The development of a process control optimisation method for machining SMEs, implemented at Technology Twente

University of Twente

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September, 2024

The following report is intended for Technology Twente and the examiners from the University of Twente.

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Publication date: 20-09-2024

This report was written as part of the bachelor assignment of the Industrial Engineering and Management educational program at the University of Twente.

Management summary

Introduction

A method for optimising process control at machining SMEs is developed in this thesis, called PCOM-MSME. The research was done at Technology Twente, a machining Small- and Medium Enterprise (SME) in Hengelo, the Netherlands. At Technology Twente, new tighter-set KPI goals on quality costs were not met. Therefore, quality costs need to decrease by 15% to meet the tighter-set Key Performance Indicator (KPI) goals. The quality costs are the costs due to a waste of the following resources; raw material, paper and time. The core problem of these wasted resources can be traced back to the absence of an efficient and effective process control procedure.

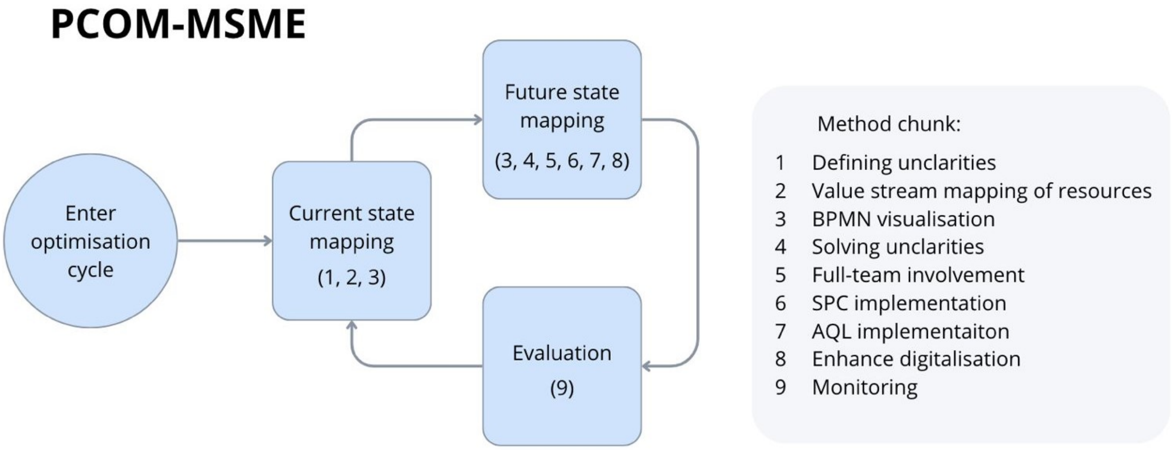
Findings

By applying situational method engineering, with an assembly-based approach, based on requirement selection and project characterisation, a method was constructed in this thesis, called PCOM-MSME. A visualisation of the method can be seen on the next page. In the first step of the method, the current state of process control was mapped, by first creating a BPMN model of the whole production process and then separating the phases of the production process that are influenced by process control. These phases are visualised and analysed in more detail. This is done by creating further specified BPMN models and describing unclarities and the value stream of the resources. After mapping the current state, the following method chunks are selected to propose a future state: Acceptance Quality Limit (AQL), Statistical Process Control (SPC), digitalisation and full-team involvement. Then, the future state was mapped. A BPMN model of the proposed future production process and their zoomed in models per phase are presented. In the last step of PCOM-MSME, the proposed future state is evaluated.

To validate the constructed method, the method was implemented at Technology Twente and since it has lowered the waste of resources, the method should be validated for all comparable machining SMEs. Through applying SPC on real data, it was proven that a severe decrease in rejections could have been realised if the method was implemented earlier. Digitalisation allows for zero paper waste and severe time waste reduction. By analysing the current and future state models and resolving unclarities in decisions, time is wasted less. Lastly, the full-team involvement by a feedback form also will reduce wasted time and and materials.

As stated, reductions in wasted materials of at least 15% were achieved and the paper waste was reduced to zero. However, the reduction in time is not qualitatively validated. Next to that, the reduction in wasted materials was validated for a product with a high batch size, making it suitable for SPC validation. But if SPC was not implemented for lower batch size orders, it cannot be quantitatively validated. Therefore, the claim that to core problem is solved cannot be made yet, but needs validation over time to measure a decrease in quality costs.

To the case company, it is recommended to apply the constructed method to further optimise their process control. After a longer time period, the method can be evaluated and when a decrease in quality costs of at least 15% is noticed, the method can be seen as fully validated.



PCOM-MSME, a method for process control optimisation at machining SMEs

Based on multiple company visits, interviews with experts and software demonstrations, a small report with more practical recommendations for Technology Twente was delivered. This resulted in the following recommendations when implementing the method at Technology Twente:

- Implement digitalisation software like High-QA to digitalise control plan generation
- Implement Bluetooth measurement devices to allow machine workers to automatically fill in the digital control plan
- Use the SPC Excel sheet of 2007 or the Excel sheet from ASML for series larger than 50
- Use AQL to determine measurement frequencies
- Format the control plan such that it forces machine workers to quantify their measurement data when possible
- Closely monitor the digitalisation of process control

Preface

Dear reader,

In front of you lies the final part of my Bachelor of Industrial Engineering and Management at the University of Twente. To finish my thesis, I worked with Technology Twente to further optimise their process control.

First, I would like to express my gratitude to Bas Schunselaar and Raymond Westerhof, my two supervisors at Technology Twente. The company visits, attended demonstrations and overall insights into an organisation are of immeasurable value for me. Next to that, the friendly atmosphere and flexibility that was offered to me helped me push through this complex project.

Also, I want to express my gratitude to Lucas Meertens, my first supervisor at the University of Twente. Although I was quite late in finding my assignment, I still had a goal, which was delivering a high-quality thesis in time, while still gaining practical experience and helping out the company. His substantive feedback on my research as well as on my progress helped me achieve these goals.

Next to that, I would like to also express my gratitude to Rogier Harmelink, The second supervisor of the University of Twente. Despite the given circumstances, I really appreciate the objective feedback that was given to all of my work.

Lastly, I want to thank my family and friends for their emotional and motivational support throughout my Bachelor's study and thesis. Even though I undertook lots of activities next to my studies, I was still able to, in the end, finish up my studies within three years, enabling me to finish my Bachelor at 20 years old.

Bram Voorbach

20th of September, 2024

Contents

List of abbreviations

AQL: Acceptance Quality Limit
BPM: Business Process Management
BPMN: Business Process Management notation
CAD: Computer-Aided Design
DSRM: Design-Science Research Method
IEM: Industrial Engineering & Management
IPQC: In-Process Quality Control
KPI: Key Performance Indicator
LSS: Lean Six Sigma
LTL: Lower Tolerane Limit
MC: Method Chunk
MCDA: Multi-Criteria Decision Analysis
MMG: Micro Machining Group
MPSM: Managerial Problem Solving Method
NC: Numerical Control
PC: Project-Characteristic
QMS: Quality Management System
SME: Small- and Medium Sized Enterprise
TQM: Total Quality Management
UTL: Upper Tolerance Limit

1 Introduction

In this chapter, an introduction will be given to the case company in Section 1.1. Then the problem the company is facing will be explained and visualised in a problem cluster in Section 1.2. Lastly, the selected solving approach will be justified and explained per solving phase in Section 1.3.

1.1 Company context

Technology Twente is a Small and Medium-sized Enterprise (SME), with approximately 40 employees, located in Hengelo (Technology Twente, 2024). Together with Germefa, an equally-sized company located in Alkmaar, they form the Micro Machining Group. The Micro Machining Group (MMG) machines and assembles high-precision complex mechanical parts. MMG serves multiple different sectors, such as the aerospace and medical sector, but also the oil and gas sector, as well as the defence sector. Large, well-known customers are for instance Airbus and ASML.

The core business is the production of raw material to finished metal part batches, e.g. ASML machine components, to then be sent to the customers. Both Germefa and Technology Twente focus on high precision and high-quality standards. There is a slight difference however between Germefa and Technology Twente. Germefa focuses on smaller-sized components in longer series, whereas Technology Twente unites high quality, speed and quantity and generally speaking constructs larger components. Germefa for instance constructs small rings and bolts, where Technology Twente constructs the parts that are combined with these rings and bolts. Having both specialities makes Micro Machining Group the perfect partner for the multiple markets as described above.

