are developed with an assessment of performance, quality, time, costs, acceptance and profitability. The result of the main study is the decision for an overall concept. This offers the possibility to integrate the further developments into an organized framework. (Jenny, 2014)

The overall concept includes

- Framework (master plan) for the next phase
- Elaborated basis for possible investment decisions
- Proposals for dividing the system into subsystems, which will be implemented within the framework of sub projects.
- Prioritized subsystems that influence the processing sequence. (Böhm, 2005)

Detailed Study

Within the scope of the detailed study, detailed solution concepts for subsystems are developed and decisions are made about suitable solution variants. The field of view is narrowed down.

The purpose of detailed studies is to

- work out detailed solution concepts and to make decisions about corresponding design areas
- concretize the individual solutions to such an extent that they can subsequently be implemented . (Böhm, 2005)

System Construction and Testing

In system construction, all previously decided solutions are put into practice. This means that systems are erected, machines, equipment, and possibly even prototypes are manufactured, and the creation of IT software including documentation is set up. But this also includes organizational activities such as the preparation of operating instructions, training for operators and users and also scheduling maintenance and servicing procedures.

The test phase is also very important here. Testing before the implementation often takes place as individual tests or as a system test. In the individual test, the individual components are tested. In the system test, the entire system is checked. It is now even common to introduce separate project phases for the execution of system tests, because acceptance testing and testing procedures are of particular importance. (Haberfellner et al., 2012)

Here is an example of how the implementation and test steps in IT could look like:

a) The system is programmed

b) The implemented system is tested

c) The corresponding documentation is created (user manual)

d) Training courses are being held (this point would also be covered in the system implementation phase) (Böhm, 2005)

System Integration

During system integration, the size and complexity of the project must be taken into account. If it is a small and simple solution, the solution as a whole can be implemented immediately without great risk. Of course, the right preparations have to be made in advance. In the case of a complex solution, however, it should be implemented in stages. If the implementation of the solution is sudden, there is a risk of incalculable side effects. A further important step in the system integration is an adequate training for the user and operator in terms of know-how transfer. In addition, the necessary warranties must be checked by the right people. This phase often ends with a final ceremony. (Haberfellner et al., 2012)

System Use

Once a system has been implemented, the project can be considered as completed. After the project has been successfully finalized, a number of final papers have to be completed. It makes sense to record operational experience while using the new system. These experiences should be collected and evaluated and can be used to improve or extend the system. In case of a necessary large change of the system, the impulse for the preliminary study is given. (Böhm, 2005)

3.4.4 "Problem Solving Cycle"

The problem solving cycle serves as a guide to solve problems. The art of the problem does not matter. The problem solving cycle can be used in every project phase. It contains the following steps: finding objectives, finding solutions and selection which can be run through several cycles as required. Finding objectives contains the situation analyses and the objective formulations, which both influence the search for the right solution in the solution finding step. The selection step consists of the evaluation and the final decision. Whereby the evaluation contains the different solution variants out of the finding solution step, but also gets objective evaluation criteria out of the objective formulation as shown in figure 6.

Situation Analysis

The situation analysis shall in particular serve the following purposes:

- Obtaining data and isolating system and environment.
- Determination of properties of the system and important environmental elements.
- Analysis of external influencing factors.
- Structuring the knowledge base and clarifying needs.
- Clarification of the degrees of freedom.

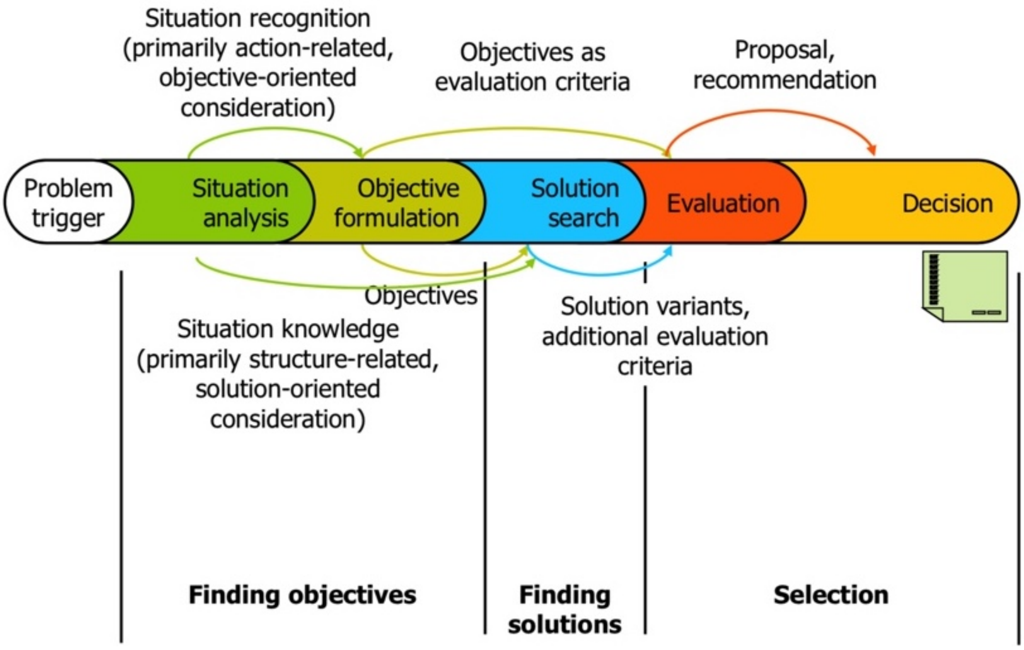


Figure 6: Structure of the Problem-Solving Cycle (Schönsleben, 2015)

Four characteristic approaches are of importance, which are closely related to each other:

a) The system-oriented approach, which is based on systemic thinking and is intended to help structure the problem area.

b) The cause-oriented (diagnostic) view, which aims to identify symptoms of an unsatisfactory situation and their possible causes.

c) The solution-oriented (therapeutic) view, which focuses on the possibilities of solutions and interventions (catalogue of resources), serves as a basis for the development of realistic goals.

d) The future-oriented view is superimposed on these approaches (view from the present into the future). (Spahni, 2000)

Objective Formulation

The purpose of the objective formulation is the systematic summary of the purposes on which the search for a solution must be based. Thereby it is important to take some ground rules into account. The objective formulation should be:

- solution-neutral, which means describing the functions and effects of solutions and not the solution itself.
- complete, which means to have all important requirements for the desired solution
- as precise (operational) and understandable as possible. Goals are understood if they are clear to the people involved and allow unambiguous communication. Goals are formulated operationally, if the achievement of the goal is clearly recognizable.
- realistic, meaning that the factual circumstances of the situation, but also the social circumstances and subjective values of decision-makers and those affected should be taken into account.

In order to be able to set priorities with regard to the importance of goals, it has proved useful in distinguishing between mandatory goals, target goals and desired goals. (Böhm, 2005)

Finding Solutions

The solution search consists of two parts. The first is the synthesis and the second is the analysis. It is often difficult to separate the two in terms of time, since the critical confrontation with the solution usually takes place intuitively at the time of the solution idea. Nevertheless, both will be explained separately in the following for better illustration. The **synthesis** of solutions is the constructive and creative step in the problem-solving cycle. The purpose of synthesis is to develop solution variants based on the results of the situation analysis. The solution variants should correspond to the level of concretization of the currently processed phases. (Böhm, 2005)

The first step in the **analysis** is to determine whether the prescribed mandatory targets have been met. In addition, the individual concept designs are checked for completeness and functionality. In addition, the effectiveness and behavior of the system under environmental conditions are checked to ensure that they meet expectations. If the variants are not satisfactory, they are revised in a further synthesis step. An important task of the concept analysis is also to determine important system properties and the concrete conditions under which the individual solutions can perform. In addition, the consequences associated with the choice of a particular solution must be identified. (Spahni, 2000)

Evaluation

The purpose of the evaluation is to compare possible variants systematically and find the most suitable solution. The evaluation step uses only solution variants that fulfil the mandatory targets.

The segregation was already made in the analysis step. The hard part of the evaluation process is to find a way how to compare solutions with completely different characteristics. There are a number of methods which can be used in the evaluation phase, like Benefit analysis, cost/benefit analysis, cost/economic feasibility analysis. Such methods must not be seen as a substitute for the decision. They only make the decision situation transparent, since they force the decision maker to think about his value standards and to how to structure them. This helps to prevent purely intuitive decisions. (Spahni, 2000)

Decision

After the analyses of the objectives and solutions, decision has been made based on the evaluation. The purpose of the decision is to give priority to the solution that represents the best option from an entrepreneurial point of view (Böhm, 2005).

3.5 Relations Between the Individual Components of the Process Model SE according to Hall-BWI

The components of the SE procedure model explained in Chapter 3.4 represent elements of an overall methodology. Those components have meaningful relations between each other. The relations shown in figure 7 should only be understood as a basic trend. The authors of the book "Systems Engineering: Grundlagen und Anwendungen" consider this modular structure to be particularly characteristic and a particular strength of the SE concept.

The interaction of the components of the procedure model:

a) From *rough to detail* (top down) and the *principle of variants* are shown in the lower part of figure 7 .

b) The component project phases (life cycle) concretizes these process principles in the sense of managing orientation by offering a time-based framework for the phases. The different steps of the top-down procedure can be assigned to the following phases:

  - The *preliminary study* covers the identification of the *problem* and the formulation of various *solution concepts*.
  - The *main study* focuses on the development of different variants for *overall concepts*.
  - The *detailed study* contains different variants for *detailed concepts*

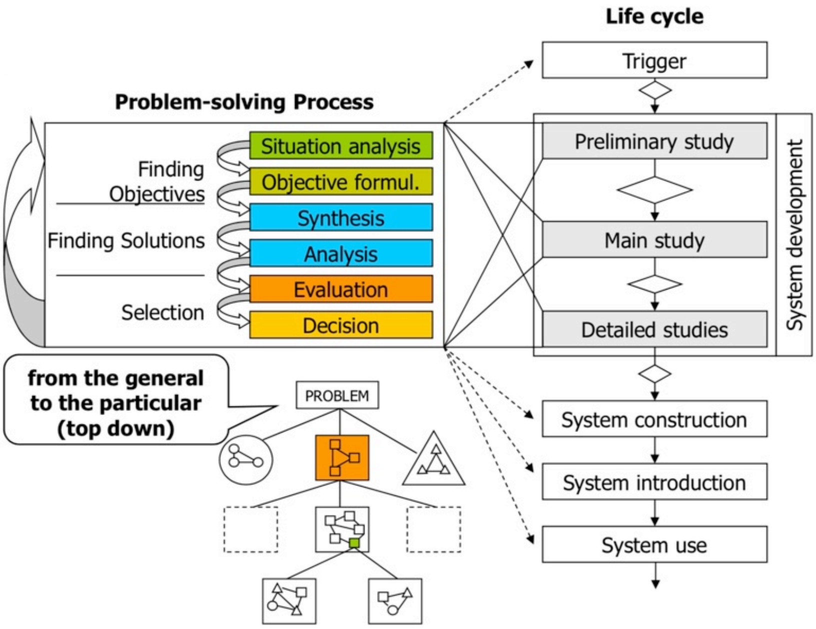


Figure 7: The Structure of the Relations Between the Individual Components of the Process Model SE (Schönsleben, 2015)

c) The *principle of variations* is also an important part for the solution search as well as for the problem-solving process.

d) The *problem-solving process* is the micro logic process, which can be used for every kind of problem.

In the following, other procedural models will be described which can be used as alternatives to the SE procedural model explained above. A basic distinction is made between plan-driven methods and agile methods. (Haberfellner et al., 2012)

3.6 Further Plan driven Methodes

Plan driven methods provide a high degree of structure, in the sense of a clear step by step sequence. This is based on the expectation of being able to develop high-quality solutions in an efficient manner. The SE process model described above, belongs without doubt to this category. Other plan driven methods are the Waterfall Model, V-Model or Simultaneous Engineering. (Haberfellner et al., 2012)

3.6.1 Waterfall Model

The Waterfall Model is one of the oldest and best-known models for system development. In its original form it was a non-interactive process model in software development. Already in 1970 the model was mentioned by Winston Royce in his article *Managing the Development of Large Software Systems* . Winston Royce divided this model into seven phases: system requirements, software requirements, requirements analysis, design, implementation, testing and implementation. A phase is usually summarized by required specification. The next phase can only be started after the successful completion of the phase before, until the end of the project is reached. In these phases only experts are used, who are occupied with the respective topic area. In the former version of the Waterfall Model no phase was allowed to be repeated. (Harwardt, 2011)

Due to the strictly sequential arrangement and the simple phase structure, projects following the Waterfall Model have a simple organisational structure. However, the users of the system are only involved in the project at the beginning of the analysis phases. This makes it difficult to change requirements during the development phases. Analysis, planning and development errors are also noticed late. In particular, if errors require changes to the results of the early phases, it is difficult to implement this with this procedure, because it is not possible to have as far- reaching feedback as needed. And also, phases cannot be interrupted and restarted at an earlier point. In addition, it is a big problem that in most cases the knowledge of all requirements is not known precisely at the beginning of the project. It is therefore not expedient to carry out all activities always and in full, which was also Royce's actual statement. Since the Waterfall Model has a strongly regulated project flow and is oriented towards the creation of documentation, project risks are only recognized late or not at all. However, risks are a critical factor, especially in the Waterfall Model, because if a risk occurs in one phase, all subsequent risks and therefore the entire project is delayed. Nevertheless, the Waterfall Model is the basis for many further structured approaches. Due to its organization in phases, it is very well suited for the implementation of well-known, low-risk procedures, e.g. tendering and contracting procedures of the public sector (e.g. V-Modell XT). (Kuhrmann, 2012)

In summary, the Waterfall Model has the following advantages and disadvantages:

Advantages

- Clear differentiation of the phases
- Simple possibilities of planning and controlling
- Effective model for stable requirements

- Simple understandable model
- Low management effort

Disadvantages

- At the project start there are only inaccurate estimations for costs and resources possible.
- The possibility to try out different features in an early stage is not possible due to late implementation phase.
- During the design phase the interaction with the user is hard due to the missing prototype. It means that the user only gets an image from the product when it is nearly finished.
- Requests for changes that go beyond cosmetic improvements are difficult to fulfil after completion and can be met mostly only with high costs.
- If there are changes in the requirements due to technical, organizational or political reasons, can lead this to big problems. (Zittera, 2002)
- In practice it is mostly unavoidable to go back in the an earlier phase (Binder et al., 2006).

3.6.2 V-Model

The V-Model was developed for military software applications on behalf of the German Federal Ministry of Defense (BMVg) and the German Federal Office of Defense (BWB). The development began in 1986, and in 1991 the use of the V-Model became mandatory for the entire defence technology sector in Germany. The German Federal Ministry of the Interior adopted the model in 1992 as a "uniform standard for the entire public sector", since the problem areas for software development in the civilian sector are similar. The aim was not only to create a development model for the public sector, but also to make the V-Model openly accessible in order to create a broad acceptance in the private sector apart from government agencies. The V-Model has its origin name in the short form of "procedure model" on the one hand, on the other hand the graphic representation of the V-Model forms the letter "V". The aim was not only to create a development model for the public sector, but also to make the V-Model openly accessible in order to create a broad acceptance in the private sector apart from government agencies. (Binder et al., 2006)

Today there are multiple interpretations of the V-Model, both in software development and in overall system development. In Germany, a formal procedure was introduced as a V-Model, especially for the development of software projects. On the basis of new development methods, the V-Model is extended to V-Model 97 and later to V-Model XT (xt = extreme tailoring). This makes the system adaptable to the respective needs and enables a stronger orientation towards agile and incremental approaches. (Haberfellner et al., 2012)

Functionality

The V-Model is a combination of a top down process and a bottom up process. The top down process on the left side of the model transfers the customer objective into technical requirements for the overall system as well as for the subsystems in the later on phases. The bottom up process on the right side, develops, tests and integrates the subsystems into the overall system step by step, verifies and validate the overall system compared to the original objectives afterwards. (Haberfellner et al., 2012)

There are two different types of proof. The **verification** is the explicit proof (usually done by measurement) of the fulfilled requirement specifications and clarifies if the implementation was right (according to requirements).The **validation** is the proof that customer's desires, which are documented in the specification sheet, are fulfilled. It provides feedback, if the right product were developed for the customer. (Timinger, 2017)

In the following the steps of the V-Model will be described in more detail, as an example of the software development. But the basic principles of the V-Model are not only applicable to IT projects, but also to other development projects, e.g. in mechanical engineering/ mechatronics as shown in picture 8.

Requirement Analyses: The first step is to select all business requirements, which have to be fulfilled during the software development. The business requirement analyses helps to find out what the customer demands. Therefore, it is useful to see the problem from a customer's point of view to better understand the functionality of an application. From that point on there will be a layout with acceptance criteria to correlate the tasks in the development phase with the overall outcome.

System Design: In this phase it is important to develop a layout for the system and application design. The system design describes detailed hard and software specification. System design phase is further divided into sub categories as follows:

- **Architectural Design:** This Design Phase has its focus on the design of technical methods regarding to the realization of the software development goals. Architectural design is often called the high-level-design which includes an overview of the solution, platform, system, product, service and support.