To ensure that the products are of the required quality and are between the given tolerances, process control is conducted. This thesis aims at developing a method for optimising process control at machining SMEs. This method can then be implemented and validated at Technology Twente.

1.2 Problem identification

1.2.1 Identification of the action problem

At Technology Twente, orders arrive together with the corresponding model in the Computer-Aided Design (CAD) software called TopSolid. When the order is accepted and the agreements are made with the customer, a Numerical Control (NC) code is written to programme the machines to execute the right movements. The products move from machine to machine to be milled and machined. Afterwards, if needed, the parts are moved to the assembly room for assembly. Before the final product can be shipped towards the customer, the product receives a final inspection. After inspecting the final product, the batch is sent towards the customer.

As one can imagine, at this final inspection, an error might be found in the finished product, resulting that there is a change that the whole batch can be thrown away. In this case, we speak of a rejection. The percentage of parts that are rejected, divided by the total number of parts, is defined as the rejection rate. As the finished products are often high-precision mechanical parts or assemblies, the products and thus the whole production process is costly. Therefore the percentage of products that are rejected should be minimised to reduce the production costs and reduce the wasted materials, thus reducing the quality costs.

During the production process, process control on the parts is done. However, a concrete procedure on when to measure the part, which part of the batch to measure and what dimension of the part to measure does not exist. When a dimension is chosen to be measured, the worker measures the part at the machine or brings the part to the measurement room. In the last case, the production of the part then cannot continue, until paper results are given from the measurement room. This increases both paper waste and time waste. Additionally, as paper is used for the process itself, time is wasted with printing, walking and waiting. All these factors contribute to an increase in quality costs, as measured as a Key Performance Indicator (KPI) by Technology Twente.

There is a clear discrepancy between norm and reality here. Due to privacy concerns absolute values are left out in the upcoming reasoning, but the real relative values are given. Two years ago, quality costs were half of what was aimed for, according to that year's KPI. Therefore, this KPI was tightened by approximately 50%. However, last year, due to the absence of an efficient and effective process control procedure, the quality costs were 15% higher than the tighter-set KPI goals. Therefore, to again meet these tighter-set KPI goals, the quality costs should be reduced by 15%.

The action problem that can be formulated for this thesis, based on the above-given description is:

The quality costs at Technology Twente are 15% higher than current tighter-set KPI goals

1.2.2 Problem cluster and core problem

Now that the action problem is defined, the core problem needs to be defined. Firstly, a problem cluster is created as can be seen in Figure 1.1 below, to visualise the problems and indicate their causes and effects, as Heerkens and Van Winden (2021) recommends.

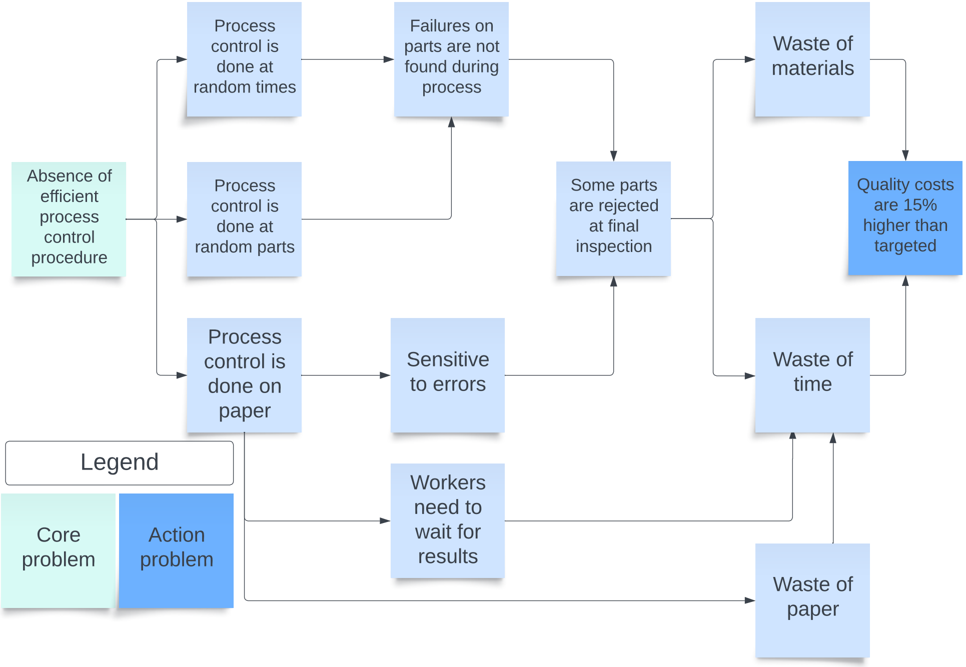


Figure 1.1: Problem cluster

The core problem can be defined according to the following two properties (Heerkens & Van Winden, 2021). The chain needs to be followed back, to find a problem that does not have a cause itself. Next to that, the core problem should be something that can be influenced by the researcher. These two reasons combined make the only possible choice for a core problem, based on the problem cluster above, the following core problem:

Technology Twente has an absence of an efficient and effective process control procedure

Now defining the norm and reality of the core problem. The reality is that Technology Twente has some sort of procedure for process control, that can be found within their Quality Management System (QMS). This procedure meets quality standards, but is not optimised to decrease production costs while still achieving exceptionally high-quality standards. The norm is that they have a clear and optimised process control procedure, that still enables the expected high-quality standards.

1.3 Problem solving approach

1.3.1 Selected problem solving approach and motivation

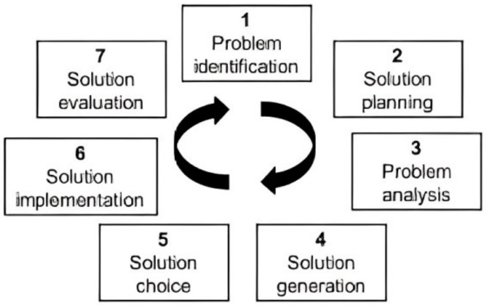


Figure 1.2: Managerial problem solving method

The problem solving approach that will be used in this research is the Managerial Problem Solving Method (MPSM). MPSM consists of the seven phases as demonstrated in Figure 1.2 above. The theory on this solving approach out of the book of Heerkens and Van Winden (2021), will be used throughout Section 1.3. As explained in this book, MPSM is a systematic approach with creative jaunts. This is useful as a systematic approach will generally yield an acceptable solution, but now with the creative jaunts, a more optimal solution could be generated. Also, MPSM is an approach that is claimed to work anywhere, anytime, making MPSM a more general problem solving approach.

As different theoretical aspects are expected to be used within this research, a more general approach like MPSM perfectly fits the research design. Also, as redesign of the quality control process is expected, creative jaunts are expected to possibly contribute to a way more efficient quality control process. The last part of the motivation of MPSM consists of its systematic nature itself. As stated, a process can always be improved, so by using the MPSM, Technology Twente has the opportunity to redo iterations of the cycle to further improve their process.

Within Section 1.3, after the solving approach is motivated the main research question is defined, the approach plan for the seven phases of MPSM with corresponding expected knowledge questions per phase will be explained. As Heerkens and Van Winden (2021) suggests to do when knowledge is required, a jump will be made from the MPSM cycle to the research cycle. In the following subsection, these phases and their expected required knowledge are described.

1.3.2 Main research question

The core problem of the research is:

Technology Twente has an absence of an efficient and effective process control procedure

The main research question needs to be established, to later be solved by continuing through the MPSM cycle. Once knowledge is required a switch to the research cycle will be made. To keep the research iterative and repeatable for other comparable machining SMEs, the main research question, resulting from the core problem, is:

How can machining SMEs make their process control more efficient and effective?

1.3.3 Solving approach phases and research questions

The main research question will be answered by broadly following the MPSM cycle as described below, as well as by answering the following knowledge problems in the process.

Phase 1: Defining the problem
This phase of MPSM consists of defining the problem, causes and effects and determining the action and core problem, which is discussed through Section 1.2

Phase 2: Formulating the approach
This phase consists of explaining the plan on what to do per phase of the MPSM cycle, what it will deliver and what knowledge is required to fulfil the phase, which is covered within this section, Section 1.3

Phase 3: Analysing the problem
In this phase of the MPSM, the current situation is analysed. The analysis of the current situation at Technology Twente will be reported to in Chapter 4. During this phase, based on the analysis of the current state, literature review will be done on which will be reported upon in Chapter 2. The following knowledge questions serve as guidelines within this phase.

Research question 1: What does the current production process look like at Technology Twente

Research question 2: How is the current production process of Technology Twente influenced by their process control procedures

Research question 3: What quality management concepts currently used for process control?

Research question 4: What makes process control for an SME's production process efficient and effective?

Research question 5: What is situational method engineering?

Phase 4 & 5: Formulating (alternative) solutions & Choosing a solution
Within this phase, the solution to the research question is developed. This will be done within chapter 3. The following research question serves as guideline within this phase:

Research question 6: How can situational method engineering be used to construct a method for improving process control at machining SMEs?

Phase 6: Implementing the solution
Within this phase, the method constructed in the previous phases will be implemented at Technology Twente. The results of the implementation are described in Chapter 5. In this phase, the constructed method will also be validated as described in Chapter 6

Phase 7: Evaluating the solution
After succesful implementation and validation, the result should be evaluated upon. However, due to time constraints this is beyond the scope of the research.

2 Literature review

This chapter serves for reviewing on the literature found with the use of systematic literature review on the research questions discussed in section 1.3. The literature reviewed will put theoretical concepts into perspective in Section 2.1. Different quality management concepts are reviewd in Section 2.2. In Section 2.3, situational method engineering will be discussed.

2.1 Theoretical perspective

This section serves to delineate the main concepts that will be used within this thesis. As the thesis aims to produce a framework for making process control more efficient and effective for SMEs, these constructs need to be defined concretely.

First, a definition is needed on what an SME is. According to the EU definition, a business that has fewer than 250 employees, less than or equal to 50 million annual turnover or less than or equal to 43 million of assets on the balance sheet can be identified as an SME (Netherlands Chamber of Commerce & Netherlands Enterprise Agency, n.d.). Now define efficient and effective process control procedures. Starting with efficiency, efficiency is the extent to which an activity achieves its goal whilst minimising resource usage. To make it more specific, efficiency is about the ability to perform well or achieve maximum results without wasted resources, effort, time or money, using the smallest quantity of resources possible (Vlasceanu et al., 2004). Effectiveness is about achieving the intended results (“Cambridge”, 2024). Thus effectiveness is a measurement for to what degree the goals are achieved. The definition of process control used at Technology Twente, based on informal interviews, is: ”Performing control on the production process, consisting of a preparation, execution and archiving phase”. As described in Chapter 4, process control consist of for instance determining frequencies or important dimensions, filling in the control form and archiving the measurement results. For this thesis, when process control is discussed, the definition of Technology Twente is used.

For the systematic literature review, process control improvement cannot solely be used, as this concept has a broader meaning in the academic world. In the academic world, the definition of process control is seen as a method that a process is operating as designed, with the objective to keep the parameters within the bounds of the reference value. (Bajpai, 2018). Process control uses both statistical data analysis and visual inspection of the process (Kinney, 2023). A more specified term is called in-process quality control (IPQC) and can be used interchangeable with the process control definition of Technology Twente and is a subset of the definition of quality control. Quality control describes the systematic process of ensuring products meet the established quality standards, consisting of incoming, in-process and outgoing quality control (“Technology Platform to Automate Purchase Orders and Payments”, n.d.). IPQC then consist of the ongoing inspections and testing to monitor whether the specifications are met. Thus, process control as known at Technology Twente is comparable to the definition of IPQC. So, efficient and effective process control at machining SMEs can be defined as performing control on the production process of a machining company with less than 250 employees, that will increase intended performance while lowering used resources, by improving the control of whether the process is operating within its specified boundaries.

2.2 Quality management concepts

This subsection servers for shortly describing process improvement methodologies. Then, more specific process control techniques for quality management are discussed that were identified during company visits, namely Statistical Process Control (SPC) and Acceptance Quality Limit (AQL).

2.2.1 Process improvement methodologies

Laoyan (2024) proposes seven different process improvement methodologies. For the last decades, process improvement methodologies s such as Lean, Six Sigma, Lean Six Sigma (LSS) and Total Quality Management (TQM) have been implemented at organisations. (Andersson et al., 2006). Business Process Management (BPM) was identified as a useful process improvement methodology by experts during company visits. These four are therefore discussed in this subsection.

2.2.1.1 Lean, Six Sigma

According to NIST (2019), Six Sigma aims to reduce variation with the use of statistical methods, to lower defects by less than 3.4 defects per million. This is done by implementing management systems. One of the Six Sigma processes is DMAIC, an improvement cycle for improving business processes (Laoyan, 2024). It consists of the following steps (Lean Six Sigma Groep, 2024):

- Define: The opportunities for improvement should be defined
- Measure: The current performance should be measured
- Analyse: Find the defects and root causes
- Improve: Adjustments by addressing root causes
- Control: Check on improved process performance

A series of tools that help manage an organisations processes is called Lean (NIST, 2019). The main goal is to reduce waste by eliminating zero-added-value activities, working with five main principles (Lean Six Sigma Groep, 2024):

- Identify value
- Value stream mapping
- Create flow
- Establish pull
- Continuous improvement

According to Yadav et al. (2020), these concepts can be combined to the LSS methodology, a proven methodology. As process control improvement is a subset of quality management systems, these methodologies are described. As discussed, efficiency and effectiveness need to be improved. Process control is a critical part within LSS (Kinney, 2023).

2.2.1.2 Total Quality Management

TQM is the system of practises that aim for quality improvement with the focus on customer satisfaction and continuous improvement (Andersson et al., 2006). Key concepts of TQM can be defined as (Laoyan, 2024):

- Customer-focus: The end-focus of TQM should still be to benefit the end-customer
- Full-team involvement: TQM is special as an improvement methodology for the fact it involves the whole team rather than only production
- Continuous improvement: The idea of TQM is making small changes which continuously optimises the process
- Data-driven decision making: Data should be collected continuously, in order to make accurate decisions

When the quality management concepts as described above are combined and integrated with quality management systems, synergy ensures better results (Yadav et al., 2020). Prashar (2023) proposes a conceptual framework for implementing quality 4.0. Quality 4.0 is defined as "digitalisation of quality of design, quality of conformance and quality of performance using modern technologies" (Sony & Naik, 2019). Quality 4.0 enhances the digitilasation, which makes it an important addition to the TQM methodology.

The framework by Prashar (2023) is based on three building blocks as can be seen in Appendix A. The three building blocks are the foundation, pillars and roof. The foundation is the maturity of the digitalisation, describing the as-is situation. The pillars represent the integration of quality management systems both horizontally and vertically. Horizontal integration is about integrating quality management systems with each other, while vertical integration focuses on integrating this integration onto a strategic level, by for instance integrating with an ERP-system. (Chiarini & Kumar, 2020). The roof of the framework represents the overall reinforcement of all the quality management systems with TQM principles.

2.2.1.3 Business process management

BPM is the act of analysing and improving business processes (Laoyan, 2024). In a business process model notation (BPMN), processes are visualised, analysed and improved. The following five main steps are used in BPM:

- Analyse: Determine the as-is state of the process. A BPMN can be used here
- Model: Model the ideal future state
- Implement: Implement the model and make the changes measurable
- Monitor: Determine whether the process is improved based on indicators
- Optimise: When the process evolves, still continue to improve the process

2.2.2 Statistical process control

A technique within Six Sigma is Statistical Process Control (SPC). The basis for quality control for high precision machine elements manufactured in mass production are post-process or in-situ based SPC (Lindner et al., 2013). Within process control, the most common approach for quality checks based on output to make interference's is SPC (Slack & Brandon-Jones, 2019, Page 585). SPC determines whether a process is "in control", based on a sample. A method for selecting the sample, is further explained in Subsection 2.2.3. SPC is argued to have higher effectiveness and reliability when larger data sets are used, thus more useful with larger series. (Montgomery, 2020).