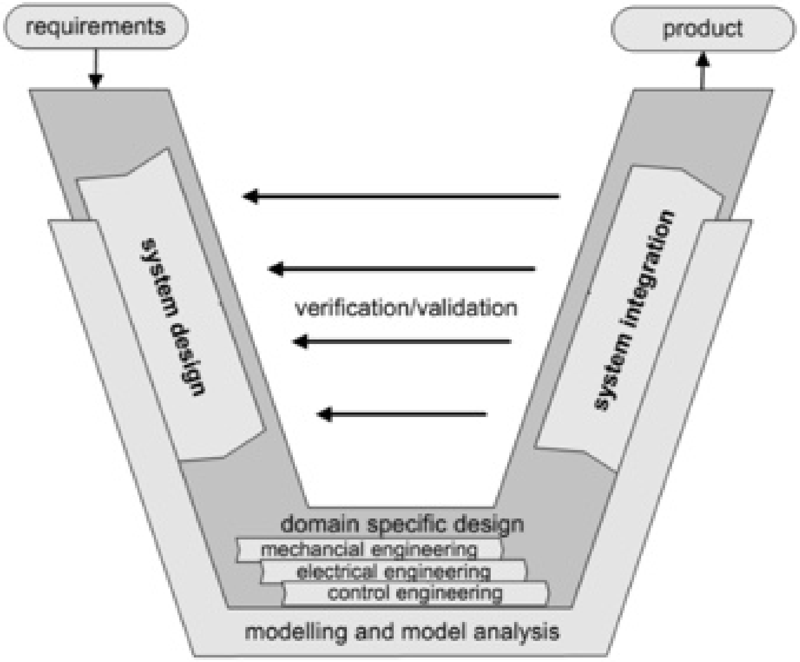


Figure 8: V-Model as a Macro Cycle (Nagya et al., 2014)

- **Module Design:** The module design on the other hand is called the low-level-design. It defines the logic on which the system functionality is based. In this phase it is important to describe the relations between the modules and their priority of interaction as good as possible.

The **system integration** phase, develops, integrates, and tests step by step, until the implementation process is completed successfully. The system integration contains several phases:

- **Unit Testing Phase:** Unit tests should verify single modules and eliminate errors if existing. A unit test runs a part of the program, to find out if the desired functionality is given.

- **Integration Testing:** The integration test makes sure that the whole program code works. Therefore, all code parts have to be performing as a single entity.

- **System Testing:** System tests are carried out, if the whole system is ready. The usage, as a whole system takes at the target environment place, to make sure that it is working properly there. It should work efficient with the smallest response time.

User Acceptance Testing: Already during the requirement analyses phase the user acceptance testing plan is made. Once the software is ready for delivery, a series of tests are carried out by the users to ensure that the product meets the intended objectives. (Professional, 2018)

Advantages

- The V-Model suites only for some kind of projects: because of his linear design, implementation and testing phases it is heavily adopted by the medicine industry. The V-Model is a great method if the project duration and the scope of the project is well defined. The technology has to be stable as well as the documentation and design specifications have to be clear.

- The V-Model is also perfect for projects with a strict time schedule and important milestones. It is relatively easy, with clear and simple understandable phases to design the time line for the whole development life cycle and also, to create important milestones.

Disadvantages

- Lack of the ability to adapt: Similar to the traditional Waterfall Model, on which the V-Model is based, it is very difficult to adapt necessary modifications during the development life cycle process. Therefore it can happen, that an overseen problem in the fundamental system design, cause a heavy setback in form of time and money later on.

- Time line Restrictions: Although the V-Model itself is not inherent, it can happen due to short calculated time lines, that the phases of testing and implementing are done in a rush only to meet the milestones in time. (Powell-Morse, 2016)

3.7 Agile Methods

The plan driven methods, which were discussed in the previous chapter, are despite the undisputed advantage that they can bring a logical process structure into the project, criticized especially in connection with IT projects. In particular, they are accused of making the (software) development process unnecessarily complicated, of requiring long development times, and of not being able to satisfy the result. This need has led to the development of so-called agile methods. (Haberfellner et al., 2012)

3.7.1 Spiral Model

The Spiral Model according to Boehm (1988) takes the possible project risks of sequential development into account and is therefore iteratively structured. The whole process is structured into four phases, as shown in figure 9. All four phases are run through several times within the framework of an evolutionary software development. This means, that in every iteration only products, which are based on the products of the previous run, are developed. And those products are the bases for the next run of phases. The four phases are:

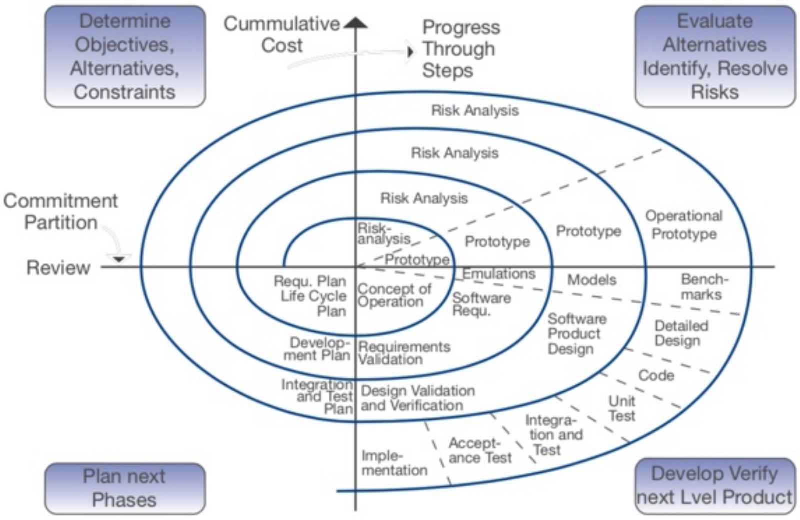


Figure 9: Spiral Model (Grechenig et al., 2010)

- **Definition of Objectives:** Every phase starts with the definition of the detailed objectives and products of the cycle. Also possible variants and constraints are analysed and recorded.
- **Risk Analyses:** In this phase all the previous objectives and variants are assessed in the light of the restrictions and risks are identified. Therefore prevention and solution strategies are developed for the assessed risks.
- **Performing the Work Steps:** Goal of this phase is to develop the indented products. Depending on the art of the project and possible identified risks, the number and the priority of the products can vary in the phases.
- **Planing the Next Phase:** After every cycle, a review is made. Results and conclusions of these reviews form the basis for planning the next cycle.

The Spiral Model is specially suitable for very large and complex projects, because the risk-controlled approach takes the complexity of a system into account. The number of cycles can only be determined during the project and is dependent of the occurred risks. Therefore the formulation of time and cost planing is difficult in the beginning. Furthermore, it is a tightrope walk of the project duration. If the project is dragged out for a long time due to uncertainties, this can lead to very expensive project costs. On the other hand, if the project duration is too short, possible risks can be overlooked and this can lead to problems in the subsequent runs. (Grechenig et al., 2010)

Advantages

- Process model is not defined for the entire development
- Integration of other process models as special cases possible Flexible
- Errors and unsuitable alternatives are eliminated at an early stage.
- Adaptation of the development to new findings/to discovered risks. (In particular also: changing requirements)
- Supports the reuse of software through the Consideration of alternatives.
- Early detection/avoidance/correction of errors and unsuitable alternatives

Disadvantages

- High management effort
- Less suitable for small and medium-sized projects
- Knowledge about identifying and managing risks is essential, but often non-existent
- Planning only covers one cycle at a time. The project cannot be fully planned from the very beginning. (Schramm, 2007)

3.7.2 Scrum

The development of the development process model Scrum goes back essentially to Jeff Sutherland and Ken Schwaber, whereby Mike Beedle contributed in particular to the distribution of Scrum. Scrum has its roots in empirical process control, which is based on constant feedback. The precondition for this is regular checks and adaptations as well as the visibility of the current state of the process. Scrum is therefore particularly suitable for concrete development situations in the software sector, which can be characterized by keywords such as complexity, unpredictability and uniqueness.

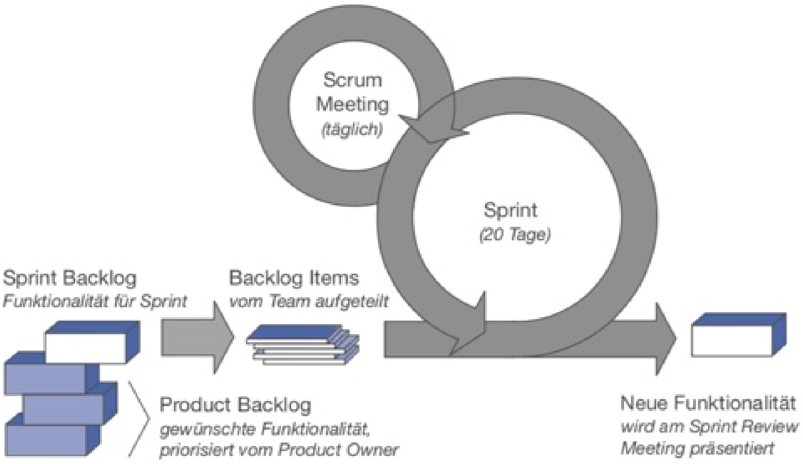


Figure 10: Scrum (Grechenig et al., 2010)

The Scrum method is structured as shown in Figure 10. In the *Product Backlog* all functional and non-functional requirements are ranked according to importance, which is constantly adjusted to the actual situation during the project. Responsible for this is the so-called *Product Owner*, who in turn receives his content for the *Product Backlog* from the stakeholders. The actual development is then carried out by a *Scrum Team*, which usually consists of about seven (+- 2) people.

The central element of Scrum is the *Sprint*. For the *Sprint* an exact duration is defined (e.g. 30 days). During this time, the iteration is implemented and the *Sprint* must end with the completion of a new functionality. In order that everyone knows what has to be done in the *Sprint*, a *Sprint Planning Meeting* is held at the beginning of the *Sprint*. In the *Sprint Backlog*, which consists of the individual *Backlog Items*, the functionalities for the *Sprint* are recorded and fixed. There is also a *Burndown Chart* to track the progress within the *Sprint*. In addition, a *Daily Scrum Meeting* takes place every day, during which the progress of the project is monitored and obstacles are identified and removed.

At the end of each *Sprint* there is a *Sprint Review Meeting* where the *Sprint* goals are checked. If this *Sprint* was successful, a new *Sprint* is built on it and started. If this is not the case, the *Sprint* will be discarded and, in the worst case, 30 days will be lost. (Grechenig et al., 2010)

Advantages

- Transparency about the progress of the project and the (increasing) accuracy of the cost estimates
- Early rearrangement in the backlog to make planning more realistic on the one hand and to relieve unnecessary pressure from the team on the other hand
- The efforts of a requirement become more conscious and better visible by the decomposition into tasks.
- The fact that the team estimates the effort itself makes the estimates more realistic than when the project manager estimates from above.
- Due to the presence of the management, they realistically experience the costs of the required features and, if necessary, with a view to the budget, the once so important features are now sorted as Nice-to-have at the end of the priority list.
- Daily Scrum Meetings improve communication within the team and let everyone know what colleagues are working on and where obstacles exist.

Disadvantages

- A disadvantage of Scrum is the focus on single tasks within a sprint and the missing overview of the whole project route. Sprint backlog and product backlog are not transparent enough. This might also be a reason why Scrum does not establish itself in other project types (architecture, vehicle development, etc.).
- A deficit that arises in practice is the missing or late integration or acceptance tests. Only the final result of a sprint will tell whether it works or not.
- It can happen that a group dynamic effect results from the missing leadership position, which is counterproductive. In this case, the organizational group leader should be involved.
- The sprint backlog and the product backlog are often not sufficiently visualized. Usually the team has a very sprint-oriented point of view.
- The overhead through Scrum can be significant if not tightly organized. (Kestler, 2019)

3.7.3 Method Comparison

Table 1 shows and summarizes a comparison between the methods described above. The area of application and characteristics are briefly described.

Table 1: Comparison between different process models

Process Model	**Primary Goals**	**Size of the Project**	**User Participation**	**Features**
Waterfall Model	Minimum Management effort	Medium	Low	Sequential, full width
V-Model	Maximum Quality (safe-to-market)	Small-Big	Low	Sequential, full width, validation, verification
Spiral Model	Risk Minimization	Big	Middle	Decision per Cycle about further procedure
Scrum	Risk Minimization	Big	High	Decision per after every sprint about further procedure

4 Systems Engineering applied to Quality Management

This chapter explains the relationship between Systems Engineering (SE) and Quality Management (QM). As early as 1999, the author David Thompson was interested in combining these two aspects. In his opinion, too many companies fail to integrate ISO 9000 or Total Quality Managment (TQM), because the standards are only explained in general terms and companies often find integration very difficult. In the following, author David Thompson explains a systematic approach based on SE to better integrate ISO 9000 and TQM approaches. (Thompson, 1999)

But not only the author David Thompson combines SE with QM, but also the International Council on Systems Engineering (Incose) handbook deals with this connection. In practice, there is an example about an SE approach to Quality Assurance for Aerospace Testing, therefore this chapter finishes with a report on this example.

4.1 Systems Engineering applied to TQM by David Thompson

Almost every company now deals with the subject of QM and improvement. A multitude of standards, norms, methods and procedures such as ISO 9000 or TQM have been developed over the years and are a prime example of this. The automotive industry has even developed its own standards for this. However, the industry has considerable difficulties in putting these initiatives into practice and is far from satisfied. The TQM in particular poses problems in this respect, as cultural challenges are added. Too many companies do not have a sound basis and nevertheless start to switch to TQM. As a result, it often happens that companies only change half-heartedly and thus achieve poor results.

Problems of the use ISO 9000 or TQM in Practice

As ISO 9000 is based on a structural structure, companies often use this process blindly without really adapting it to the company. Because ISO 9000 offers a very wide bandwidth for users, ISO 9000 does not address each specific use case, but is a general guideline that must be adapted by each company itself. A system approach is missing here. For this reason there are dissatisfactions after the introduction of ISO 9000 in companies. Total QM is extended to the entire organization. This means not only processes, but also people, management and cultures. Here, however, the problem often arises that the actual processes can hardly be converted to TQM. If this cannot be changed over properly, how can a company culture adapt to it?

Solution

In order to solve the problems described above, it is necessary to return to the first principles. Here, it is important to focus on the actual basic building blocks, since each transformation process converts inputs into added value. If one does not use however the correct inputs, in this case fundamental building blocks of the enterprise then this can lead to an unsatisfactory result. The enabler is responsible for success and competent operation of the process. As can be seen in Figure 11, the monitoring of process paramters, output performance, and quality is very important in order to provide meaningful feedback for the input. In this way, corrective measures can be taken in the process in order to guarantee a flawless transformation. By taking a systematic step-by-step approach, the author describes the introduction via the transforming model as a principle of SE applied to business processes like ISO 9000 and TQM. (Thompson, 1999)

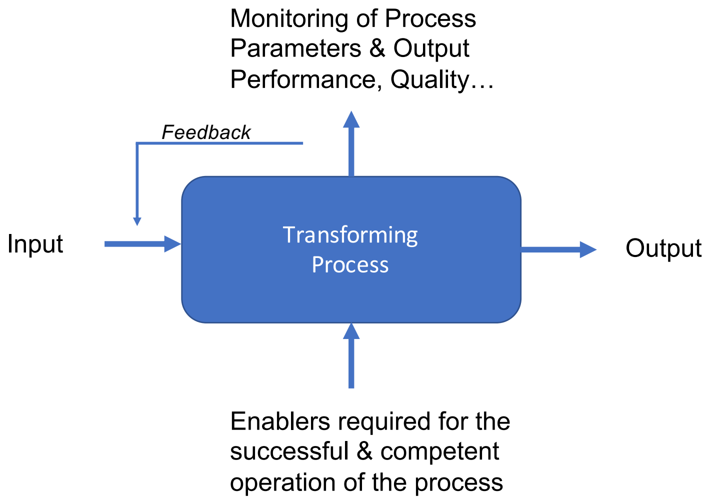


Figure 11: Transforming Process (cf. Thompson, 1999)

4.2 Use of Quality Management in Systems Engineering by Incose

The SE Handbook from Incose is a guide to System Life Cycle Processes and activities. QM is presented in the Enterprise and Agreement Processes chapter as well as a support activity of SE. The purpose of introducing a QM process in SE is to make customer satisfaction visible, which is achieved through quality objectives. The application of this handbook of SE is an approach to bring a quality discipline into a company. The QM focuses on the implementation and continuous improvement of customer satisfaction and company goals. In order to ensure that the expenditure for the QM is not too high, it should under no circumstances exceed the total value of the process. For the analysis of the quality effects, the strategic enterprise documentation can be consulted. In the documentation the missions, strategies, goals and objectives of a company are recorded. Existing agreements can be used to find out how much attention is paid to quality at the moment within the company. In order to be able to evaluate quality, projects have their own measurements and evaluation systems, which should then provide clear indications of improvements. In case of a successful implementation of a QM process one has to expect the following:

- Guidelines are defined to make quality targets for processes and systems measurable and therefore as neutral as possible.
- In QM, responsibilities are assigned within the company and realistic resources are made available for this purpose.
- In addition the satisfaction of the customers is examined and measures are taken in order to be able to reach the quality goals further.

Recommendation for Quality Management Implementation

Furthermore, the handbook provides some important tips to ensure a successful implementation of QM.

- It is important that everyone is aware of the quality policy in the company and follows it. Decisive here is the commitment of the management. If the quality is carried out by the management team, the rest of the company will follow.
- Quality is part of the daily focus.

- By developing an Intranet, internal communication can be promoted and quality guidelines can be communicated to employees. It also gives employees the opportunity to provide valuable feedback.

- Another important aspect is the analysis of various statistics from process audits, tests and evaluations. Furthermore, the customer satisfaction should not be lost sight of.

- QM is a big building block in a company. There is no need to reinvent it and many standards, methods and techniques can be applied. In this context the ISO 9000 series as well as TQM should be mentioned.

- In order to achieve a high level of customer satisfaction, both the requirements of the customer and the requirements of the process should be met.