As Slack and Brandon-Jones (2019, Page 603) describes, SPC is used for monitoring over time rather then checking a single sample. Measurement results can show variation. The variation can be called acceptable if the natural variation of the process is between the specification range, thus in between upper- and lower tolerance limit (UTL & LTL). A way to quantify the variation is by measuring the C$_p$ value. The C$_p$ value is a measure of capability of the process and is calculated with the following formula:

$$C_p = \frac{UTL - LTL}{6s} \tag{1}$$

The specification range UTL - LTL is divided by six times the standard deviation, s, of the process variability. This number is six due to the empirical rule. The empirical rule states that 99,7% of the values that follow a normal distribution will lie between three standard deviations of the mean (Hayes, 2024). The C$_p$ value however provides information on the spread of the process, but not about the centering of the process. This can be calculated with the C$_p$k value by dividing the difference of the mean, $\bar{X}$ and the LTL/UTL, with three standard deviations.

$$C_pk = min(\frac{\bar{X} - LTL}{3s}, \frac{UTL - \bar{X}}{3s}) \tag{2}$$

Acceptable for the C$_p$ and C$_p$k values are between 1.33 and 1.67 ("Process Capability and Performance (Pp, Ppk, Cp, Cpk)", 2024). Lower values indicate a less capable process and higher values indicate to much inspections.

2.2.3 Acceptance quality limit

The acceptance quality limit (AQL) is a statistical method that can be used to determine the number of rejections allowed within a shipment, while still meeting quality standards (Bureau Veritas, n.d.). AQL is an important statistic when seeking a Six Sigma level of quality control for the company (Banton, 2022).

AQL makes use of AQL tables to, accordingly determine sample size for inspection. The tables are derived from quality standards. The ANSI ASQ Z1.4 standard is the most widely used quality standard and consist of two tables as shown in Appendix B (Bureau Veritas, n.d.). As can be seen in B.1, the sample size code letter firstly need to be determined based on the lot size and the inspection levels. With the code letters known, in Appendix B.2, the rejection number can be determined. For this, an AQL level need to be chosen. This number is based on tolerance from customers. A higher value corresponds to a higher tolerance to defects. AQL 2.5 is the most widely used model (Bureau Veritas, n.d.).

The drawback of implementing AQL in process control, is that according to AQL, batches are still shipped with possibly a few parts that fall beyond specifications. This is not a suitable concept for certain markets, such as machining SMEs at which customers require high-quality standards. These customers do not want any wrong parts in their batch. Germefa, the sister-company of Technology, also has procedures for process control. At Germefa, AQL is used to determine the measurement frequencies for process control. Dividing this with the total batch size gives the measurement frequency that should be used according to AQL. Performing measurements according to the sample size code letters and then when a part is wrong, only inspecting back until the previous successful measurement, will result in a 100% approved batch without 100% inspection.

2.3 Situational method engineering

As stated, a methodology for improving process control for machining SMEs need to be constructed. This section explains how to create a methodology with the use of situational method engineering.

Situational method engineering is defined as a methodology for engineering a method for a particular situation. (Henderson-Sellers et al., 2014, Section 1.1) In this definition, engineering means either creating such a method ab initio and/or modifying an existing method. Constructing a method can be done according to seven different strategies described in the book. After method construction, a fine-tuning method called method tailoring can be applied, which will be discussed in Subsection 2.3.2.

Out of the method construction strategies, the two most interesting are assembly-based and paradigm-based, according to Henderson-Sellers et al. (2014, Section 6.1). Assembly-based strategy uses repository-stored methods and assembles them into a new method. Paradigm-based approach generates fragments from a metamodel (Cervera et al., 2011). Henderson-Sellers et al. (2014, Section 6.2.1) states that the key difference is for the assembly-based approach, the fragments already exist in contradiction with the paradigm-based approach. The assembly-based approach is thus chosen in this research as fragments of process control optimisation already exist. This will be done by assembling method chunks, as will be explained in Subsection 2.3.1. The definition, according to Henderson-Sellers et al. (2014, Section 2.2), used for method chunks is an autonomous and coherent part of a method.

2.3.1 Assembly-based approach

Below, a visualisation is shown of the modified assembly-based approach by Kornyshova et al. (2007) in figure 2.1. Explanation is on the next page for formatting reasons.

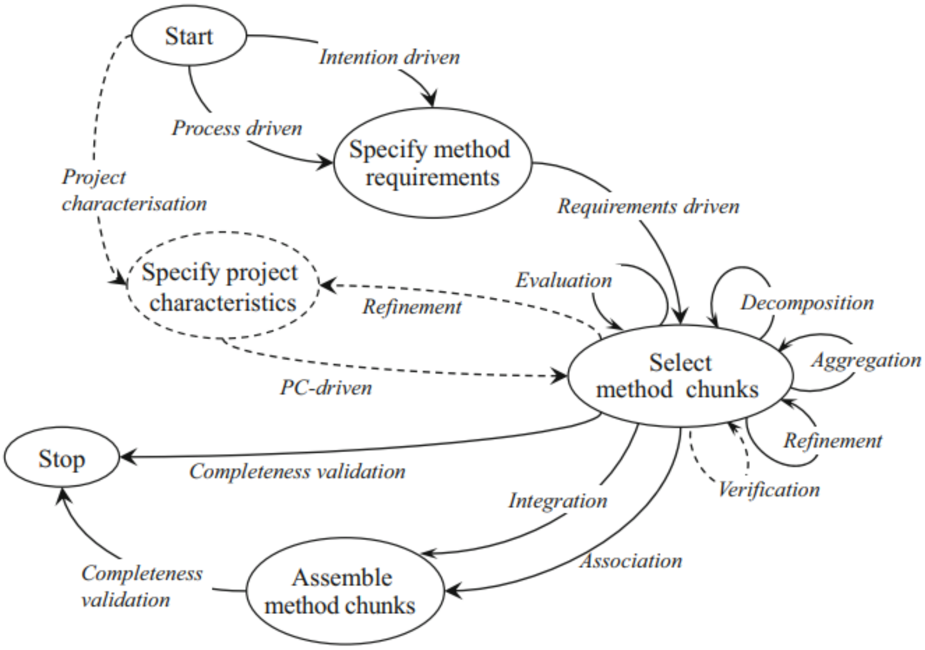


Figure 2.1: Modified assembly-based approach (Kornyshova et al., 2007, Figure 7)

The original assembly-based approach constructed by Ralyte (2001), was later extended by giving additional advice on chunk identification by Kornyshova et al. (2007). This extended model integrates new parameters into the chunk selection by analysing the project characteristics (PCs). (Henderson-Sellers et al., 2014, subsection 6.1.1). In Figure 2.1, both the original and the extended approach are visualised. This can be seen as the original approach is visualised in solid lines and the extensions of the approach are visualised in dashed lines. As can be seen, four new lines are drawn representing four new sections; Project characterisation, refinement, verification and method chunk selection by PC-driven strategy.

Within these sections, four different dimensions represent the PC; organisational, human, application domain and development strategy. The different characteristic values that identify these dimensions help specifying the four sections of PC.

As shown in the demonstrated approach, three different phases can be distinguished. The first phase consists of specifying the method requirements and establishing PC. The second phase is selecting the method chunks and the last part is assembling these method chunks. Of course, after the method is constructed, method validation is needed. The following paragraphs serve for shortly explaining how each phase should be followed.

2.3.1.1 Requirement selection and project characterisation

Ralyté (2002), proposes two different strategies for method requirement selection, namely intention-driven and process-driven, which will be further elaborated upon in this paragraph.

The process-driven strategy is applicable in the situation where a fully new method needs to be constructed. This strategy starts with an activity-driven strategy to come up with the final requirements map after aggregation, decomposing and or validation. It is a structured and systematic way to create the requirement selection, as visualised in Appendix C.1. The intention-driven strategy lays the focus on aligning the intentions of the method with the goals of for instance the stakeholders and could give some rationale. The complexity to combine both strategies is beyond the scope of this thesis and these approaches should therefore be used as a guideline for requirement selection.

Project characterisation can be done according to the four different characteristic values given above, in subsection 2.3.1. By specifying these characteristics, method chunks can also be selected accordingly as will be explained in the following paragraph.

2.3.1.2 Method chunk selection

The method chunk selection can be done based on two different ways. As can be seen in Figure 2.1, it can be done requirements-driven and PC-driven. Next to that, method part refinement can be done with the use of decomposition, aggregation and refinement strategy (Ralyte, 2001). The decomposition strategy is for when a method part is a compound chunk and the smaller parts are not usefull for the current construction. Aggregation is used when the method part only covers a part of the requirements. The refinement strategy suggests another method chunk that has broader guidelines.

Requirements driven method chunk selection is done with method fragments chosen from the OPF repository, the OPEN process framework (Firesmith & Henderson-Sellers, 2002). Since this method is for improving process control, the selection will be made out of process improvement methods as found in this literature review. Out of multiple method chunks, the most relevant can be chosen with the use of a Deontic matrix (Zowghi et al., 2007).

The PC-driven strategy uses multi-criteria techniques to for selecting method chunks based on the specific PC. (Henderson-Sellers et al., 2014, Section 6.1.1) This is done by defining weights and priorities, as is illustrated in figure C.2. (Kornyshova et al., 2007, Figure 2). The result should then be the one half of the final selection with which the assembly can be done.

2.3.1.3 Method chunk assembly

When the method chunks are selected, through goal analysis they can be constructed. Henderson-Sellers et al. (2014) describes goal analysis as considering the final goal of each process step from point of views of specific actors. This is done based on three reasoning techniques, means-ends analysis, contribution analysis and AND/OR decomposition (Bresciani et al., 2004).

Means-end analysis is an iterative process of identifying the plans, resources and soft goals to find the means for achieving the goal. Contribution analysis can be seen as an addition to means-end analysis and identifies positive and negative influences towards the attainment. AND/OR decomposition further defines the goal structure with either alternatives or additives.

2.3.2 Method tailoring approach

In principle, after constructing a method with the use of the extended assembly-based approach the first enactment should follow smoothly. This is as the method is already made situational during construction. It can however occur that some situations change and for instance the industry within process control changes. It should then still be possible to make modifications to the constructed methodology. This concept is called method tailoring. (Henderson-Sellers et al., 2014, chapter 7). A method tailoring approach followed from industry experience is a continuous evolution approach. This process configuration approach should create solution specific methods based on a method base that can continuously evolve. (Bajec et al., 2007, section 4.3) The base method evolves continuously due to knowledge and experience gathered on the project. By continuously iterating the existing method, the method will be tailored to the fitting situation, as visualised in figure C.3

As can be seen in Appendix C.3, the main takeaway is to apply method tailoring even after the first version of the constructed method is finished, to keep on adapting to a continuously changing method base.

2.4 Chapter conclusion

Summarising the literature combined with the thesis' goal, the research will create and implement a methodology aimed for machining companies with less than 250 employees that will increase intended performance while lowering used resources, by improving the control of whether the process is operating within its specified boundaries. A method will be constructed by following situational method engineering, using the assembly-based approach with a requirement selection and project characteristics.

3 Methodology development

In this chapter, situational method engineering will be applied to develop a generic method for process control optimisation at machining SMEs. This will be done by assembling the method chunks discussed in Section 2.2, according to the approach discussed in Section 2.3.

3.1 Method requirement selection

3.1.1 Requirement selection

The first phase of constructing a method is setting the method requirements, which is beneficial for the whole method development process (Gupta & Prakash, 2001). As discussed in Paragraph 2.3.1.1, the required selection can be made both process-driven and intention driven. The requirements for a method for improving process control at machining SMEs will be discussed in this subsection and at the end summarised in bullet points.

3.1.1.1 Process-driven

As stated, the process-driven strategy focuses more on the predefined processes and frameworks. This thesis uses the MPSM cycle to optimise process control and the aim is to improve rather than design. Thus, the first requirement is that the machining SME already has some sort of process control design.

The main goal of the method is to reduce quality costs, which can be done by reducing material, paper and time waste. So one of the requirements is that the method should lower quality costs.

With the introduction of Industry 4.0, manufacturing industries have started to improve on efficiency and performance and this increase is expected to stay continuous (Seraj et al., 2022). When developing a methodology for the machinery industry, it is thus important to generate a methodology that allows for continuous improvement.

The method that is created is aimed for SMEs. Researchers found that, for process improvement within SMEs, it is important to be able to show tangible results in a relative smaller time period (Kumar et al., 2006). Therefore, if the method is someway step-wise, the results can be monitored during the method implementation, allowing for tangible results can be acquired. If for instance after the first steps it is noticed the process is not improved but worsened, adjustments can still be made.

3.1.1.2 Intention-driven

Discussing the intention-driven strategy, the stakeholders of the constructed method need to be clarified. After informal interviews at Technology Twente, the two identified stakeholders of the method are the management team and the machine operators for the constructed method. The reason customers are not included, is because the output of the products won't differ for the customers, the quality costs for the machining SME will be lowered.

The method is created for machining SMEs, thus companies with a profit motive. For the management team, it is therefore of interest the method reduces the wasted materials, which is in line with the core problem that is tackled this thesis. Thus the requirement that follows is that the method should reduce the wasted materials to lower quality costs.

The machine workers also have a common interest for simplicity. The machine operators need to work with the result of the method. Therefore the result of the method should be easy to use for possibly lower-educated machine workers.

3.1.1.3 Final requirement selection

- Some sort of process control design or procedure needs to pre-exist at the company
- The method should allow for continuous improvement.
- The method should be step-wise in some way, to allow for tangible results
- The method should reduce wasted materials for the SMEs
- The method result should be easy to utilise by machine operators

3.1.2 Project characterisation

As described in the first part of Paragraph 2.3.1.1, project characterisation is done based on four dimensions, namely organisational, human, application domain and development strategy. Kornyshova et al. (2007, page 64-78) proposes four tables with multiple PCs per dimension. The application and development domain are not applicable for this method, as they are aimed for software development. The tables of the possible project characteristics of the organisational and human dimension that the paper proposes based on multiple other sources, are shown in Appendix D.

With these tables, the book of Kornyshova et al. (2007) proposes that the researcher can make a selection of these PCs, to ensure they fit the correct constructs. Out of the demonstrated organisational project characteristics presented in Appendix D.1, the following are chosen: Size and level of innovation. This is because the process control needs to become SME, thus size specific. Next to that, As explained in Paragraph 3.1.1.1, due to the constant innovation, the methodology that is developed has a characteristic of innovation.

Out of the human project characteristics presented in Appendix D.2, Expertise and clarity and stability are chosen. This is as the specific knowledge, experience and skills are required when optimising a process. Then this also again correlates to clarity and stability.

These are the following PCs followed from the project characterisation phase above:

- Level of innovation
- Size
- Expertise (knowledge, experience, and skills)
- Clarity and stability

3.2 Method chuck selection

As was shown in Figure 2.1, the selection can be PC-driven or requirements driven. During this phase, evaluation, aggregation, refinement, decomposition and validation are executed continuously.

3.2.1 Requirements-driven method chunk selection

The theory on process improvement concepts in Subsection 2.2.1 discussed a variety of methodologies, with method chunks within them. In this subsection the requirements will be connected to these method chunks, if possible.

Starting off, a current design of the company's process control needs to pre-exist as the constructed method should improve a procedure rather than designing a new procedure. Therefore, opportunities should be searched for in the current state analysis. This results in method chunk "analyse" of the BPM method and the chunk "define" of the DMAIC method. This also correlates to the first two described principles of lean management, identify value and value stream mapping.

Continuous improvement as a requirement is found in multiple method chunks. This concept is known within TQM, but also within lean manufacturing. Also BPM seeks for continuous improvement at the last step called "optimise".

As solving the waste of paper and time results in the lowering of quality costs, which is the main goal of the method, a method chunk that follows is digitalisation.

Allowing for tangible results can follow from the method chunk "monitor" from BPM. Through this method chunk, the results of the improvement can directly be measured by monitoring key variables.

Reducing wasted materials leads to the LSS methodology explained in Paragraph 2.2.1.1. For the method chunks, it can be lead back to identifying the value and mapping the value stream.