- In order to guarantee a good QM, the commitment of the top management plays a central role. In one point above, the importance of the presence of the management team was discussed. In this point, the importance of the timely decision to be made by the management is discussed. (Haskins, 2007)

4.3 Systems Engineering Approach to Quality Assurance in Aerospace Testing

The aviation industry has its own quality standard, the so-called AS9100. In this standard there is little described about the application itself. It does not explain how to apply a QM system to aerospace test programs. But if by referring the procedure of the SE to the standard AS9100 it is known how to integrate the quality. SE is widely used in the aerospace industry. It is used to ensure that delivered products or services meet the expectations of stakeholders. Less well known is that SE is also used for test projects (such as research projects). In this case, author Christena Shepherd uses NASA’s SE process (NPR 7123.1 SE "Engine"). The process is shown in Figure 12. It consists of seventeen processes. In this seventeen processes there are many possibilities to integrate quality assurance. (Shepherd, 2014)

> *»“quality assurance - the things a company does to make sure that its products and services are as good as they should be"«* (Dictionary, 2019)

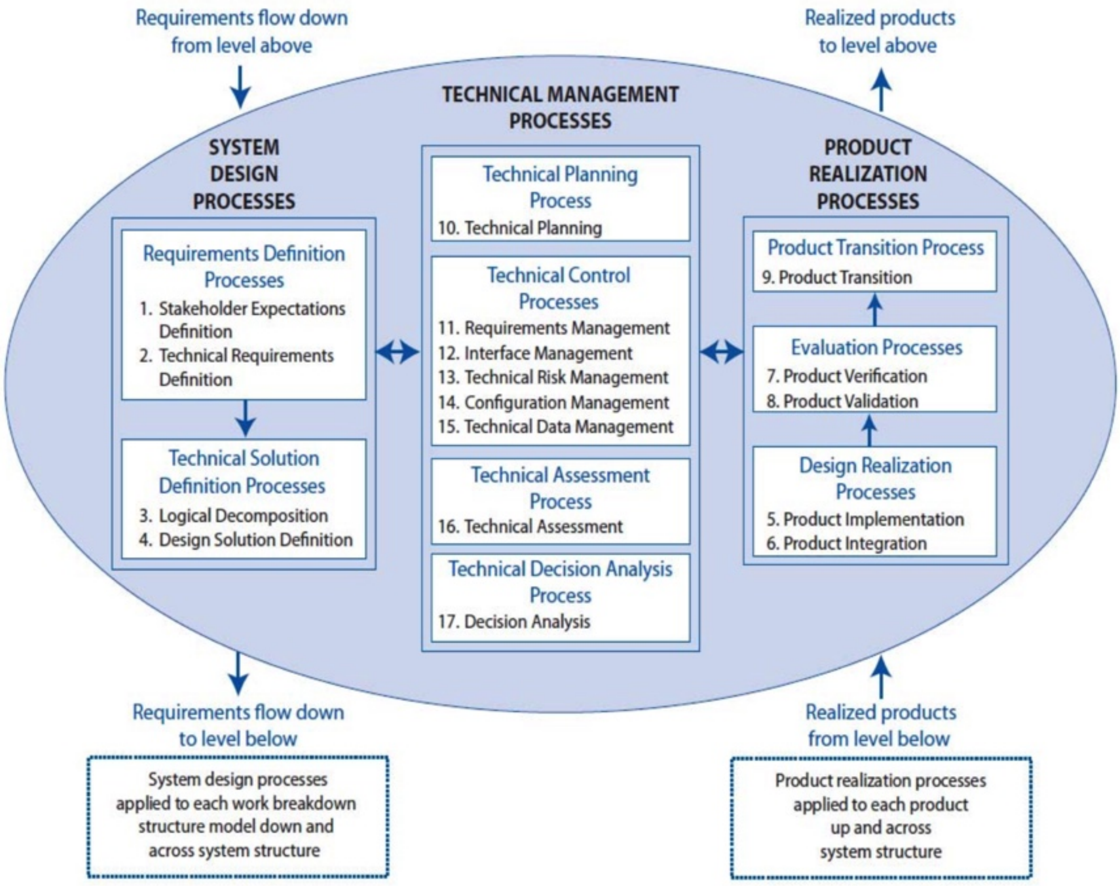


Figure 12: System Enginnering Approch of Nasa for "Engine" (Shepherd, 2014)

Technical Management Processes

The author describes how important it is that there is a test team that is present in every process. The test team must take part in the technical planning and control procedures with the agreement of the customer. This is an iterative process that can take up to several months. In process 15, all important data are managed, which are assessed in process 16 and then analysed in process 17.

System Design Processes

At the beginning, the requirements are defined by the stakeholders and the technical requirements. In the third process, the entire process is broken down by the test team and run through with the customer in order to ensure that the customer's requirements are understood exactly. Then the design of the devices, use of new facilities must be defined and start with the programming of software.

Table 2: Systems Engineering mapped to Quality Norm AS9100 (cf. Shepherd, 2014)

SE PROCESS	**AS9100 REQUIREMENT**
Stakeholder	Customer Requirements
Technical Requirements Definition	Planning of Product Realization
Logical Decomposition	Design and Development Input
Design Solution Definition	Design and Development Output
Product Implementation	Control of Production
Product Integration	Control of Production
Product Verification	Verification
Product Validation	Validation
Product Transition	Control of Work Transfer; Post Delivery Support, Preservation
Technical Planning	Planning of Product Realization; Review of Requirements; Measurement, Analysis and Improvement
Requirements Management	Design and Development Planning; Purchasing
Interface Management	Configuration Management
Technical Risk Management	Risk Management
Configuration Management	Configuration Management; Identification and Traceability; Control of Nonconforming Product
Technical Data Management	Control of Documents; Control of Records; Control of Design and Development Changes
Technical Assessment	Design and Development Review
Decision Analysis	Measurement, Analysis and Improvement; Analysis of Data

Product Realization Process

In process 5, the ordered and developed products are implemented in order to be integrated into the system in the next step. This is followed by the verification and validation process. All new or modified systems must be examined to see whether the performance works as required. After the test phase, the product is handed over to the customer. The author uses the quality standard AS9100 and converts it to the seventeen process steps of the SE process of the nose. Here, for example, the requirements of the customer are assigned to the first process of the SE stakeholder expectation. The individual assignments can be found in table 2. (Shepherd, 2014)

5 Introduction of the Case Study

The case study was carried out in cooperation with the company Miba HydraMechanica Corp. This chapter will therefore briefly introduce Miba AG and explain the initial situation of this case study. Furthermore, the products are presented and the quality requirements are explained. Finally, the production process is explained, in order to simplify the understanding of the practical application.

5.1 Company Miba AG

In 1927, Franz Mitterbauer founded the family business Miba AG in Laakirchen. The company has become one of the leading strategic partners in the international engine and automotive industry, as well as in power generation and power transmission. Miba AG offers a wide range of products. Starting with sintered components, through friction materials and coatings to power electronics and special mechanical engineering components. The individual Miba Groups are divided into these five divisions. Because Miba Friction Group was involved in this thesis, this site will be further explained in more detail.

The Miba Friction Group produces friction materials, which are mainly used in clutches and brakes in the international automotive and machine industries. The constant striving for new and better developments help to increase the efficiency of clutches and brakes. Miba Friction Group has six plants worldwide (Europe, USA, China and India), more than 1350 employees (as of 2017/2018) and annual sales of EUR 179 Million.

Miba Friction Group attaches particular importance to research and development. It offers one of the broadest material portfolios for friction linings worldwide. In the laboratory, these different materials such as fiber composites, sinter, molybdenum and carbon are developed, tested and analyzed. In this way, individual customer requirements can be tested and easily taken into account. In this area, Miba AG cooperates primarily with international research centers and universities.

In cooperation with Miba HydraMechanica Corp in Sterling Heights in Michigan, USA, the practical case for the thesis was realized. The two automated quality controls, which are optimized during the thesis, are located directly on site in the production hall. In this context, it should also be mentioned that Miba HydraMechanica Corp is ISO 9001:2015 certified. (Miba, 2017)

5.2 Initial Situation

As part of an automation upgrade, one automated quality control of the friction plates were purchased and implemented about 2.5 years ago. A second system was purchased a few months after the first one to prevent bottleneck situations in the production. However, both systems are equipped identically. Since the quality requirements of the customers have increased in the last months, the machines could no longer be used, because it could no longer be guaranteed that the machine sorted correctly into good and bad parts. In order not to sell a bad part to the customer, the company switched back to manual quality control until the automated quality control was optimized. For this purpose, a methodology should be developed to be able to react more quickly to the quality requirements in the future and to optimize the machines more efficiently. Optimization in this context mean, that the machine has to recognize 100% good parts because of the quality requirements of the product. Therefore no bad part should be detected as a good part. Furthermore, the proportion of good parts that are recognized as bad parts by the machine should also be reduced. In addition, Miba HydraMechanica Corp wants a statistical tool that allows to draw conclusions about the quality of the production process automatically. The exact requirements for the optimization process are described in chapter 6.1. The following section explains which products are produced, which quality requirements are currently demanded by the customer and how the friction plates are produced.

5.2.1 Product Description

The company Miba HydraMechanica Corp in Sterling Heights produces, among other products, friction plates for the automotive industry. Four different types of friction plates are produced.

- **Friction plate with grooved paper segments** has 24 grooved paper segments on both sides of the carrier. On the outside diameter there is a sprocket with 32 teeth. Detailed dimensions of these friction plates are not discussed here due to trade secrets. This friction plate is shown in figure 13.

- **Friction plate with smooth paper segments** is a very similar product to the first friction plate. It differentiates only by the paper segments. They are smooth instead of grooved in this product.

- **Endplate with grooved paper segments** has on one side of the carrier 24 grooved paper segment and the other side of the plate is blanc. The carrier has also 32 teeth on the outside diameter. These endplates are usually thicker than the friction plates with paper segments on both sides.

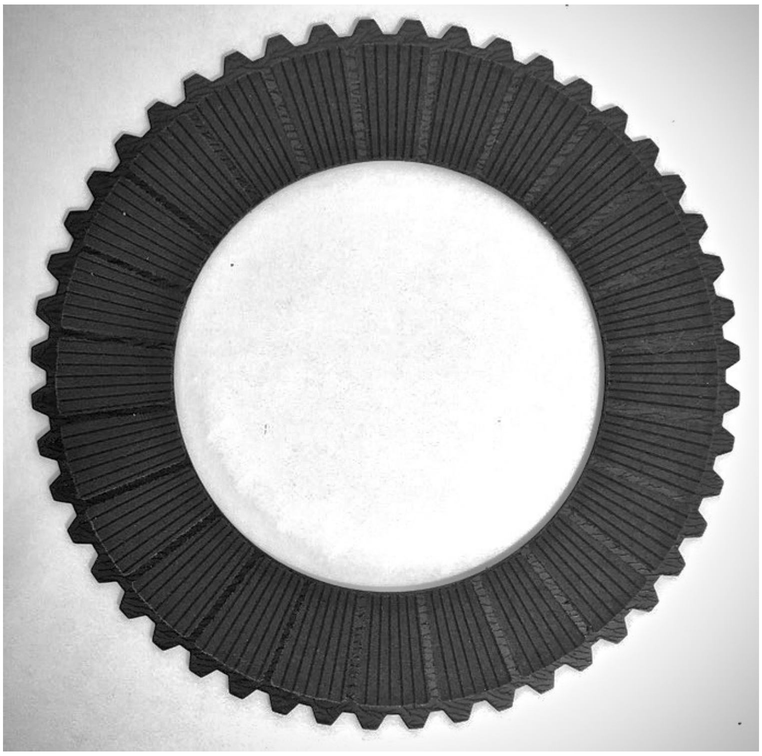


Figure 13: Friction Plate with Grooved Paper Segments

- **Endplate with smooth paper segments** is very similar to the endplate with grooved paper segments, which was described above. The only difference between them are the paper segments. In this case the paper segments are smooth and not grooved.

These friction plates are not sold separately, but as a clutch package. Therefore, an endplate is needed for both ends and between them there are blank plates alternating to the friction plates with segments on both sides.

5.2.2 Quality Requirements

There are several quality requirements which the part must fulfil to ensure the high standards of quality. In the following the deficiencies are explained which will not be tolerated.

- **Missing Tooth** - The blanc carriers, which arrive already pre-punched, must have 32 teeth. If there is a tooth missing the part is out of range.

- **Missing Glue** - The adhesive must be distributed carefully, evenly and over the entire surface of the carrier to ensure that the segments, which are later attached on it, are secured. Parts with missing glue over a certain amount of an area (in square mm) are not in order.

- **Missing Segment** - The Friction plate must have 24 paper segments on each side, for the double-sided friction plates. For the Endplate there have to be also 24 paper segments but only on one side of the carrier. If there is one segment missing the friction coefficient is influenced and therefore the part is not in order. In Figure 14 is a part shown with three missing segments.

Figure 14: Defective Friction Plate because of Missing Segments

- **Paper Short** - The paper segments are punched out of a paper roll. If punching errors occur and, for example, the corners of a segment are missing, it is called paper shorts. As a result, the quality of this part is no longer guaranteed. Due to the paper short the friction coefficient is influenced negatively. The part is not in order.

- **Segment Overhang** - The segments must be positioned on the carrier. It is not allowed that one segment is overhanging into the inner circle.

- **Segment Underhang** - The Segments cannot be positioned over the sprocket. Not even a piece of the segment is allowed to look over the sprocket.

- **Misaligned Segment** - The position of each segment is tolerated. Therefore, it has to be a gap between each segment. If there is no gap or the gap is too big in-between it is called misaligned. If there is a segment sticking on another it is also misaligned and not in order. In figure 15 is one segment misaligned and therefore the distance to the next segment is not in order. The distance to the left sided segment is too big and too small on the right side. In this case, the oil in the friction pack could not be flown off due to the missing gap.

- **Gauges** - This are imprints in the segments. The grooves are pressed into the segments during the last process step. If, however, there is something sticking on the press plates, it can happen that the press makes gauges into the segments. These impressions also have

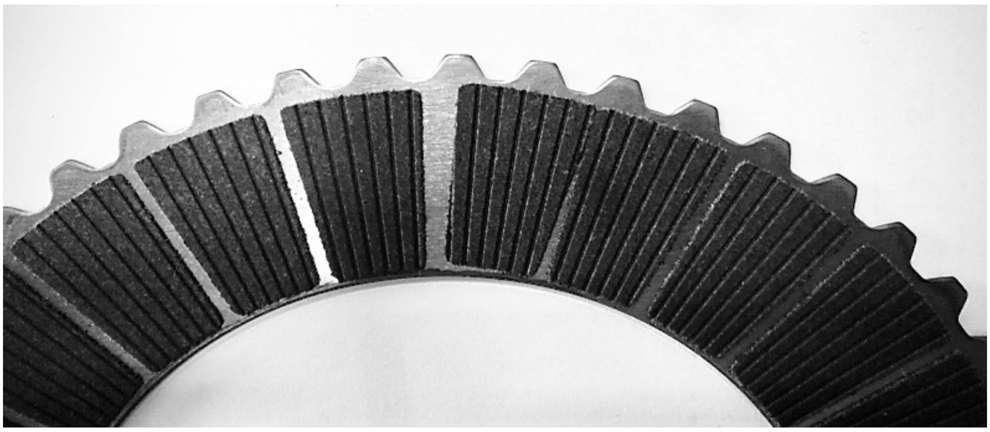


Figure 15: Defective Friction Plate because of Misaligned Segments

a negative effect on the friction coefficient and must therefore not exceed a certain size, otherwise it is out of range. In figure 16 there are three gauges on four segments visible, two on the left side and one on the right side. This part is not in order.

Figure 16: Defective Friction Plate because of Gauges

- **Blanc Side only for Endplates** - The blanc side has to be free from segments and scratches.

The exact tolerances will not be discussed further in this master thesis due to trade secrets.

5.2.3 Production Process

The carriers arrive blanc and already pre-punched at the company. In the first process step, the plates are etched on both sides to achieve a suitable surface for the next process step, the glue application. A glue layer is then applied to one side of the carrier and dried in a heat oven. The same is then repeated on the second side. In the next step, the 24 paper segments get punched and positioned on both sides of the carriers. After positioning, the segments have to be secured. This happens in the next process step. The carriers are inserted into a press where the segments are pressed onto the carriers by pressure and temperature. The glue hardens due to the temperature and the segments are secured. In this step the grooves are made also. The press has different press plates – grooved ones and smooth ones. By using diverse press plates, different friction plates are produced. After the pressing, the parts have to be cooled down. If they are cool enough the next step is to check the friction plates for unevenness. If the friction plates have sufficient flatness, they are taken to the quality control. In future, an automatic machine should use an imaging process to decide whether a good or bad part is involved and sort it out accordingly. At this point, the machine is not yet adjusted to the current requirements of certain quality features, which is one of the purposes of this work. At this moment, the friction plates are manually inspected for defects. After inspection, the double-sided friction plates, endplates and blank plates are combined into coupling packages, get oiled and shipped. The production process for the endplates is completely the same, expect that every process step effect only one side of the carrier and the other side is left blanc.

6 Method for the Optimization of Automated Quality Control

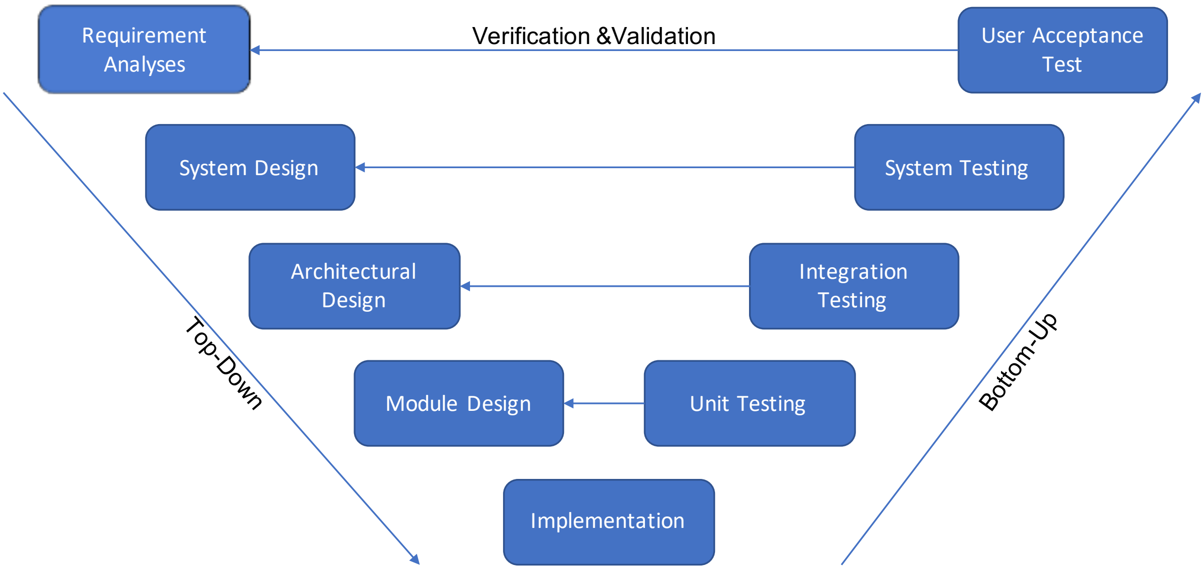


Figure 17: Design of the V-Model (cf. Yadav, 2012)

In the theoretical chapter 3 Systems Engineering (SE) and its components have been explained in detail. Furthermore, other process methods such as the V-Model were discussed. Since the V-Model is a very widespread process model for software development, and the practical applications is mostly about the optimization of an automated quality control software, this model is selected. Another important aspect is the constant verification and validation of the V-Model in the implementation and test phase. In addition, components from SE such as the problem-solving cycle or variant creation are used. Each phase of the V-Model is visible in Figure 17 and will be explained in detail in the following chapters. In the subsequent lines, a brief explanation is given of each phase. Only after the successful completion of the phase, the next phase can be started. Each individual phase is verified within the test phases. If this is negative, then the opposite phase of the V-Model must be re-entered. Only with a positive verification the next phase will be continued.

Requirement Analyses: All requirements demanded by Miba HydraMechanica Corp are split into functional and non-functional requirements and explained in more detail.

System Design: In this phase, the problem-solving cycle is applied. The aim is to evaluate, which objects should be used in terms of the quality inspection (cameras, sensors, software, etc.,) in order to guarantee proper automated quality control. At the beginning the initial situation is explained, afterwards several solution variants are set up, compared, evaluated and finally the decision and explanation how the system design was realized, is made.

Architectural Design: First and foremost, the structure of the software is explained here. The rough components of the program are explained.

Module Design: The individual components of the program are dealt with more specifically. Each used module is explained in detail. Every Module consists of one tool at least. Furthermore the selection of the right tool is described.

Implementation: In this step the individual modules or tools are implemented. For this purpose the appropriate threshold values are required to guarantee the recognition of good and bad parts. How to get data to determine these thresholds and how machine learning works is explained in this chapter. The exact implementation sequence and procedure is also explained in a concrete example.

Unit Testing: In this phase, the individual modules are tested and verified. Furthermore an example is presented, to demonstrate how to proceed if the verification is not positive.

Integraion Testing: In contrast to the testing phase before the program is tested as a complete package in this phase. It is checked whether all modules work perfectly with each other. Special attention is also paid to the display to ensure that the values are correctly transferred to the display. Also this test phase is done in the simulation mode on the computer.

System Testing: Going one step further, the software is transferred to the controller of the automated quality control. A series of tests are performed to ensure that the machine correctly distinguishes between good and bad parts and that the display shows the performing of the machine accurately. This means that if the display shows a not in order, the machine must place the part on the conveyor belt for bad parts.The Phase also verifies, if the machine detects the correct defect classes.

User Acceptance Testing: In this test phase, the system is presented to the customer. All employees affected by the quality of the product are summoned to a meeting. It is explained how the machine was optimized and what exactly is measured. Operators also receive trainings. Afterwards the test phase starts in which the company tests the optimized automated quality control. For this purpose, the good parts are additionally checked by hand after the quality control has been completed. This ensures that the machine does not sort actual bad parts into the stack of good parts. After the successful test run, the system is handed over together with the documentation.

6.1 Requirement Analyses

In this chapter, all requirements demanded by Miba HydraMechanica Corp are addressed. In order to get a better overview, the requirements are divided into functional and non-functional requirements. Table 3 lists the requirements sorted accordingly.

Functional Requirements are the description of the functions/services that the system shall provide. It must be clarified how the system should react under certain inputs and in special situations.

Non-Functional Requirements are requirements on the functions/services that do not describe their behaviour, but rather their specifications. For example,the quality characteristics, the development process, the applicable standards and norms, and the legal framework conditions. (Grechenig et al., 2010)

Table 3: Requirements sorted into Functional and Non-Functional

Functional Requirements	**Non- Functional Requirements**
Automated Quality Control	Programming Language
100% Good Part Recognition	Development Process
False Negative as low as possible	Display
Product Differentiation	Standardized Method
Statistical Tool	

6.1.1 Functional Requirements

Automated Quality Control

About 2.5 years ago, Miba HydraMechanica Corp bought and implemented two automated quality control machines. However, since the quality requirements for the product have changed over time and the machines have not yet been adapted to these requirements, the machines are currently out of operation. At the moment the quality of the products are determined by hand. It has been requested that the automated quality control should be used again in daily operations and therefore has to be optimized.

Furthermore, it should be investigated, whether it is technically possible to examine the desired quality requirements with the current equipment, or if new technology (such as sensors, cameras, ...) is necessary for the machine.

The machine needs to be adapted for every product, which is currently produced. The products were explained in chapter 5.2.1. The exact quality requirements regarding the product is described in chapter 5.2.2.

100% Good Part Recognition

The automated quality control should examine the parts according to the desired quality criteria and sort the products into good and bad ones. The bad products are scrap and the good products are delivered directly to the customer. This means that the automated quality control has to guarantee, that the stack of good inspected parts contains only actual good parts. There must be no defective product among the good parts. Otherwise this can involve very high costs (e.g. recall action) and reduce customer satisfaction drastically. Therefore it is very important goal for the optimization.

False Negative as low as possible

The term Pseudo Scrap is used in Miba HydraMechanica Corp when the machine detects an actual good product and defines it as a defective product. Therefore it gets sorted out wrong. In technical terminology, this is called a false negative. The proportion of false negatives should be as low as possible. Any product that is sorted out as a false negative would have been a saleable product and the company therefore loses turnover and profit. The opposite would be the term false positive, where the machine would recognize a bad part as a good one. As discussed above, this must not happen under any circumstances.

Product Differentiation

As there are four different products involved, some of which are very similar, it is necessary to determine whether the product in question is the right one. In the event of misuse by the operator of the machine, it should nevertheless be possible to ensure that no bad part is sorted out as a good one. If the operator of the machine selects the wrong product, the machine should sort out all products as bad parts. This process is useful because it can happen that a single part is in the wrong product stack, and this single wrong part should be sorted out as bad.

Statistical Tool

Furthermore, a statistical tool is desired by the company. This should be a simple display indicating how many defective products were found due to which errors. The errors should be divided into meaningful error categories. The error categories should be designed in consultation with the management team.

6.1.2 Non-Functional Requirements

Programming Language

It is required to use the software of the manufacturer Keyence, because this software was originally used for the implementation of the automated quality control and thus good experiences were made. All components used (sensors, actuators, etc.) are already connected to the Keyence software and are fully functional. For this reason it would not be an advantage for the company to use any other software.

Development Process

Miba HydraMechanica Corp requires a weekly report on the development process. The report consists of written documentation on all work and programming steps as well as an update meeting with the management board.

Display

The automated quality control machine is equipped with a display, which provides information about the current status of the inspected part. Here the product is visually displayed and all defect classes are shown. The defect classes are marked with a green "In Order" or with a red "not in order" field. So you can see at a glance whether it is a good or bad part and why. Furthermore, all parts and defective parts are counted and these numbers are also displayed on the screen. The adaptation to the new error classes is desired here. As well as the output of the statistics on the display.

Standardized Method

After the development and application of the method for the optimization of automated quality control, Miba HydroMechanica Corp, would like to introduce it as a standard method for future optimization, if the work is successfully completed.

6.2 System Design

In order to design the system in the best possible way, the problem-solving cycle is applied here. It consists of three large blocks as explained in chapter 3.4.4. It starts with Finding Objectives, which again consists of two sub-phases. It continues with the solution search and is completed with the selection.

6.2.1 Finding Objectives

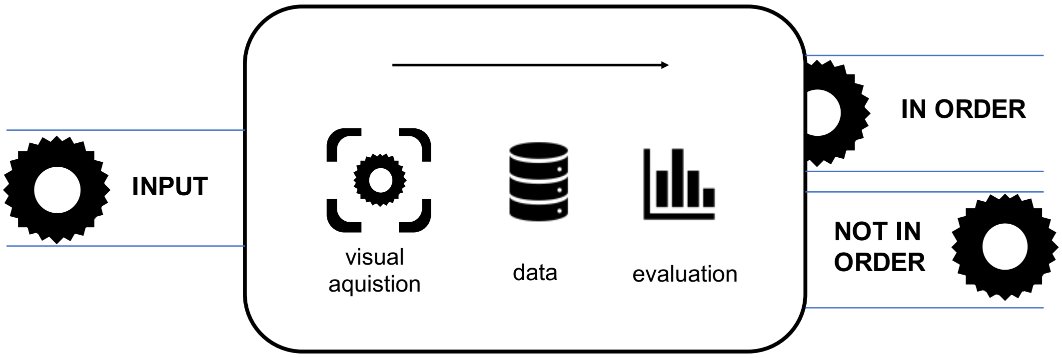


Figure 18: Design of the System

Situation Analysis

The design of the system is as shown in Figure 18. The object to be examined (in this case the friction plate) is inserted into the machine on the right side. In the machine, the friction plate is detected by a visual measuring unit and the data is then transferred to the evaluation unit. The evaluation unit decides according to certain criteria whether the friction plate has the required quality or if it is scrap.

Objective Formulation

An optical measuring unit is required, which is able to visually capture the quality characteristics of the friction plate. Furthermore, the top and bottom sides of the friction plate are inspected simultaneously, this means both measuring units are mounted mirror-inverted on top of each other (shown in figure 21). In this case it is important that the measuring units function in this constellation and do not influence each other during the measurement. In addition, the system should recognize the following features on the friction plate:

- Detection of material defects (missing glue, scrachtes on endplates)
- Measurability of distances
- Profile recognition (for gear rim)
- Detection of pads (for completeness, single and total, impressions in pads, grooves in pads)

Moreover, the solution must be compatible with the current system.

6.2.2 Finding Solutions / Variants Creation

Due to the fact, that the first solution that comes into mind, is not always the best, different solution variants should be considered. The already explained "Principle of Variation" in chapter 3.4.2, is used for finding different technical solutions for the measuring unit. A short excursion into the theory will be made for this purpose. It will be briefly explained, which optical methods are commonly used in the industry and shortly explained.

Syntheses of Solution: Optical Methods for Quality Control in Industry

The Industry uses:

- line scan camera,
- area scan camera and
- laser scanner

frequently for optical quality determination. For many image acquisition methods, sensors are used in order to enable the required quality and accuracy.

The two most common sensors are:

- CCD sensors
- CMOS sensors

The types of optical quality detection and the two sensors, which were mentioned are briefly explained below.

CCD Sensors

The light, which falls through the lens hits a *charge-coupled device*, short CCD sensor, which consists of a large number of light-sensitive semiconductor elements, the pixels. These are arranged in the form of a line (for a line scan camera) or a matrix (for an area scan camera). CCD detectors work on the basis of the internal photoelectric effect. In this process, incoming light hit the semiconductor material and charge carriers are generated, separated in the barrier layer of the photo diode and stored in a capacitor. This capacitor is connected to the surrounding circuit via a metal-oxide-semiconductor field-effect transistor. When the switch is open, the charge is collected to the capacitor and dissipated when the switch is closed. The integrated charge quantity is proportional to the amount of incoming light. The term architecture refers to the way in which the information of the individual detector elements is combined and converted into a serial data stream. Again, there are several types of CCD converter techniques. They will not be explained in detail, but only the basic features of a converter will be discussed. The charge is transferred from the light-sensitive sensor surface into the darkened shift register cell. How this transfer takes place depends on the converter technology. Then line by line is shifted from the shift register into the read-out register, which can only read out one line at a time. For easier understanding, figure 19 shows a picture of how the transport of charge can look like. In the left picture the charges are transferred into a darkened shift register. In the middle picture, charges are transferred to the horizontal readout register and then read out serially in the right picture. As already mentioned above, there are many different ways to transfer and read the charges. CCD sensors are mainly used in line scan cameras and black and white area cameras. Erhardt, 2008)

CMOS Sensors

Since CCD sensors have two major disadvantages, *Complementary Metal-Oxide Semiconductor*,short CMOS sensors have become very popular on the market. CCD sensors have on the one hand the disadvantage that the so-called Blooming can occur and on the other hand that it involves a serial readout register which slows down the data transfer substantially. Blooming occurs when

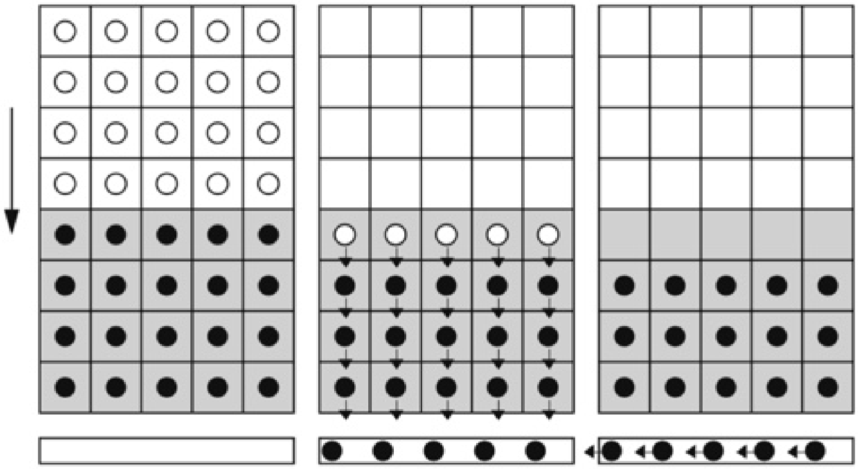


Figure 19: Transport of Charge (Erhardt, 2008)

local overexposure occurs. The result in the image is a bright spot at this point, which spreads out, whereby the image information is lost.

The CMOS sensor, like the CCD sensor, is based on the internal photoelectric effect, whereby electrons are lifted from the valence band by photons into the energetically higher conduction band, so that the conductivity of the semiconductor material increases under illumination. (Erhardt, 2008)

In the meantime, it has become possible to install a separate pre-amplifier and further evaluation electronics at each pixel. Such a pixel is an active pixel sensor. This means that it is no longer necessary to transport the accumulated charges via the chip. In principle, the voltages generated by the pre-amplifiers at each pixel can be read out in any order. This makes it possible, to read out parts of the sensor without loss of speed, i.e. at a frame rate that is essentially inversely proportional to the number of pixels read out. (Jähne, 2012)

Line Scan Camera

The CCD sensor is mostly used in line scan cameras. Line scan cameras contain only one CCD sensor line. They are used where a higher resolution is required or only one object dimension has to be captured. In order to keep the losses during charge shift low, an alternating readout takes place on both sides of the line. This results in a very short readout time, and also short integration time, which in turn requires a high light intensity for the illumination. (Erhardt, 2008)

Field of Application: Line Scan Cameras are used for inspecting many objects, which are moving fast on a conveyor belt. The reason why line scan cameras are better suited than matrix cameras for these purpose, is due to the fundamentally different structure of these two technologies. Area scan cameras deliver a fixed (synchronous) or variable (asynchronous) image sequence of a moving object, depending on the camera type. In practice, images are captured by overlapping the images to ensure seamless capture of endless objects. The individual images then have to be elaborately cut to size using software, freed from distortion and lined up next to each other. Line scan cameras, on the other hand, only have a single row of light-sensitive image elements that continuously scan moving objects at high line frequency. (Imaging, 2013)

Area Scan Camera

Area scan cameras are used to capture two-dimensional images using optoelectronic image sensors with visible light, in the ultraviolet or near infra-red range. The image sensor is constructed as a flat matrix with a large number of parallel rows of light-sensitive photo diodes. Using a shutter, all pixels (picture elements) are exposed synchronously, which generates a charge pattern on the diode matrix corresponding to the image. With CCD sensors, all charges of a line are read out serially by a central readout amplifier. CMOS sensors, on the other hand, record and read the charge of each individual pixel separately.

Field of Application: Area scan cameras are used for object recognition, presence and completeness checks, assembly checks or barcode and plain text readings as well as for measuring tasks. They can be used universally for a variety of applications in industrial manufacturing, such as testing and measuring tasks, 2D position determination or process monitoring. Industries which uses the area scan cameras commonly are the internal equipment construction, system integrators of image processing systems or special machine construction, e.g. for the automotive supplier and automotive industry, electronics manufacturers, the pharmaceutical industry, the food and beverage industry and many other industries. (Xpertgate, 2014)

Laser Scanner

The measuring principle of the laser scanner works as follows: A laser beam is expanded into a line and then projected onto the surface of a measuring object. The reflected light hits a receiver. The receiver is a CMOS sensor, which measure positions, detect deformations, displacement and shape. This is a three Dimensional optical measurement method. A laser scanner does not need external lightning.

Field of Application: The laser scanner is mainly used wherever a height profile is required, for example for quality recognition characteristics of profiles. (Keyence, 2016)

Analyses of the Solutions

The systems that are compared with each other , are all from the same manufacturer Keyence. On the one hand because the company has already made good experiences with this manufacturer and on the other hand the company Keyence offers compatible systems. The same image processing system can be used for the evaluation of the data. Since Miba HydraMechanica Corp already owns the image processing system, it would not make sense to compare other manufacturers. For this reason, no solution is sought for the evaluation unit, since the image processing system takes care of that.

Line Scan Camera with LumiTrax Specular Reflection Mode

Area Scan Camera with Multispectral Illumination

Laser Profile Sensor

Figure 20: Different Solution Variants (cf. Keyence, 2018)

A line scan camera, an area scan camera and a laser scanner are compared as shown in figure 20. All three systems are state of the art models and are mostly equipped with additional features (e.g. lighting).

LumiTrax Line Scan Camera

The line scan camera is equipped with a special illumination (LumiTrax mirror reflection mode). With the LumiTrax mirror reflection mode, several images can be generated from a single acquisition sequence, depending on the application, so that the user can specifically select the image data relevant for the respective defect. The stripe pattern of the high-speed LED projector allows the component to be captured under different reflection conditions in a single capture sequence. This illumination makes it possible to detect material defects (scoring, unevenness or impurities) on the surface very well. By this illumination the system offers good conditions to detect missing glue or scratches on enplates. In addition, the manufacturer offers a profile recognition function that can determine in detail whether the profile looks correct. This function is important, for example, for the recognition of the tooth profile. In addition, a separate wizard has been developed for the LumiTrax system to help identify errors. This means that the error location is marked and the system automatically recognizes the error next time.