Easy implementation and easy utilisation is about how well the management team can implement the constructed method and how easy the machine operators can utilise the results of the method. This can be correlated to the "full-team involvement" of TQM.

3.2.2 PC-driven method chunk selection

In this subsection, PC-driven method chunk selection will be executed, according to Appendix C.2. To start of, the project characteristics receive a weightings and will afterwards be prioritised with Multi-Criteria Decision Analysis (MCDA) to select the corresponding method chunks.

The project characteristics established in Subsection 3.1.2 are level of innovation, clarity and stability, size and expertise.

Firstly, these project characteristics are characterised to the current project, which is improving process control at machining SMEs. As can be found in Appendix D.1, the value for Size should thus be low. The level of innovation is high as discussed in Paragraph 3.1.1.1. As process control has influence on both the management and on the work floor, business innovation and technology innovation are the values. As can be seen in Appendix D.2, for the human characteristics, the expertise of the project is high and at the analyst side, because quality engineering requires professionals that do analysis on the quality delivered.

Now determining the weighting per characteristic. To further specify the method to an SME, size and the level of innovation can be considered more important than the two human characteristics, as the problem that is solved lies within the organisational part of the organisation. Therefore, the weights will be 30% for both organisational characteristics and 20% for both human characteristics. Kornyshova et al. (2007) states that when no other means are available, the researcher can estimate the weights, which was done here.

In Appendix D.3 the MCDA is demonstrated. The calculation is done with the weights determined above. A cross is set when the method chunk either fits or attributes to the described project characteristic. Following the MCDA analysis, with the weighted sum at the end, there are three method chunks that contribute to all four project characteristics, namely SPC, AQL and the define part within DMAIC. Also, the control part of DMAIC and full-team involvement of TQM score highest. Notable might be to see the size characteristic score a cross at every method chunk. This characteristic is still kept in the analysis as since the method is designed for SMEs, it is mandatory for the method chunk to be applicable to SMEs. Therefore the methods need to be checked whether they match this characteristic.

3.2.3 Method chunk refinement

In this subsection, the selected method chunks are summarised, to then be refined, aggregated and decomposed if necessary, finally giving the final selection of selected method chunks.

The method chunks define from DMAIC and full-team involvement of Lean follow from both selection methods and are needed only once.

Identifying the value and value stream mapping out of Lean, can be aggregated into: Map value stream of resources.
Continuous improvement method chunk was found from both TQM, Lean and BPM and can from now be referred to as continuous improvement. Monitor from BPM was also a method chunk found, allowing for tangible results.

The collected method chunks, from both the PC-driven and requirements driven approach are:

- Define unclarities
- Visualising with a BPMN
- Map value stream of resources
- Continuous improvement
- Full-team involvement
- Control improved process performance
- Statistical process control
- Acceptance quality limit
- Solving unclarities
- Monitor
- Digitalisation

3.3 Method chunk assembly

In this section, the theory on method chunk assembly as described in Section 3.3 will be used to assembly the first version of the final method. A goal-based approach will be used, with means-end analysis, contribution analysis and AND/OR decomposition.

The goal of the method is to further optimise process control, so that wasted resources as materials. paper and time are reduced. This is done by creating an efficient and effective process control procedure. Applying means end analysis with the goal in mind, the constructed method should look like: Identifying the present and desired state and selecting the procedure to end up in the desired state. Following the ADD/OR decomposition, an improved process should be evaluated before further optimising. Continuous improvement is achieved by developing a cycle method rather than a step-wise method. Therefore, three main phases apart from entering the cycle can be identified, as visualised in figure 3.1 below.

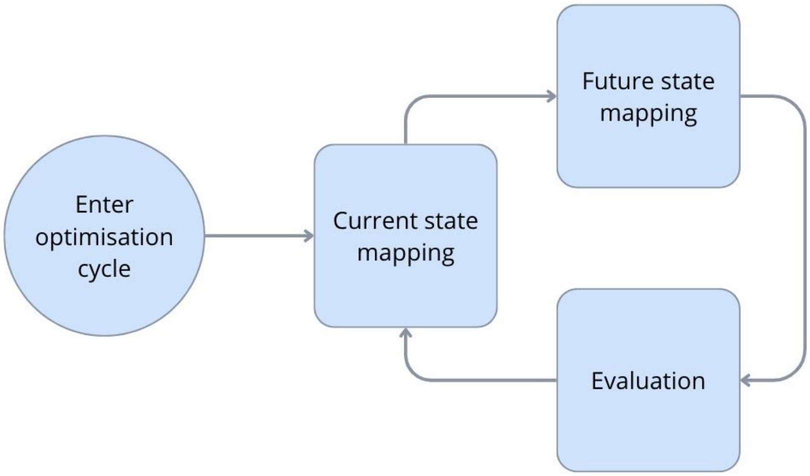


Figure 3.1: Method assembly, phases

To further construct the method, the remaining method chunks will be analysed with a contribution analysis and AND/OR decomposition. The following method chunks remain.

- Define unclarities
- Visualising with a BPMN
- Map value stream of resources
- Full-team involvement
- Control improved process performance
- Statistical process control
- Acceptance quality limit
- Solving unclarities
- Monitor
- Digitalisation

Contribution analysis and AND/OR decomposition are meant to identify positive and negative influences to the end-goal, and be open for additions and alternatives. Thus theses methodologies are used informally below to connect the remaining method chunks to phases they can contribute to.

Defining unclarities adds the most value in the current state mapping, where solving unclarities is a method chunk that is useful in the future state mapping. Visualising with a BPMN can be useful to visualise both the current and future state. Mapping the value stream of the resources can be done during current state mapping to help further identify opportunities and unclarities. When the opportunities and unclarities are defined, the management team can then solve these by communicating them with the machine operators. Full-team involvement is a method chunk used for improvement, thus can be useful in the future state mapping. Monitoring the method and the improved process is a typical method chunk of evaluation. Enhancing digitalisation reduces paper waste in any case, thus with the goal in mind is a useful method chunk at future state mapping

Performing control as discussed in DMAIC can be done with the use of SPC and can thus be aggregated to the method chunk: SPC implementation. This chunk is then defined as performing SPC when applicable, to ensure a stable and clear production process.

AQL as a method chunk is there for clarity as well as it takes away decisions that do not have a definition of who takes them. Then AQL results in the method chunk: AQL implementation. with the definition: release unclarity with the use of AQL for measurement frequencies decisions.

Summarising the discussion above and numbering the method chunks results in the following:

- Current state mapping
  - Defining unclarities (MC1)
  - Value stream mapping of resources (MC2)
  - BPMN visualisation (MC3)
- Future state mapping
  - BPMN visualisation (MC3)
  - Solving unclarities (MC4)
  - Full-team involvement (MC5)
  - SPC implementation (MC6)
  - AQL implementation (MC7)
  - Enhance Digitalisation (MC8)
- Evaluation
  - Monitoring (MC9)

3.4 Method tailoring

As stated in Subsection 2.3.2, the developed method is already specified. In this case, the method is already specified to optimising process control at machining SMEs. Therefore, this method does not require further tailoring at the moment. However, as also discussed in Subsection 2.3.2, the method can be tailored if the situation is changed. Tailoring can then be done according to Appendix C.3.

3.5 Final method

Combining all the information that is discussed, the following method follows after final assembly, demonstrated in Figure 3.2 and with a brief explanation of the method chunks below. The name that was given to the constructed method is called PCOM-MSME, which stands for Process Control Optimisation Method, for Machining Small- and Medium sized Enterprise.