Area Scan Camera with Multi-Spectral Illumination

The second possible variant is the area scan camera, which is equipped with multi-spectral illumination. The multi-spectral illumination offers image acquisition from eight different images with eight wavelengths. A very fast monochrome camera combined with multi-spectral illumination is used for this purpose. The spectrum ranges from ultraviolet to infrared. This system is also distinguished by its very good measurement of distances.

Laser Profile Sensor

The third solution is the 3D laser profile sensor. It is the only one of the three solutions that offers height measurement. In addition, no illumination is required for this system. The laser profile sensor offers many different measurement modes regarding the geometry. Distances can be measured very easily, but height differences are no problem either. In addition, two images are obtained, one with elevation information and the second is a grayscale image with 256 gradations. These two images offer a variety of quality flaws detection possibilities. The system is equipped with the same profile recognition function as the area scan camera described above (ShapeTrax3). The big advantage over the other two solutions is that no lighting is required. Since both measuring systems are mounted on top of each other, the illuminations could influence each other in their measurement. (Keyence, 2018)

6.2.3 Selection

Evaluation

In order to make the right decision, which system of these three solutions are best suited for the quality control at Miba HydraMechanica Corp, a benefit analysis, as shown in table 4 was carried out. The following criteria were decided by the company and the author together in order to be able to compare the systems as best as possible with the requirements that are necessary. In cooperation with an expert from Miba Automation System GmbH, the individual criteria were evaluated on a scale of 0-5 (Degree of Fullfilment). The individual criteria and the corresponding rating scales are explained in more detail below. Furthermore, notes were made on the ratings in order to be able to understand them comprehensibly.

Table 4: Benefit Analyses of Different Solution Variants for the System Design

		Line Scan Camera		**Area Scan Camera**		**Laser Profile Scanner**	
	Weighting	Degree of Fulfillment	Utility Value	Degree of Fulfillment	Utility Value	Degree of Fulfillment	Utility Value
Detection of Material Defects	15%	4	0,6	2	0,3	4	0,6
Measurability of Distances	15%	3	0,45	4	0,6	2	0,3
Profile Recognition (e.g. gear rim)	15%	5	0,75	4	0,6	5	0,75
Elevation Profile	10%	4	0,4	0	0	5	0,5
Detection of Paper Segments	15%	5	0,75	4	0,6	5	0,75
Integration Capability	(25%)						
-Configuration	15%	3	0,3	3	0,3	5	0,5
-Compatibility	10%	5	0,75	5	0,75	5	0,75
Expenses	5%	2	0,1	4	0,2	4	0,2
Utility Value	100%		**4,1**		**3,35**		**4,35**

Detection of Material Defects: This criterion must be met by the system. In particular, missing glue and scratches on end plates must be detected.
Rating Scale: 0 cannot be detected – 3 partially detected – 5 can be detected

Note on scoring: None of the three methods is perfectly suited for this. The line scan camera and the laser profile sensor are much better than the matrix camera.

Measurability of Distances: Here it is important that the system offers a measurement possibility. Different distances of the paper segments are measured to determine their position accuracy. The distance between the segments is important, as is the distance between the segments and the gear rim. This is again a must criterion.
Rating Scale: 0 cannot be measured – 3 partially measured – 5 can be measured

Note on scoring: The matrix camera is best suited for this measurement as no rotation is required. This means that the matrix camera scans the whole area at once from above. This reduces possible measuring influences such as the tumbling of the friction plate. The line scan camera is available with a higher resolution than the laser profile scanner, therefore there is one point less for the laser profile scanner.

Profile Recognition (e.g. gear rim): Profile recognition is primarily about clarifying whether all teeth are in place on the gear rim.
Rating Scale: 0 cannot be recognized – 3 partially recognized – 5 can be recognized

Note on scoring: All three systems are very suitable for the Profile Recognition. Only the matrix camera could have problems, if for example a tooth is missing an edge, to recognize this clearly.

Elevation Profiles: This tool can be helpful to take a closer look at the paper segment. Gauges in the paper segment or grooves are clearly measurable by the height profile.But if all of this can be detected correctly in the Detection of Paper Segments, the elevation profile is not a must.

Rating Scale: 0 not existent – 3 partially existent - 5 existent

Note on scoring: The laser profile sensor gets an actual 3D image, whereas the line scan camera gets a calculated 3D image. The matrix camera on the other hand does not produce 3D images at all.

Detection of Paper Segments: The individual paper segments should be detected. It should be checked whether all pads are present, but also each one should be examined in detail. Here it should be recognized whether the pad is complete or whether too much was punched away during the punching process and whether one corner of the pad is missing (p̄aper short). Furthermore, it is important to be able to examine the paper segments for possible gauges and to determine whether the segments are grooved or smooth, if there is no elevation profile.
Rating Scale: 0 cannot be detected – 3 partially detected – 5 can be detected

Note on scoring: The Detection of Pads can be set up very robustly with all three methods.

Integration Capability

- **Compatibility:** For this it is important that the systems are compatible with the already existing image processing system. Since it has already been explained that all three solutions are compatible, all three solutions are given the highest number of points here.
  Rating Scale: 0 is not compatible – 3 partially compatible (need extra interfaces) - 5 fully compatible

  Note on scoring: All components can be connected to the current controller. If the highest resolution line scan camera were chosen, it would benefit from the stronger controller. But it would also work on the current controller.

- **Configuration:** The arrangement of the measuring unit has already been explained above. Since the systems are located one above the other, they must not influence each other in their measurements. Unfortunately, this could be the case for systems with additional light sources.
  Rating Scale: 0 configuration does not work – 3 partially works – 5 fully works

  Note on scoring: The line-scan camera flashes continuously during rotation, while the matrix camera takes 4 pictures at standstill. In practice it would be possible to flash or take 4 pictures alternately. But this increases the cycle time of the measurement enormously. The 3D measurement is not influenced, because the laser has a certain wavelength (blue tone) and in front of the sensor is also a narrow bandwidth bandpass, which allows only this part to pass.

Expenses: Another factor, of course, are the costs. The more expensive the method, the less points will be awarded.
Rating Scale: 0 €€€ - 3 €€ - 5 €

Note on scoring: The big advantage of the laser profile sensor is that it does not need any illumination and really only consists of "head and cable". The matrix camera with illumination is in the same price segment. Whereby the line scan camera with Lumitrax is a lot more expensive due to its innovation.

Decision

The result of the benefit analysis, as shown in Table 4, indicates that the laser profile sensor is best suited to the requirements. It offers the great advantage over other systems that it does not require (external) illumination and therefore the measurement is independent of the ambient lighting. In addition, the laser profile sensor does not influence its measurement, even though they are mounted mirror-inverted, so that the bottom and upper side can be examined simultaneously. Furthermore, the Laser Profile Sensor meets all mandatory criteria.

As the problem-solving cycle has shown, the laser profile sensor is very well suited to the requirements of Objective Formulation described above. One of the requirements in Chapter Functional Requirements 6.1.1 was the analysis of the current state of the art. Is the current state of the art sufficient, or is the system to be replaced/extended by a newer, or by newer components?

Miba HydraMechanica Corp already owns the laser profile sensors and as the benefit analysis has shown, all demanded requirements are fulfilled with the system and no further cameras or sensors, are needed and the system does not have to be replaced by a newer one. With the current standard, the system is absolutely at the state of the art. In the next chapter, the realization of the automated quality control is described.

6.2.4 Realization of System Design

In figure 21 there is a schematic illustration of the constructed automatic quality control machine. At the machine entrance of the automated quality machine, there is a rotating magazine in which the parts are inserted. The gripper takes the first part and places it on the provided holder. The friction plate is clamped and positioned over the inner circle. Then the plate is turned by approximately 420 degrees. During rotation, two laser profile sensors, one from below and one from above, record a series of measured profile data. The laser sensors are mounted on top of each other. The measured data is processed into two images. The first image is a 256-level grayscale image, converted from elevation data. It is shown in Figure 22 . The second image, shown in Figure 23, contains elevation

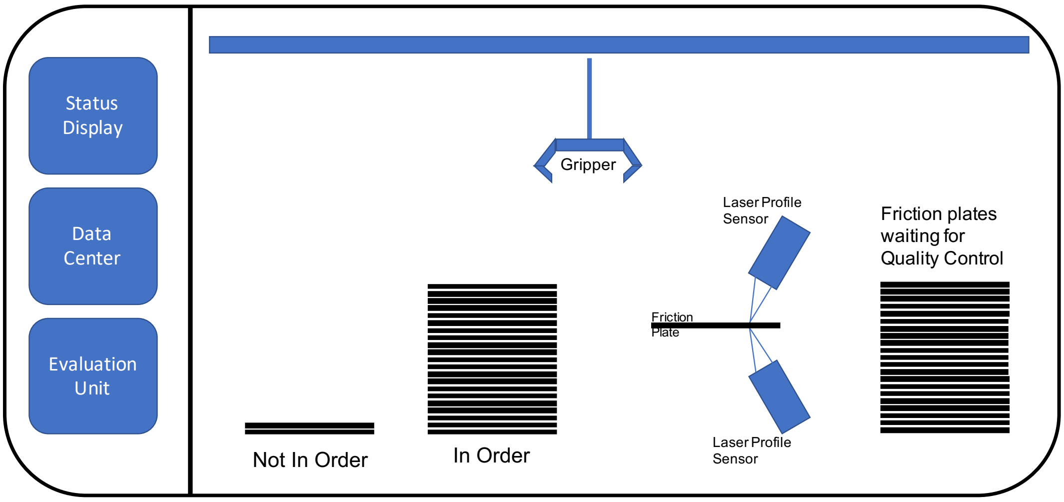


Figure 21: Structure of the Automated Quality Control Machine

data, in order be able to check different quality aspects. Both images contain both sides of the friction plates. After recording the data, they are evaluated based on various quality aspects and the friction plates are accordingly sorted out as good or bad on a conveyor system.

6.3 Architectural Design

The automated quality control machine has a software solution from the company Keyence as already mentioned above. Keyence's software program offers prefabricated tools to determine the quality characteristics more easily. For example, there is a scratch tool which is able to recognize scratches in a simple way. The challenge is to use the right tool for the right quality measurement to sort the parts correctly in good and bad ones.

As shown in Figure 24, the flowchart is located on the left side of the screen. Programming is done in the flowchart. The individual tools can be placed by drag and drop. The flowchart is processed from top to bottom. This means that the order of these tools is very important. After consultation with the company, the following architectural design was determined:

a) **Capture Setting:** This tool plays a very important role and decisively influences nearly all following tools. In this settings, sampling rate and exposure time are adjusted.

b) **Positioning Tools:** This tools are used to determine positions on the friction plates. For example to identify the position of the first tooth. All positioning, which are set with those tools, can be obtained later from the error type tools, if required.

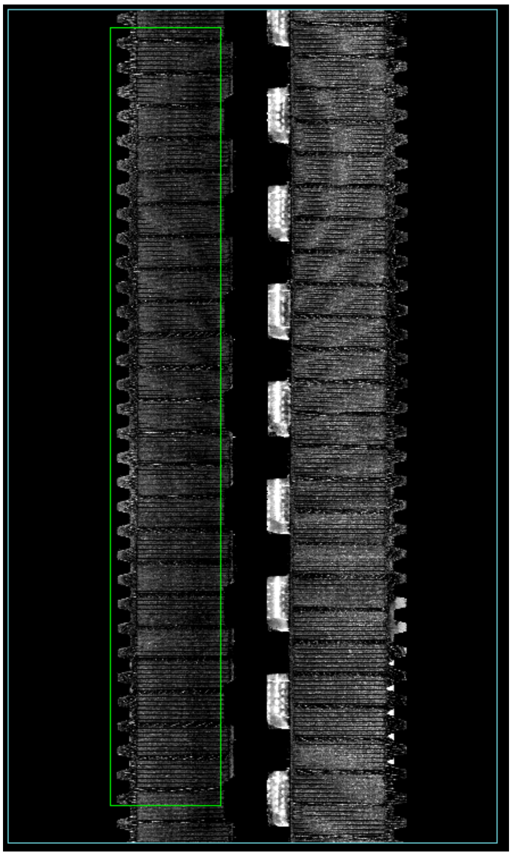


Figure 22: Grayscale Image captured by the Laser Profile Sensor

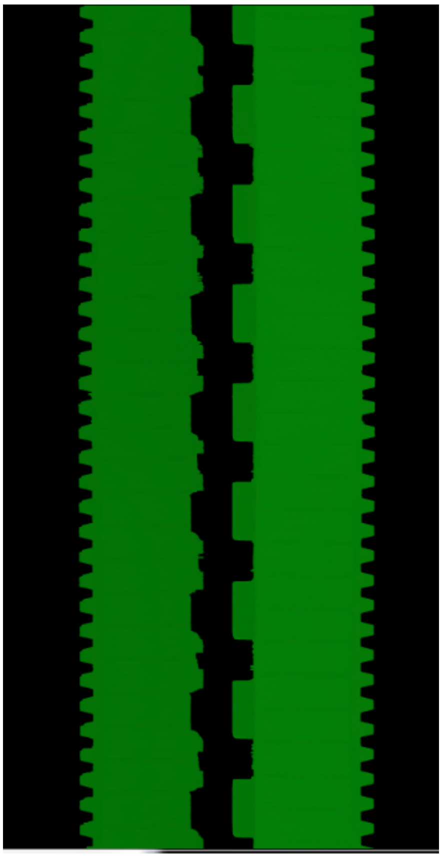
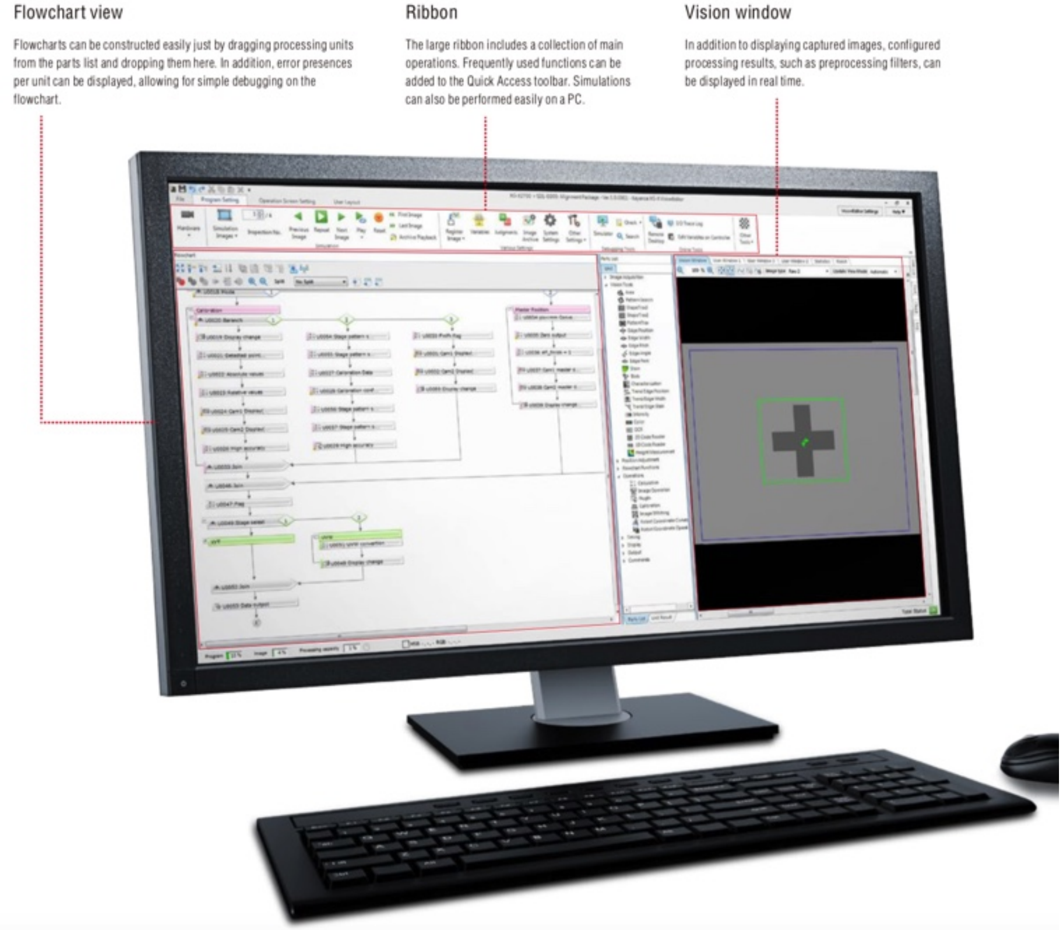


Figure 23: Elevation Image captured by the Laser Profile Sensor

c) **Defect Type Tools:** In this step the friction plate is examined for all quality defects as described in chapter Quality Requirements 5.2.2. This means that at least one tool is used for each type of defect. Which defect is examined first or last is not so important in this context, because the program must examine all modules in order to be able to establish the causes of the defect for the statistics. The program would be a little bit faster if it were aborted immediately after detecting the first quality defect, but the information is more important for the statistics and time is not significant longer, therefore all tools are always executed.

d) **Statistic Tool:** In the end, the data is summarized and displayed in a statistic. The structure of the statistic will be explained in the next chapter.



Flowchart view

Flowcharts can be constructed easily just by dragging processing units from the parts list and dropping them here. In addition, error presences per unit can be displayed, allowing for simple debugging on the flowchart.

Ribbon

The large ribbon includes a collection of main operations. Frequently used functions can be added to the Quick Access toolbar. Simulations can also be performed easily on a PC.

Vision window

In addition to displaying captured images, configured processing results, such as preprocessing filters, can be displayed in real time.

Figure 24: Structure of the Keyence Software Program (Keyence, 2017)

6.4 Module Design

In this phase, the individual tools are described and used accordingly to the configuration, described in the chapter above. Because of the fact, that the program was already used, not everything has to be renewed. For this purpose a list, which tools must be optimized, was provided by Miba:

- Capture Settings
- Positioning Tools
- Missing Tooth
- Missing Glue

- Gauges
- Bottom Inspection on Endplates (scratches, pads)
- Rill Detection
- Statistic tool

The other tools will be of course be checked during the module testing phase, to ensure that they meet the requirements. If not,the tool will be added to the list.

6.4.1 Capture Settings

It is important to select the correct settings for exposure time and sampling rate. There are empirical values for this. Therefore, the sampling rate was not changed, but the exposure time. It is important that the exposure time is not too short, but also not too long. If the exposure time is too short, the image will be very dark. If the exposure time is too long, the image will be overexposed and very bright. Figure 25 shows an image with an exposure time, which was set too short.

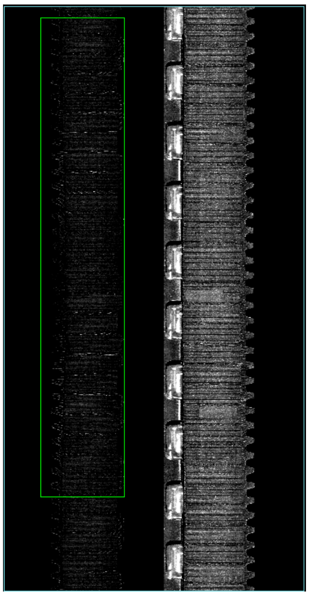


Figure 25: Different exposure times

6.4.2 Defect Type Tools

In order to choose the right tool for the respective defect detection, the first decision is to determine, if the error is better recognized by means of the grey scale image or the elevation image. After selecting the type of image, the appropriate tool can be chosen. In some cases, there is already a tool, which was developed exactly for the needed application. For example the profile recognition tool, is an excellent tool to determine, if all teeth are on the sprocket, or, if any are missing. But the decision, which tool to use, is not always that easy. Therefore it will be explained in detail, how and why the tools were chosen.

Missing Tooth

In this step it is important to be able to determine whether all teeth are present on the sprocket. There is a simple profile (pattern) recognition tool that extracts the profile from the grayscale image. In order to use the profile recognition tool correctly, position tools are used in the first place, to determine the position of the first tooth. These coordinates are then transferred to the profile recognition tool. This tool detects the contour of one tooth. The specified inspection area is exactly 32 teeth long and one tooth wide. If the profile of a tooth is detected 32 times in this area, the friction plate has 32 teeth and is therefore okay. If, however, more or fewer teeth are recognized, the part is not in order.

Missing Glue

In the missing glue error category, it is determined whether the glue is evenly applied on the friction plate. If glue is missing, the adhesion of the individual paper segments is no longer guaranteed. Because the area under the segments is not visible, only the visible area of the adhesive surfaces is examined. If there are missing glue spots, it must be assumed that glue is also missing under the segments. The friction plate is defective.

In order to choose the right tool for missing missing glue, the first step is to determine the right type of image. The elevation image can not be used in this case, due to the fact that the layer of glue is too thin in order to measure the hight. Therefore a tool, which works on the basis of the grayscale image has to be chosen.

The most suitable tool is the Blob. If the laser beam is absorbed, the color will be black on the image, but if the beam is reflected very well, the dot will be white. There are 256 gradations between black and white. The Blob divides all grey points into black and white ones.

The point at which a dot is considered black or white, can be adjusted. In order to determine the defect, the area of the white points are summed up. Therefore the part is not allowed to exceed a certain threshold value, otherwise it is a defective part.

Gauges

Gauges are unwanted imprints in the paper segments. The decision which image to use here is no longer as "simple" as with the Missing Glue. For this reason, all variants are compared in Figure 26.

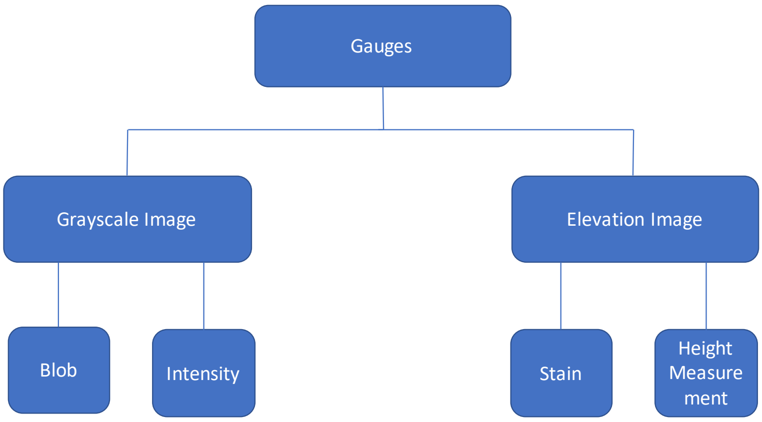


Figure 26: Different Possibilities to detect Gauges

Grayscale Image In the greyscale image the Gauges can be seen, because the grooves are interrupted there. But if it is a Segment without grooves, the Gauges are harder to see, there is only a "bright" spot visible. Since this "bright" spot is very vaguely defined, the decision is made to use the elevation image.

Elevation Image The height image can determine the imprint on the basis of the different height gradations. Therefore two tools could be used:

- **Stain:** In this tool the zero plane is defined from which the measurement starts. The surface is divided into many small segments and measured. It is checked whether these segments deviate from the zero plane. If the measurement detects an imprint, that is lower than the zero plane, it is recognized as an error. If the total value of the deviating areas is higher than the permissible total value, the part is sorted out as bad.

- **Height Measurement:** This tool measures the hight of different points, which are be determined before. Because it is not possibly to know on which point the imprints occur, the points can not be defined. By defining the whole area, the tool can not differentiate between rills and actual imprints. Therefore the better decision is, to use the Stain Tool.

The stain tool is used in a loop. The inspected area is one paper segment at a time. The loop lasts 24 times, so every paper segment gets checked separately. If one paper segment has a gauge, the part indicates inadequate quality.

Bottom Inspection

During the inspecting of the backside of endplates, it is important to check that there are, no paper segments or scratches. The inspection area is the whole blank surface of the part.

Scratches: The tool, which is used here, is a special tool for scratches. It works with the grayscale image again. Different filter properties make the scratches better visible. Also in this case, a threshold value is used to determine whether it is a good or bad part.

Paper Segment on Endplate: For this detection purpose, the same tool, as explained in gauges, is used here too. Using the hight profile, it is easy to detect a sticking pad on the endplate.

Rill Detection

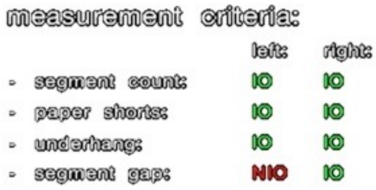
The requirements in Chapter 6.1.1 Product Differentiation demanded, that in case of an incorrect inspection program, the machine rejects the parts as bad parts. There are a separate programs for each product, to which the threshold values of each product must be adapted individually. This is the only way to ensure that the machine sorts the friction plate correctly into good and bad parts. If an operator selects the wrong program, all parts will be recognized as bad and sorted out accordingly. Another advantage of this procedure is the detection of mixed parts. If products were mixed within a batch, the machine sorts out the different products.

In order for the program to know whether the product in question is the right one, it checks the grooves. This is done using the edge position tool. This tool searches for edges. In this case, a groove forms an edge. Segments with grooves have more "edges" than smooth paper segments. With this tool it can easily determined, if this is the right product. The inspection area applies to the paper segments.

6.4.3 Statistic Tool

Two options are available for the statistical tool.

a) **Use of all Mesuarment Critera:** If this option is selected, each time an error occur, the system displays the count, at the screen of the respective measurment criteria, increased by one. As already explained, every error that can occur is displayed on the screen. At the moment it is only shown if the error is present or not, by means of a Green IO (In Order) and a Red NIO (Not In Order) see Figure 27. However, it is not recorded how often this IO or NIO is occurred in the individual measurement criteria.



measurement criteria:

	left:	right:
▫ segment count:	IO	IO
▫ paper shorts:	IO	IO
▫ underhang:	IO	IO
▫ segment gap:	NIO	IO

Figure 27: Display of the Measurement Criteria

b) **Division into Error Categories:** The second possibility would be to divide the errors into so-called error classes and to be able to assign these to the corresponding process steps. This offers the great advantage of being able to see at a glance which production step produces the most rejects. At the moment this is very difficult to understand. This could make errors in the process more transparent and solve them faster. Furthermore, the quality in production can be increased as a result. The individual categories should be clearly visible on the display.

Due to the advantages mentioned above, the company and the author together have selected the 2nd option to divide the defect into fault classes that reflect the process steps. The next section describes how the defect classes are defined.

Error Categories

As already described in the upper section, error categories are assigned to the individual process steps. How the friction plates are produced has already been explained in chapter 5.2.3. In order to make the classification easier to understand, the production process is explained again and illustrated schematically in Figure 28. Four error categories are chosen for the double-sided friction plates. The endplates have the same four categories, but get an additional fifth category, the bottom inspection.

a) **Missing Tooth**

The first step of the production line is the receipt of the blank, pre-cut plates. Since the quality machine checks at the end whether all teeth are present on the gear rim, this is already the first error category.

Causes of error: If teeth are missing from the sprocket, the supplier delivered scrap plates. In this case, the supplier should be contacted.

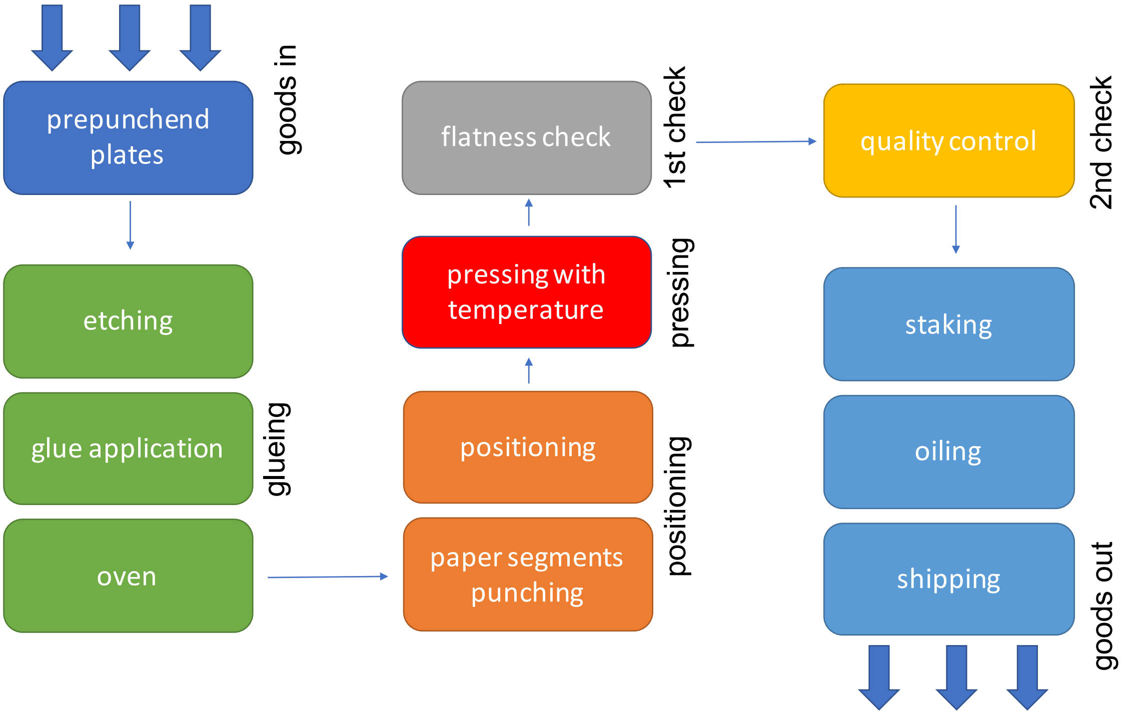


Figure 28: Schematic Illustration of the Production Process

b) **Missing Glue**

The next three process steps are responsible for the glue application. The first step is to clean the plates on both sides and prepare the surfaces for adhesive application (etching). In the next step, the glue is distributed evenly onto the upper side of the carrier. The friction plate is then placed in the oven, which dries the adhesive. If this is an endplate, the gluing process is already complete. If, however, it is a double-sided friction plate, the glue is now applied to the other side and transferred into the oven again.

Causes of error: Missing adhesive on the carrier can occur if the viscosity of the glue is not correct. Because the production line is not cooled in summer and this location has very hot summers (over 40 degrees), the viscosity of the adhesive changes and decreases. In winter, however, the exact opposite is the case and the viscosity increases again. The production is of course heated in winter, but the viscosity still increases.

c) **Misaligned**

After the glue application, the carriers are transported to the next machine. This consists of two process steps. In the first step, the paper segments are punched out of a roll of paper. In the next step, those segments are positioned on the carriers. They are only positioned on the carriers with low pressure. The segments are going to be fixed in the next process step. In this step, the position of the paper segments is determined. Any kind of misalignment of the paper segment belongs to this category. For example the missing or the underhanging over the sprocket of a segment, is classified here.

Causes of error: On the one hand paper segments can be punched out incompletely, or on the other hand too much can be punched away, the problem lies either way in the punching process. The positioning of the segments is very important. If the segments are located too close to the gear rim, the positioning tool must be readjusted. However, if a single segment is misaligned, the individual positioning elements must be examined. In this case it can happen, that an element is contaminated and the necessary negative pressure can no longer be applied, this also leads to missing segments on the carrier.

d) **Gauge**

The carrier with the positioned paper segments is conveyed further to the press. The press has different press inserts. Here the grooves are pressed into the paper segments when a product with grooves is desired. By applying pressure and temperature, the glue hardens and the paper segments are fixed on the carrier.

Causes of errors: If there is something sticking on the press inserts, such as an unwanted paper segment, this is pressed in the friction plate. This produces the so-called gauges. This can be avoided by regularly checking and cleaning the press inserts.

e) **Bottom Inspection**

This category only affects endplates. Because one side is blanc, this side must be checked for scratches and paper segments. None of these is allowed.

Causes of error: The reasons why a segment is on the underside is not very transparent. It can happen that a segment falls down between the positioning and fixing process. The segment then remains still in the process and can possibly picked up by the underside of the endplate.

A calculation tool is used to implement the statistic. In this tool it is possible to program simple conditions (command IF) and increase the number of error classes if those occur. The values of the calculation tool can then simply be transferred to the display via a command.

6.5 Implementation

In this step, the individual tools are implemented. This requires a number of thresholds to be able to determine, if a part is good or bad. In order to do this, data is required, which can be evaluated. In the next chapters therefore is explained how to get data, how to analyze them correctly and how to program tools. Only one tool is described here, because the programming method of the tools is very similar.

6.5.1 Obtain Data

The tools explained and used in the previous step must be set and programmed correctly in this step. In order to determine the correct settings and thresholds, a data analysis must first be performed. This requires data. In order to obtain data, as many bad parts as possible are collected in each fault class. Each bad part is passed once through the quality machine and all data (in the form of images) is stored on an SD card. But before letting friction plates through the machine, the capture setting must be selected correctly. In order to choose the right setting, it is necessary to follow the previous experienced values of the company. From the greyscale image, it is easily recognizable if the correct exposure time has been chosen. In this case, there are only prefabricated exposure times available (30,60,120..us). If the image is too dark, the exposure time should be increased. Each Grayscale image depends on the exposure time. This means, as soon as the exposure time is changed, the friction plates have to be passed through the machine again in order to get the current data. Therefore, the following sequence is important:

a) Insert SD card (only the use of an SD card from Keyence is possible)

b) Set capture settings correctly for the selected product (only once per product)

c) In the settings: select save to SD card

d) Let defective or good parts (but never mix them) of the selected product through the machine

e) This step is only required for Double-Sided Friction Plates: The plates are taken out of the machine, turned over once and passed through quality control again.

f) Eject SD card

g) Save SD card data on an external hard disk or computer with the correct identification (product XY - bad part or good part - e.g. MissingGlue)

h) Delete data from the SD card

In order to avoid errors during saving, it is useful to transfer the data to the computer after each individual data recording procedure. For this purpose, the data is stored on the computer immediately after an error category, such as for example missing glue, has been processed and then the empty SD card is used again for the processing of the next parts, for example missing tooth. In the case of Double-Sided Friction Plates, the plates have to pass the quality control twice. This means the upper laser profile scanner and the lower laser profile scanner gets the defective side once. Accordingly, this should be noted with upper or bottom side during the saving process. In order for this to work, a sorting is required. This means that the defective side is turned upwards at one time and downwards at the other.

6.5.2 Data Analyses

The data obtained is divided into two data records. One third of the dataset is used for machine learning, the other two thirds are used for testing (Modules Testing and Integration Testing). A so-called Confusion Matrix is used to determine the performance of machine learning. The predicted values are recorded on the vertical axis and the actual values on the horizontal axis as shown in table 5. In both cases there is a positive and a negative outcome. This results in four combinations of actual and predicted values.

Table 5: Confusion Matrix (cf. Narkhede, 2018)

		Actual Values	
		Positive	**Negative**
Predicted Values	**Positive**	True Positive	False Positive
	Negative	False Negative	True Negative

True Positive: This means that the machine recognizes the part as a good part and it is actually a good part. Prediction and actual Value is true.