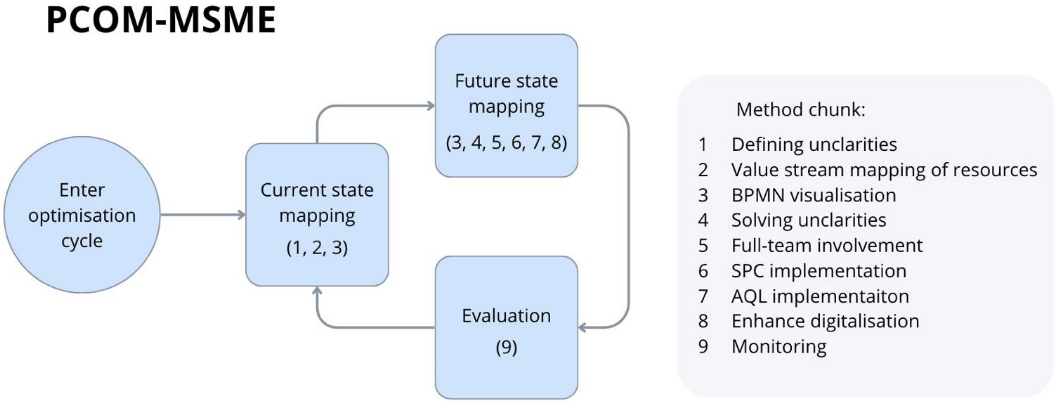


Figure 3.2: PCOM-MSME, Final constructed method

Defining unclarities (MC1): This method chunk is for defining the unclarities within process control.

Value stream mapping of resources (MC2): The value stream mapping of resources is meant to demonstrate when resources are used. Resources are defined as materials, time and paper.

BPMN visualisation (MC3): This method chunk is to visualise the state of the process in a BPMN, which then helps to identify unclarities and it helps with value stream mapping.

Solving unclarities (MC4): Solving unclarities is meant to solve the previous defined unclarities.

Full-team involvement (MC5): Full-team involvement should be enhanced, which aims to gather insights from the whole organisation.

SPC implementation (MC6): SPC implementation can be implemented in the procedure when the series are of larger size, as explained in Subsection 2.2.2. This method chunk enhances the clarity.

AQL implementation (MC7): The AQL implementation takes away the uncertainty of the measurement frequency. AQL is always applicable and should therefore be used whenever the customer does not require specific measurement frequencies.

Enhance digitalisation (MC8): Digitalising the process where possible further enhances paper and time waste.

Monitoring (MC9): Monitoring the impact of the implementation of the method. This can be done by monitoring KPI's.

4 Current state - Case study

In this chapter, the current situation at Technology will be discussed. In Section 4.1, the current production process at Technology Twente will be analysed, described and visualised in a BPMN. Furthermore, in Section 4.2, the current process control design will be split up between three phases, to then be analysed how these phases influence the current production process.

4.1 Current production process

As discussed before Technology Twente is a machining SME. The complete delineations of the concepts can be found in Section 2.1. This section describes the current production process at Technology Twente, including all phases of product control.

4.1.1 Production process description

During the production process, four main product control activities can be distinguished. These are First Article Inspection (FAI), process control, intermediate control and final control. As the thesis is aimed at developing a framework for process control improvement, the production process is analysed from launching the machines up to the products being finished, as process control has influence from work preparation up until finishing the goods.

The production process starts at work preparation. Here, the product form and control plan are established after the order is received and components and raw material is ordered. Firstly, the machine produces one part after which FAI, First Article Inspection is conducted. After positive results, production is released. During production, process control is conducted and when products fail to meet specifications, production is paused and either the machine or the CNC-code is adjusted. After the machine finishes its program, either intermediate control or final control is conducted, depending on whether it was the final step on the product form or still an intermediate step. In case final inspection is successful, the data is archived and the production process is finished.

In Subsection 4.1.3 on the next page, the description of the production process as described above is visualised in Figure 4.1 in a BPMN, a Business Process Modelling Notation. A BPMN is an internationally standardised method for representing and executing processes allowing for technical aspects to be mapped. (Gadatsch, 2023). As can be seen, process control influences the production process at three phases. These will be further analysed in Section 4.2

4.1.2 Assumptions

To construct a simplified BPMN of the current production process, assumptions need to be made. The main assumption is that this is a BPMN for the production of products that require process control. As stated before, the described production process is already simplified to from and until process control has influence. Next to that, within this part of the production process, some processes are left away for simplicity.

For instance, some parts also need to go to the assembly room, which is a sub-process of the production without process control as there is no machining there. Also, when a part results to be out of the specifications, not the whole batch is thrown away, but all parts are inspected up until the parts are within specs again. The correct parts can then still be used and the out of spec parts can then be rejected.

4.1.3 BPMN of current production process

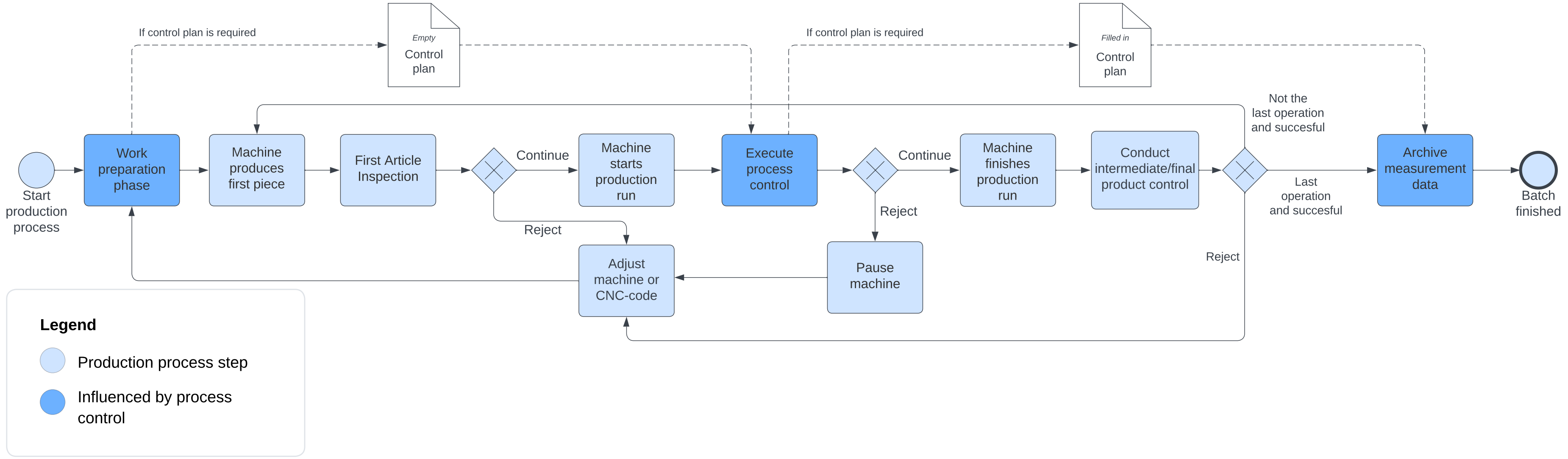


Figure 4.1: Current production process

4.2 Current process control design

This section zooms in on the parts of the production process that are influenced by process control. As can be seen in Figure 4.2, process control consists of three main phases, for which the current situation at Technology Twente will be analysed for each of these phases.

Figure 4.2: Process control phases

The procedures that currently exist will be visualised in BPMN. The current procedures will be analysed, to then later define the unclarities, notable observations and define the value stream of the resources as explained in the constructed method.

4.2.1 Preparing process control

4.2.1.1 Procedure

The first phase of process control starts during work preparation and consists of preparing process control, as is visualised in Figure 4.3. For writing the product form, the codes per department are written at the work preparation department. The 006-code and 008-code are of importance for process control. The 006-code contains instructions for the programmers department with special remarks for coding the CNC-code. The 008-code contains code with instructions for the quality department. Then, the programmers write the CNC-code and in communication with the measurement room, the process control procedure is determined. When finished, both the control plan and the product form can be printed out.