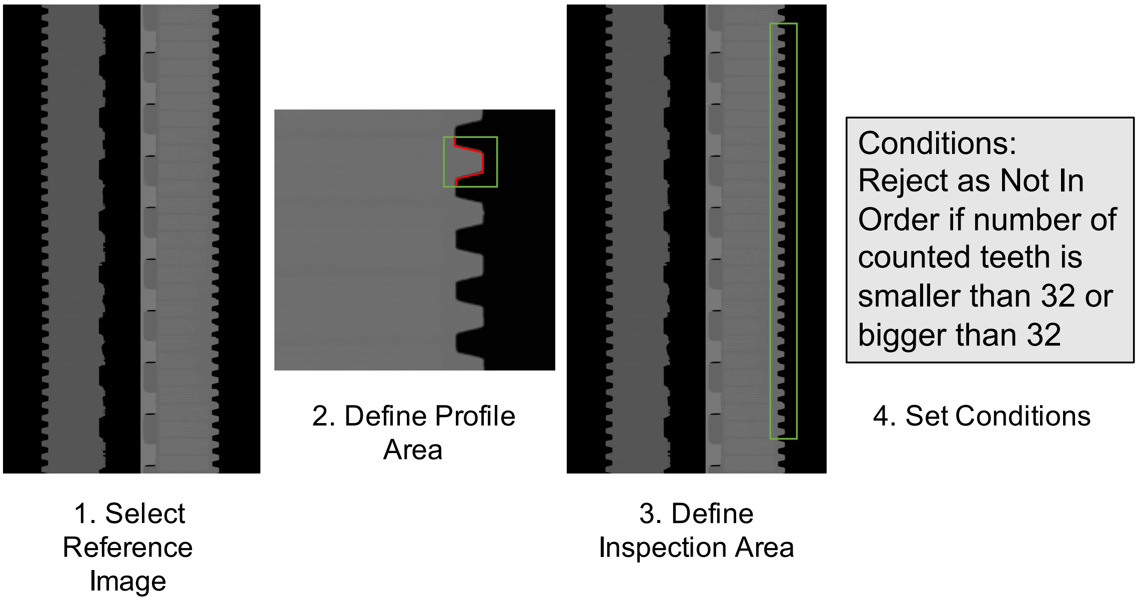
True Negative: Here the same principle is used, only for the bad parts. This means that the machine predicts that it is a bad part and in fact it is a bad part. In short, the predicted bad part is true.

False Positive: In this case the machine says that this is a good part, but in fact it is a bad part. The machine predicts a good part, but it is wrong. As already described in the requirements, this value must be close to zero. No bad part should be sold because it is of poor quality and drastically reduces customer satisfaction. Additionally, very high costs such as for example recall actions can be involved. Therefore it should not happen under any circumstances that a bad part is recognized as a good part.

False negatives: With this constellation, the machine predicts that this is a bad part, although it is actually a good part. According to the requirements, this proportion should be kept as low as possible. All these parts could be sold, because they are of good quality, and so the turnover and thus the possible profit is lost. (Narkhede, 2018)

The goal during the training phase is to optimize the performance of machine learning according to the criteria above. In the next chapters, an example will explain how machine learning works in more detail.

6.5.3 Implementation Example Missing Tooth



Conditions:
Reject as Not In Order if number of counted teeth is smaller than 32 or bigger than 32

Figure 29: Steps for Implementation of a Profile Recognition Tool

In order to check whether all teeth are located on the gear rim, the profile recognition tool is used, as already described in the Module Design. Before this tool is used, a position tool is used to determine the position of the first tooth and transfer the coordinates to the profile recognition tool. Now the implementation steps of the tool will be described, as shown in Figure 29.

a) **Select Reference Image:** In order to set the right references, an image is selected from the database in which all teeth are clearly displayed. This image is used to set the right examination areas.

b) **Define Profile Area:** In this step the area of one tooth is selected, see figure 29 step 2. The profile of the tooth is recognized by itself. The filters over the grayscale image create this gray image as shown in Figure 29. The filters contribute to the unambiguous recognition of the tooth.

c) **Define Inspection Area:** The entire inspection area is specified here to ensure that all teeth are present. This means that the examination area is 32 teeth long and one tooth wide.

d) **Set Conditions and Other Values:** In this step all important conditions and settings are made. Many different settings can be made. For example the number of degrees by which the search range can change. In this case the search range is not allowed to rotate because the teeth have always the same direction. Therefore, this setting is given a zero. The coordinates defined by the positioning tool are also transferred here. The tool then automatically creates the Inspection Area from the coordinates to ensure that the measurement starts from the first complete visible tooth. In addition, the threshold values at which a part is scrap are also defined here. In this case, there must be exactly 32 teeth on the sprocket. The condition is therefore: With more or less than 32 teeth, the part is sorted out as a bad part.

e) **Check:** Now the one third of the obtained data is used to check whether the settings have been made correctly. If necessary, values or examination areas can still be adjusted here (machine learning). This is not yet the Test Phase module. In this step, only one third of data is used to check whether the tool is correctly set up and working. It is really important to check the performance of the machine learning, as described in the data analyses. The false positive should be zero and the false negative should be as small as possible. In this particular case, this means that if a tooth is missing, the machine must recognize it as a bad part. On the other hand, it means that the machine should recognize a part with 32 teeth as a good part.

This procedure is identical for all used tools, only the setting options vary per tool, therefore each tool will not be explained in detail. Most tools have to be implemented twice, once for the bottom side and once for the upper side. Concerning the endplates, different tools are needed for the upper and lower side, as already explained in the module Design. In the case of endplates, the lower laser always examines the blank side.

6.6 Unit Testing

After all modules have been successfully implemented, they have to be tested individually. The remaining two thirds of the received data are used for this purpose. Each module is checked to see if it recognizes a good part as this and also if it recognizes a bad part as bad. At the beginning of the chapter module design is described, which modules must be renewed or optimized. There are modules which were already optimized according to Miba HydraMechanica Corp. In this step, however, each module has to be checked. This means not only all the modules described in the last chapters, but every module in the flowchart will be tested. In this step the individual modules are verified. The modules must meet the requirements discussed at the beginning. This means that each module is checked to see if it recognizes the assigned quality defect. If this is not the case, an automatic return is made to the phase Module Design, as shown in the V-Model 17. On the other hand, if there is no quality defect, this should also be detected by the machine correctly and therefore sorted out as a good part and not as a bad one. It should be noted that the proportion of false negative should be as low as possible. For this reason, it is necessary to take a step back into the Module Design again in case of frequent occurrences, because the requirement false negative as low as possible was not fulfilled satisfactorily.

The individual modules are tested in the simulation mode of the Keyence's Software. It is indicated with a red color, if a quality defect was recognized. The colour green means that no quality defect has been detected and the product is in order.

In the next subchapter, a case is described where the false negative portion was too high and therefore a step back into the modul design phase has to be taken in order ot solve this problem.

6.6.1 Minimizing False Negatives on the Example of Missing Tooth

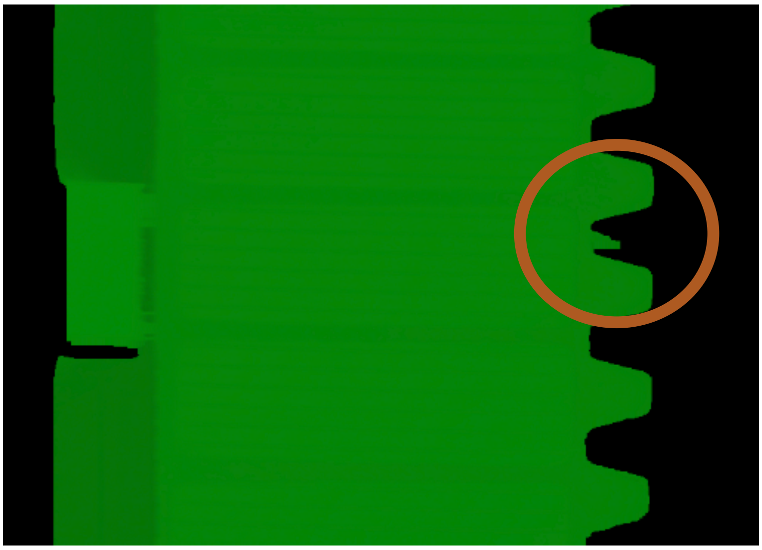


Figure 30: False Negative Missing Tooth

The procedure is always the same. If the verification has been classified as negative in a test, a step back to the opposite phase of the V-Model at the same level is taken. In this case this is the module design. In order to be able to solve the problem as transparently and simply as possible, the problem solution cycle is also used here. If the phase of the module design is successfully completed, the Implementation is carried out again and afterwards the Implementation.

Module Design Phase

Situation/Error Analysis: Figure 30 shows an "additional tooth". This image was taken by the upper laser. In fact, the part does not have one tooth too much, but it is an error in the image. Analysing the situation, the reason for the recording error is probably the fact that the friction plate rotates during the image acquisition and that there was a lot of glue on the edge, so because of the exposure time and the rotation something was reflected for the laser, which is really not there. The part is actual a good one, but the machine recognizes this as an additional tooth and due to the condition set in the implementation, this is a criterion to declare the plate as bad. Due to the fact that this measuring error unfortunately occurs more often and the false negative part is too high (approx. 4%) this part of false negatives should be reduced.

Objective Formulation: The target formulation is very simple, the false negative part should be minimized. This means the machine should recognize the good part as a good one.

Finding Solution: When arriving at the Model Design phase, the first question that arises is: Was the right tool used? Is there a better tool? Is possibly another tool needed?

Syntheses of Solution:

- **Tool Change:** another tool might work better, or the settings in the tool should be changed.
- **Using Additional Tools:** maybe due to an additional tool the false negative part can be reduced.
- **Changing the Measurement Methodology:** if the measurement would be changed, the error would not occur in the first place.

Evaluation: The profile of the tooth is recognized perfectly. Therefore the right tool was already chosen and used. The problem is not with the tool, but with the way it is measured. Since changing the measurement methodology is associated with enormous costs and consequences of changes, it will not be changed.

Decision: In this case, the only option is to use another tool, as the other solution variants have already been excluded (see Evaluation).

Realization: Therefore, all images that cause this measurement error are first examined and compared. This shows that this error sometimes occurs on the bottom and sometimes on the upper side. However, the error never occurs at the top as well as at the bottom at the same time. This phenomenon can be exploited to determine with a simple condition when it is actually a defective part and when it is only a measurement error. The condition is defined in a calculation tool. The number of teeth is measured from both sides, the upper and lower laser. If a tooth is missing, this is detected by both lasers, but if only one measurement error has occurred, this measurement error is very likely to occur in only one of the two lasers. The condition indicates that this is a measurement error and the part is recognized as a good one. With a very low probability, it can happen that both lasers have a measurement error at the same time and a good part is still recognized as bad. This is why the requirement for the false negative part is as low as possible, because unfortunately it cannot be avoided per a 100%.

All this steps are done in the Module Design. After the successful run of the problem solving cycle in this Phase,a new phase of the V-Model has been initiated, the Implementation.

Implementation Phase

After selecting the calculation tool, it is implemented as shown in Table 6.

Table 6: Example of Calculation Tool

Calculation Tool

IF (number_ teeth _ top = negative AND number_ teeth_ bottom = negative)
number_ teeth = negative
 	
ELSE
number_ teeth = positive

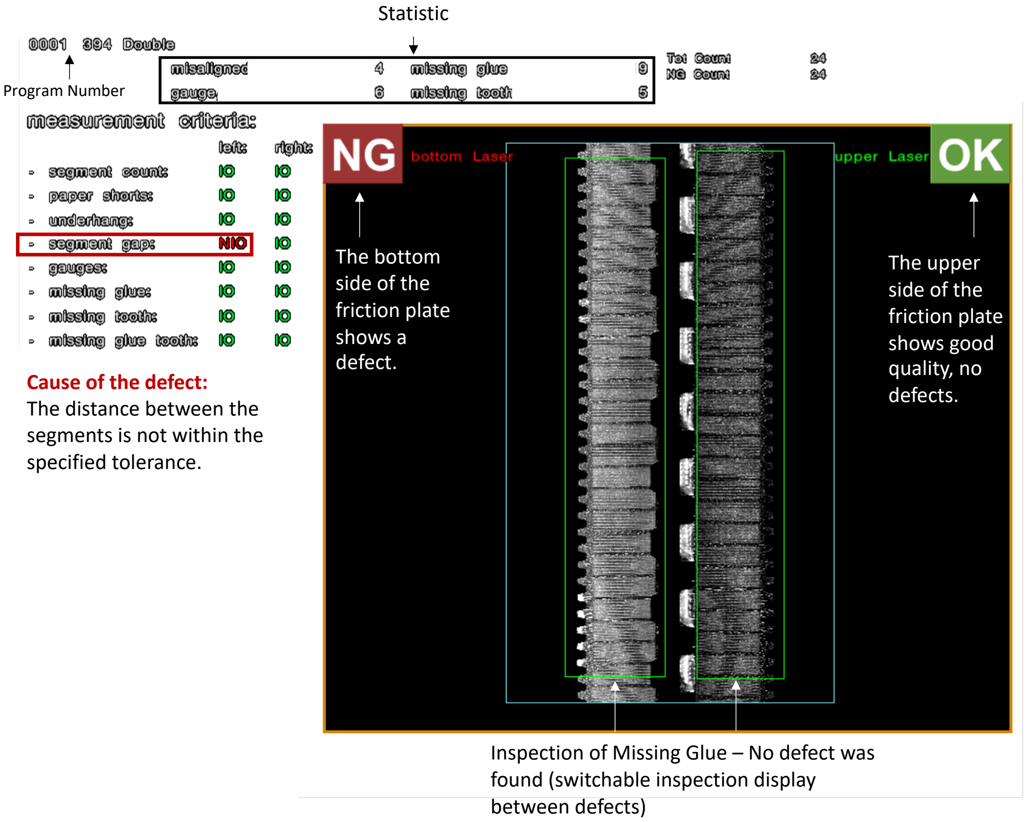
The simple condition that can be programmed in the calculation tool is, if the part has actually insufficient quality, there will be an error in the count of teeth above AND below. After the successful implementation, the next step is taken into the unit testing phase.

Unit Testing Phase: Module Missing Tooth

Here the module, which was extended by the calculation tool, is tested and verified again. The false negative proportion was reduced from 4% to almost 0.1% (the 0.1% is the probability that both laser sensors show the measurement error at the same time).

6.7 Integration Testing

If the unit testing phase has been successfully completed, the integration testing phase will be continued. In this test phase, the simulation is still running on the computer. At this stage all modules are tested to ensure that they work together. This means that the entire program is tested



0001 394 Double

misaligned	4	missing glue	9
gauge	6	missing tooth	5

Tot Count 24
NG Count 24

measurement criteria:

	left:	right:
segment count:	IO	IO
paper shorts:	IO	IO
underhang:	IO	IO
segment gap:	NIO	IO
gauges:	IO	IO
missing glue:	IO	IO
missing tooth:	IO	IO
missing glue tooth:	IO	IO

Statistic

Program Number

Cause of the defect:
The distance between the segments is not within the specified tolerance.

The bottom side of the friction plate shows a defect.

The upper side of the friction plate shows good quality, no defects.

Inspection of Missing Glue – No defect was found (switchable inspection display between defects)

Figure 31: Structure of the Display

instead of testing modules by modules. It is important to include the display here as well, because every error is shown on the display and in the statistics the number in the respective error category must increase by one. That means on the one hand the programmed flowchart is checked and on the other hand it is assured that the values (in order and not in order) are correctly transmitted to the display. In detail, this means that if for example the missing tooth module is shown red in the flowchart, the display must also show missing tooth as not in order. And the statistics must increase the value for missing tooth by one. As already explained, all errors are run through, although if the program encounters an error, it is still continued. For this reason, several errors can be found on one part. This is also reflected in the statistics. Therefore, if all values of the statistics are added together, tit is possible to exceed the value of the sum of negative counts.

Figure 31 shows the structure of the display. In the middle of the display an image of the current recording is shown. The right side is the upper side of the friction plate and the left side the lower side. To the left of the image the individual measurement criteria are displayed and marked with a red NIO (Not In Order) or a green IO (In Order). In this way it is easy to see at a glance whether it is a good part or a bad part. If it is a bad part, the reason is immediately visible. In the left corner is the program name. At the top center is the statistic. As in the chapter statistic tool, it was divided into four categories, which refer to the individual process steps. Next to it is the number of total count and of negative counts. The statistic values as well as the total number can be set to zero by the operator. This makes sense because the friction plates are ran trough in batches and conclusions on every batch can be drawn.

This phase is also verified. This means that the program requirements, such as 100 % detection of bad parts and keeping the false negative part as low as possible, must also apply here. In addition, all requirements for the display must be fulfilled. For this it is important that each error module corresponds to its own measurement criteria on the display and shows correctly whether in order or not in order. The statistics must also be verified. If a segment is missing, the missing segment is NIO, at the same time the distance between the segments is no longer correct and the error segment gap is also NIO. Both errors are errors for the statistics category misaligned. However, the statistics for misaligned should only increase by one in order to avoid falsifying it.

If the verification is positive, the V-Model continues with system testing. If, however, the requirements are not fulfilled, then a step is taken back to the opposite phase of the V-Model, the architectural design.

6.8 System Testing

After successful completion of the integration test phase, the system testing starts. The first step is to transfer the software to the automated quality control. The laptop can be connected via cable directly to the image processing controller. It is important to know that the new program overwrites the old one. Therefore, it is essential to backup the file to the computer beforehand. The transfer of the updated software takes only a few minutes.

In order to be able to test the behaviour of the entire system, so-called Red and Green Rabbits were introduced. Red Rabbits are categorized bad parts, which are provided with a number. Green Rabbits are therefore good parts that also have a number. For this purpose there is a list, each number indicates whether it is a good or bad part and the type of error. Red and Green Rabbits are mixed together in a stack. Now the automated quality control has to sort the friction plates properly into good and bad parts. These Red and Green Rabbits are of course available for all four products.

Begin with the Rabbits of a product (e.g. grooved double-sided friction plates), select the correct program number on the quality machine and let the parts through the machine once. There are two different conveyor belts, on which the friction plates leave the machine. Now the numbers are used to check whether there are only Green Rabbits on the conveyor belt for good parts and only Red Rabbits on the conveyor belt for bad parts. The conveyor belt for the bad parts is equipped with a red lid, which must be opened to reach the friction plates. It is intended to avoid mixing up good and bad parts. If the machine has sorted out all friction plates correctly, the friction plates are turned over once and the process starts from the beginning. The turnover is necessary to check whether both lasers detect the defect. It is also important to keep an eye on the display. If the display shows not in order, the gripper must place the friction plate on the conveyor belt for bad parts. However, if no error is displayed, the gripper must place the friction plate on the other conveyor belt. If the gripper does not do this, it must be checked whether all commands are transmitted. This is done in the software by checking the respective modules.

Next step is to sort out the parts by error category and turn the defective side upwards. It is important to allow the individual categories to pass through the machine, in order to check the display, if the right error is occurring. The display must show the correct error at the upper laser, as well as the statistics must increase in the correct category by one. Assuming starting with missing glue parts, the right side on the display must be marked with NIO and the statistics at missing glue must be increased by one. After this test run the friction plates are turned over once and tested again. The display must now show that the lower laser detects the missing glue error and the statistics must increase again accordingly.

If these first two tests are positive, i.e. the machine was able to assign the errors correctly and detect 100% of defective parts, good parts (200-300 pieces) that have already passed the manual quality control are now taken and tested. In this case, it is important that the false negative portion is kept to a minimum of a few percent.

So far, the requirements for 100% good part recognition and that the false negative percentage is low have been verified. In addition, the functionality of the machine was checked to see whether the gripper does the same thing as the display. However, an important verification is still pending. Namely the differentiation of products. To do this, the products are mixed together and sent through the automated quality machine. It should be noted here that the machine rejects any part that is not equipped with double-sided grooved paper segments as negative.

If all these tests have been completed positively, the process is restarted with another product. Once all the products have been passed through and everything has been positively verified, the User Acceptance Testing phase can now be continued. However, if problems arise, such as sorting out bad parts as good parts, it is necessary to switch to the opposite phase of the V-Model, the System Design. It must then be clarified there whether the correct measurement methodology has been selected. It quickly becomes apparent that the later an error is discovered, the more costs are incurred. Therefore, the test phases should be run through very carefully so that the risk of later errors can be minimized.

The complete System Testing Process described above is illustrated in a flowchart in figure 32. When the enplates are tested, the plates do not get turned after the first run, they continue with the next test. The blanc side of the endplates always faces downwards.

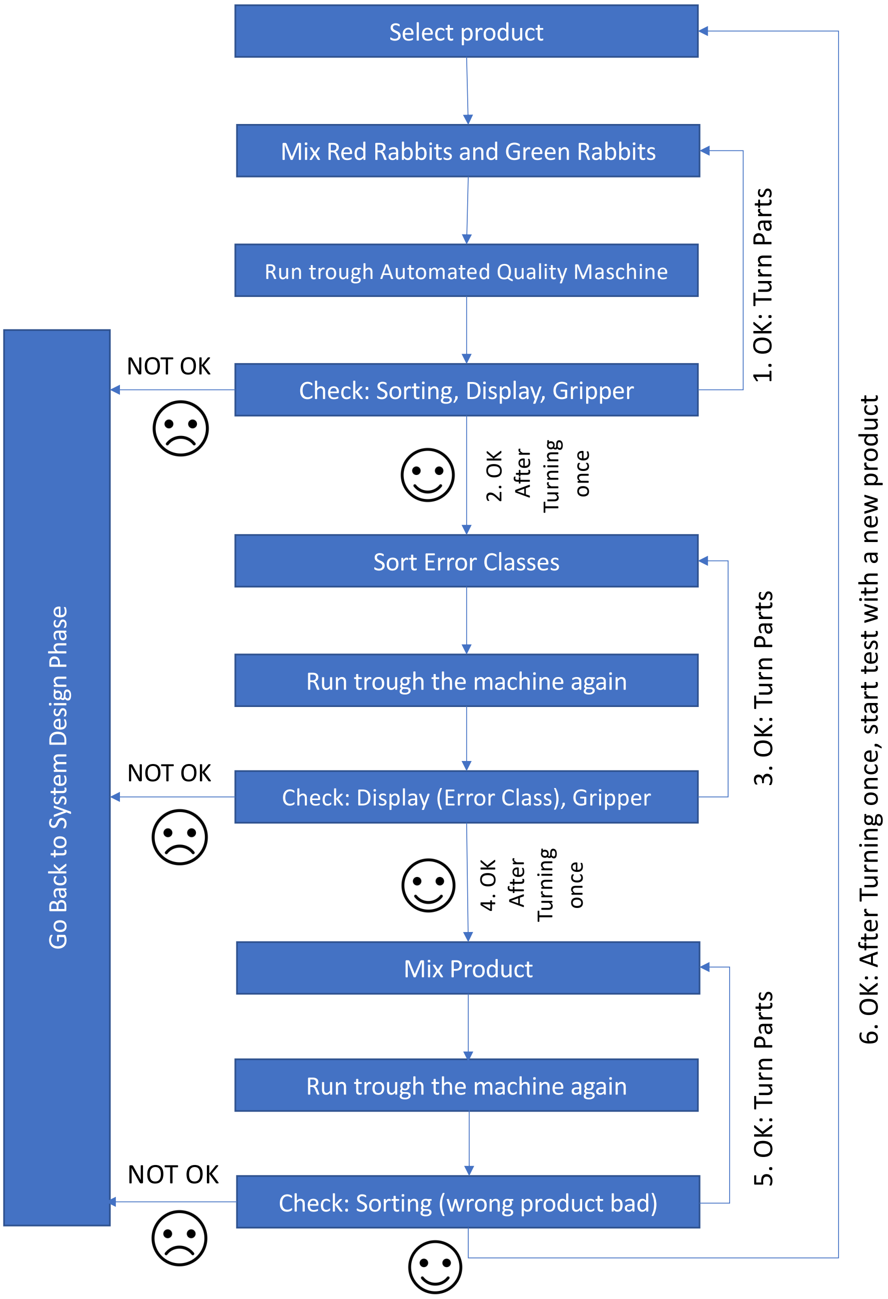


Figure 32: Procedure of the System Testing

6.9 User Acceptance Testing

In this phase it is important to inform all employees who work on the machine or in the quality area, about the changes which have been made on the automated quality control machine. For this purpose, a meeting was arranged. This meeting explained in detail how the machine was optimized and what the machine is currently inspecting. The new statistics function was also explained. In future, the operator will be responsible for writing down the statistics,. In addition, the operator must test the Red and Green Rabbits before running the machine. If a Red Rabbit is sorted out as good, the operator is not allowed to put the machine into operation and must report this immediately.

After all employees had been trained, the user acceptance test phase is started. The test phase lasts two weeks per product. The products are checked manually after they have passed through the automated quality process. During this time, the double-sided friction plates are randomly (20%) rechecked. If there is one bad part in the good parts, the system switches to a 100% follow-up inspection. During this time, more than 100,000 parts pass through the machine (for one product). The one-sided end plates are also inspected for 2 weeks, but to 100%. If a single bad part is found, the V-Model must be run through again because the requirements have not been met. The percentage of the follow-up check of good parts was requested by Miba HydraMechanica Corp. The sequence of user accaptance testing is shown in Figure 33.

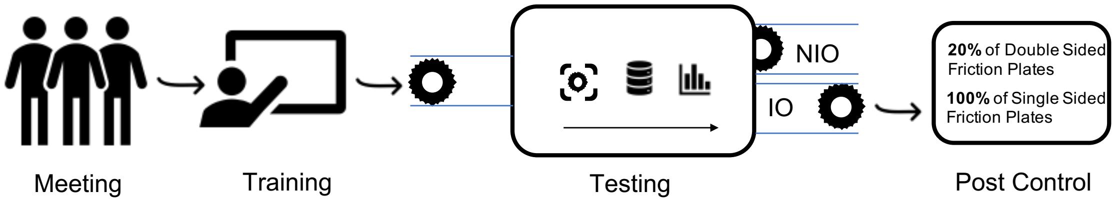


Figure 33: Sequence of User Acceptance Testing

Since the machine was purchased more than 2 years ago, the bad rejected parts of the machine have been sent through the machine again to minimize the false negative portion.

Why can the machine recognize parts as good at the second pass, which was recognized as bad at the first pass?

The answer to this question is very diverse, there are several reasons for this. Firstly, the different distances between the paper segments or the distances between the segment and the sprocket are measured in pixels. If a paper segment is at the tolerance limit, it is possible that more pixels are measured during the first pass than during the second. This small difference in pixels is decisive for whether the friction plate is recognized as good or bad. The pixels are converted into mm using an algorithm. The tolerance limit is therefore entered in mm according to the technical drawing. On the other hand, there are often segments of paper particles between the paper segments which get caught by not carefully punching. As a result, the distance between the paper segments is no longer given. Since the paper particles can be removed very easily, they often fall down by themselves. This means that by picking them up and putting them back into the quality control machine, these paper particles can have come loose and in the second pass the machine recognizes the part as a good part. Measuring errors also occur. As already explained, sometimes a measuring error occurs. One example were the teeth, as already mentioned. How the false negative portion was prevented was explained in chapter 6.6.1. Another measurement error, which unfortunately is a small part of the false negative, is a reflection error. This occurs mainly in the Missing Glue measurement. Sometimes the entire friction plate reflects so brightly that the system thinks it is missing glue. Why this measurement error occurs is not really known. One theory would be the tumbling. Since the plate is rotated during the recording, the plate is slightly wobbling. If the plate tumbles too much, there will be errors in the measurement.

Due to the fact that the machine was optimized, and this was also reflected by the user acceptance test phase, the second run of the bad parts was cancelled. The false negative percentage could only be reduced minimally in the second pass. This means that a large proportion of the parts are actually bad parts and the false negative part is smaller than before.

After several weeks, the test phase was successfully completed. No bad part was detected in the good parts. After this phase, the following decisions were made in consultation with Miba HydraMechanica Corp, see also Figure 34. As mentioned above, there is no second run for the bad parts anymore. All good parts will be sent to the customer without any further inspection.

Figure 34: Follow-up decisions after Completion of User Acceptance Testing

Miba HydraMechanica Corp received a detailed documentation with all optimized changes that were made. After verifying and validating this phase, it turned out that the false negative percentage could ideally be further reduced. Since Keyence's current software has largely reached its limits, another software or open source programming might play a role in the future. More details will be given in the next chapter. Because one requirement was to keep false negative as small as possible and this was achieved with the current state of the art, the project will be completed in this step. The training, the respective instructions for the operators, as well as the documentation were provided. All requirements have been verified and validated and the acceptance of the system has taken place.

7 Conclusion

The optimization of the two automated quality controls was successfully completed several weeks ago using Systems Engineering (SE). All four programs for the four different products per machine were optimized. Both machines are in daily operation. All requirements explained in Chapter 6.1 were implemented. The optimization achieved the following results:

- **100% Good Parts:** After the optimization process, not a single bad part was found in the good parts. The friction plates, which are sorted out by the automatic quality control as good parts, are sent directly to the customer, without further quality controls. The satisfaction of the customer can therefore be sustained.

- **Reduction of false negative by almost 10%:** The optimization of the automated quality control system resulted in a reduction of almost 10% of the false negative proportion compared to its last use.

- **Product Differentiation:** The machine can differentiate between the products. If there is an incorrect product in the batch, it is detected and sorted out as a bad part.

- **No Second Run:** As already explained in chapter 6.9, there used to be a second run for the bad parts. After the machine checked all parts, the bad parts were sent through the machine a second time to minimize the false negative portion. Considering that the false negative proportion was already significantly reduced by the optimization, therefore only a small part of the false negative proportion could be eliminated during the second run. For this reason, the second run of the automated quality control was cancelled. Cancelling the second run saves time and costs.

- **Customer Satisfaction:** The optimization has ensured that only high-quality products are delivered to the customer. This promotes customer satisfaction.

- **Confidence in Automated Quality Control:** Unfortunately, in the past, the optimization processes did not work perfectly, so employees were sceptical about this one. By using the transparent, plausible methodology, involving and informing employees about the optimization process, it was possible to restore employees' confidence in the automated quality control.

- **Quality of the Production Process more Transparent:** The introduction of statistics has made the quality of the production process more transparent. This means that the statistic clearly shows which production steps cause rejects, which therefore should be improved and those that function flawlessly.

- **Standardized Methodology:** Miba HydroMechanica Corp was given a methodology, with which they can easily and effectively optimize the automated quality machine in the future, if quality requirements change.

7.1 Summary

The theoretical part of the thesis refers mainly to Quality Management (QM) Systems and Systems Engineering (SE). ISO 9001 and Total Quality Management (TQM) are explained in more detail in the chapter QM. Concluding this chapter with a description of quality-related costs.

In the chapter SE, terms for comprehensibility are explained at the beginning. The individual components of the SE are explained subsequently. At the end, other process models are described and compared with their advantages and disadvantages.

Due to the increasing complexity of the products and their requirements, QM has to be implemented in the production process to keep the high quality standards. To maintain such a high standards in the complex systems, the combination of SE and QM enables to be competitive. The practical use of SE and QM together was explained in the last theory chapter.

In the practical part of the thesis a methodology for the optimization of automated quality control is developed and applied. In chapter 5.1, the company, with which the cooperation was established, is presented. In addition, the products which are controlled by the automated quality control were explained. Furthermore, the exact quality requirements for the products are explained. Finally, the manufacturing process is described.

The following chapter 6 explains the methodology for the optimization process. The methodology basically consists of a V-Model in combination with SE components. The V-Model itself, basically also consists of components from SE, for this reason it is often referred to the methodology SE in the context of the thesis.

By applying the top-down principle, it was possible to go into more detail phase by phase. This allows a step-by-step approach to a preciser understanding of the user. In the first phase, **requirement analysis,** all requirements defined by the company are divided into functional and non-functional requirements and explained in more detail. The most important requirements were, that the machine should not reject a bad part as a good part (false positive). In addition, the proportion of parts that are falsely recognized as bad, but are actually good parts (false negatives) should be kept as low as possible. Furthermore, a statistic of the defective parts was requested. In the next phase, the **system design**, the principle of variant formation and the problem-solving cycle were applied. In this phase, different solutions for the optical inspection process are sought, based on the creation of variants. The problem-solving cycle explained the initial situation, compared the solution variants that have been created, evaluated them on the basis of a benefit analysis and helped with the decision. Finally, the practical realization of the entire system is explained. The **architecture design** is dedicated to the basic structure of the software. In this phase the rough program structure is explained. The **module design**, on the other hand, goes one step further into the detail of the program. Here, the individual tools are explained that are used to check certain quality characteristics. In order to find the proper tool for the individual applications, the principle of variant formation is used here. The **implementation phase** marks the end of the top-down principle and the start of the bottom-up principle. In this phase, the tools described are implemented on the basis of machine learning. It is also explained how to obtain the required data for machine learning and later test phases. In the **unit testing phase**, the individual modules are tested and verified on the computer simulator. If a problem occurs in the test or verification phase, it is necessary to switch to the opposite phase of V-Model. In this case to the module design in order to be able to correct the error. This applies to each further test phase. After successful verification, the next test phase can be continued. The next testing phase is the **integration testing**. During this phase the entire program and the statistic is tested and verified. This tests have also taken place on the computer in the simulation mode. In the case of system testing, the program is transferred to the automated quality control for the first time. After the implementation of the new programme, the entire system is examined. A series of tests are carried out, to verify the judgement of the automated quality control. After successful verification of this phase, the last phase is to be continued. In the last phase, the **user acceptance testing phase**, the system is presented to the company. For this purpose, all employees, which are involved with the automated quality control are invited to a meeting. Furthermore, the optimization process of the machines is explained in detail. In addition it is explained exactly, which quality characteristics are examined. Additionally the new statistic was discussed. Afterwards the operators were trained. Then the user acceptance test started. The behaviour of the machine was tested for several weeks. Many random samples were taken and examined to see whether the machine rejected any bad parts as good.

After the end of the test phase, it quickly became apparent that not a single bad part was among the good parts, that the false negative share could be reduced and that the statistic was meaningful. Due to the application of SE the optimization resulted in cost savings, sustained customer satisfaction and a more transparent understanding of the quality of the production process.

7.2 Recommendation

Quality Management

Miba HydraMechanica Corp is ISO 9001:2015 certified and strives for good QM. By introducing the statistic, the quality of the individual process steps can be better assessed and measures can be taken in future to increase the quality of the products. The statistic is directly correlated to the production process steps. Every category out of the statistic stands in relation to the specific production step. Therefore, if the statistic shows an unusually high number in one category, the conclusion can be made that the correlated production step has an error and produces defective parts. In this case measures have to be taken immediately in order to provide proper quality and save costs. Therefore the costs of poor quality can be decreased and the QM improved by using the statistic.

Reduce False Negative Percentage

Another important point is the false negative proportion. Due to measurement errors, boarderliners or small paper particles, false negatives can occur. False negatives means that the machine rejects the part as a bad part even though it is actually a good part. If the paper segments are too close to the upper or lower tolerance limit, the machine often recognizes this as a bad part although it is still within tolerance. Another reason are paper particles that get caught between the paper segments due to bad punching. Of course, the machine recognizes this as an error, because the gap between the segments is not given. However, the paper flake can be removed very easily, and therefore the part counts as a good part and not as a bad one. In the future, the false negative part should be further reduced. One method would be to further optimize the program, especially in misalignment. Due to the software used by Keyence, however, a further optimization is conditionally possible. An Open Source Programming would be better suited, because it offers more possibilities to examine the error more exactly. For this reason, Miba took part in a hackathon. In the course of this I was allowed to serve as a mentor. Five different startups worked for 48 hours on a solution, to further reduce the false negative percentage. A wide variety of solutions were found, but one of them was the best suited for Miba. This startup presented an adaptive software model. On the one hand, the user could mark the defect directly on the image. The software remembers the defect and develops an algorithm for the error. If the error occurs again the next time, the machine automatically detect it. In this way, errors can be easily categorized and assigned. Marking the errors directly on the image is also very user-friendly. On the other hand, the software learns itself from bad images without marks. The big disadvantage, however, is that the internal algorithm does not allow you to check, if the false positive proportion is zero. This means that as soon as you give the program an input, it has to be tested.

I believe that in the future, by combining Keyence software with Open Source Programming, that the false negative part can be reduced. But you have to be aware that first of all you will never reduce the false negative portion to 0% and secondly all tests described in the methodology have to be repeated with every program change. This is the only way to ensure that no bad part passes as a good one.

Costs

An important point, of course, are costs. In this case, it is useful to analyze which costs could be saved due to the optimization process. Furthermore, the costs incurred due to poor quality are also important, as explained in chapter 2.3. These are particularly interesting in connection with process step two. For this purpose, it is easy to calculate from which reject rate, a further quality control would be profitable directly after the second process step. In this sense, the costs are only mentioned so far, but not further explained in detail due to trade secrets of the company.

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