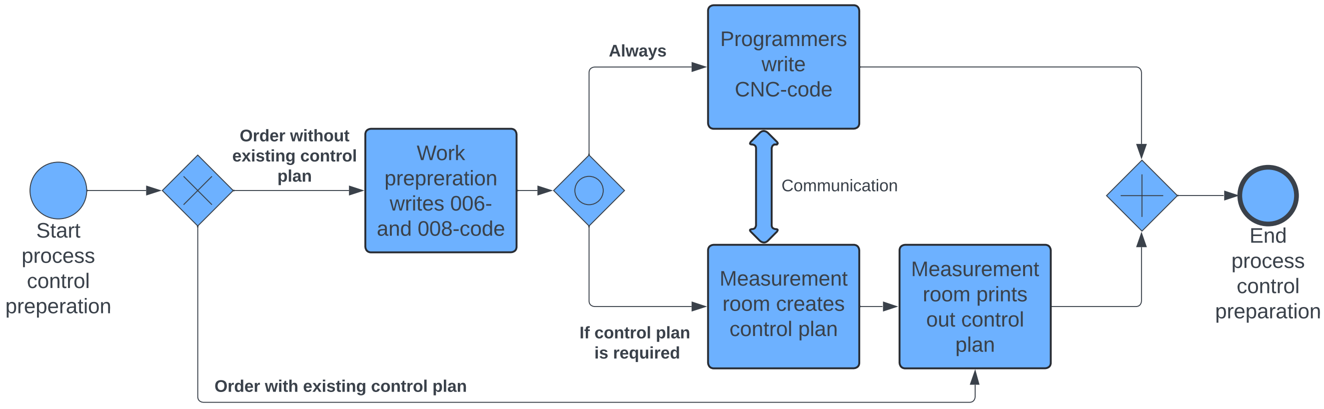


Figure 4.3: Current process control preparation

4.2.1.2 Unclarities and value stream

As discussed this is the current procedure. However, some parts of the process contain decisions that are not based on concrete theory. Next to that, it is unclear who makes these certain decisions. Firstly, the decision on to what degree process control is needed is not based on a procedure. In the quality manual, it is stated that that frequent control is required for all products and that when indicated on product form, control plan needs to be filled in (Westerhof, 2023). This however makes it unclear who decides whether to use the control plan or not. Next to that, a concrete procedure for determining the measurement frequency and which dimensions to measure is not present. Currently the decisions are made based on previous orders and based on professionalism.

Now, the value stream will be shortly discussed, according to the method. The control plan is printed out, which can can be considered as time and paper waste, as they are created digital in the first instance. No materials are wasted in the preparation phase.

4.2.2 Executing process control

4.2.2.1 Procedure

The second phase of process control is the actual execution of the process control, as visualised in Figure 4.4.

The execution starts with the machine operator reading the instructions from the product form. Process control can be executed at two different locations. The machine operator can either measure dimensions at the work floor or at the measurement room. If during the preparation phase the decision is made to use the control plan sheet apart from frequent measurements, these can be done at both the measurement room or the work floor. The dimensions Y are measured every X% of the time, as described on the product form and control plan, to then be written down on the sheet or kept digital when the measurements are done in the measurement room.

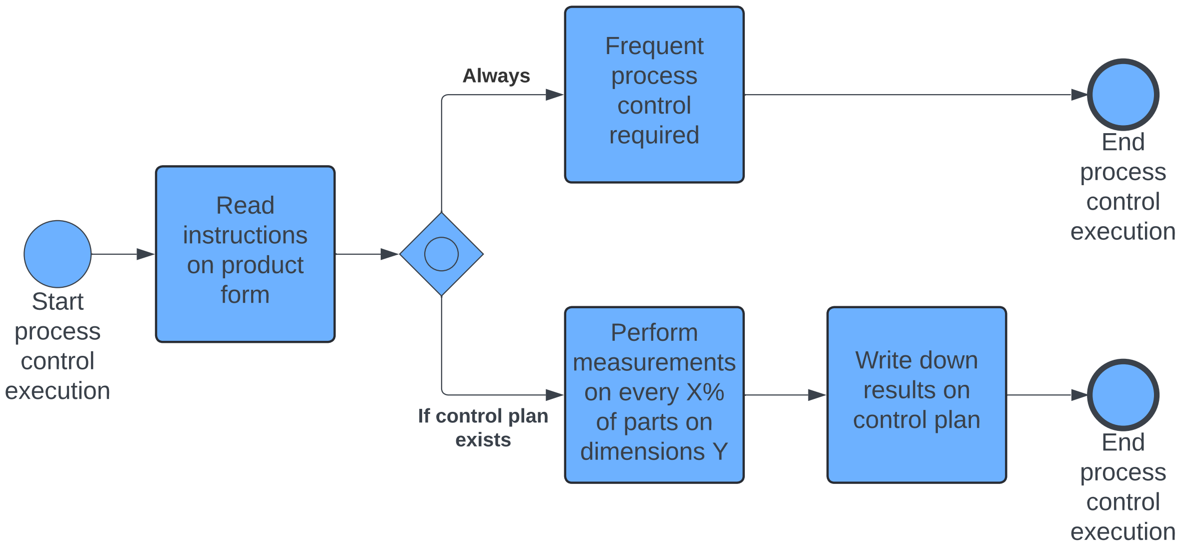


Figure 4.4: Current process control execution

4.2.2.2 Unclarities and value stream

Notable at the execution phase is that when control plan is said to not be required, it is the responsibility of the machine operator to deliver the batch for final inspection all within specifications. The current procedure notes to fill in the control plan during production (Westerhof, 2023). It is however not indicated who needs to perform the measurements or at which location the measurements need to be done. It can be stated that this description is rather vague, as practical experiences demonstrate some operators using it as a checklist, while others fill in the real measurement results. Next to that, it is also unclear whether to note all measurement results that are asked, or only the measurement results that meet specifications. Currently in some cases, the parts are rejected and the CNC-code or machine is adjusted, but the measurement results is not written down until they fall within specifications again. Also, some of the measurements are not quantified but only checked or rejected, restricting possible SPC.

Now the value stream will be shortly discussed. In the procedure, it is not denoted to throw away materials when they fall beyond specifications. Next tot that, due to the unclarity of who performs the measurements and because the measurements are not always quantified, parts are rejected. Also time is wasted as the machine operators need to fill in the measurements by hand rather than the measurement device automatically reporting the data.

4.2.3 Archiving process control

4.2.3.1 Procedure

The last phase of process control is archiving the measurement results. For process control this contains the process controls sheets, digital and on paper, as visualised in Figure 4.5

The current procedure instructs the operator to archive the documentation according to the (title is translated): ”WI-TT-60-003 Traceability and archiving of product related quality documents”. (Westerhof, 2023). In this work instruction, it is stated that out of the process control measurement results, the measurement results are checked and later stored in the cloud. (Legtenberg, 2022)

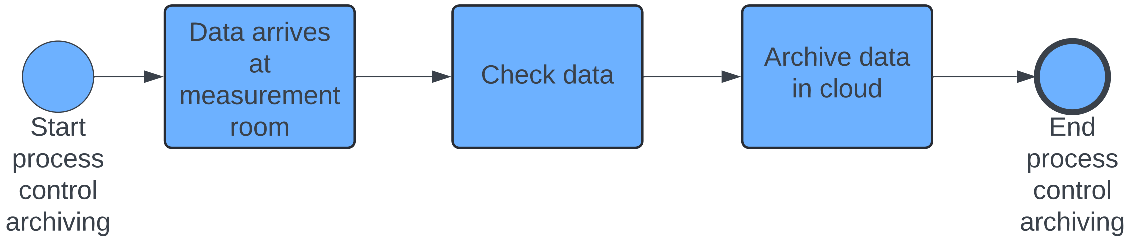


Figure 4.5: Current process control archivation

4.2.3.2 Unclarities and value stream

As is notable, this procedure is quite short. No distinction is made between handwritten and digital measurement data. As a result, the control plan that are filled in on paper are not stored somewhere, but thrown away after check and can never be traced back. This makes it not possible to for instance perform statistical analysis on the measurement data. Next tot that, the online data is not analysed during or after the production process, but only when customers request measurement data after the production process. This is not indicated in one of the procedures. Discussing the value stream, paper and time is wasted in this phase as useful measurement data is thrown away. The time that was put in collecting this data is then also thrown away.

4.3 Chapter conclusion

Chapter 4 served for giving insight into the current situation at Technology Twente, regarding their process control procedures. This was done by firstly discussing the current existing process control procedures and then discussing their unclarities and value stream.

5 Proposed future state - Case study

The first phase of the constructed method in Chapter 3, was executed in Chapter 4. In this chapter, the future state mapping will be executed. This will be done by investigating the unclarities and value stream. Then the following method chunks will be used to map the future state; AQL, SPC, digitalisation and full-team involvement. Firstly, per phase influenced by process control the proposed changes will be explained and visualised. Afterwards, the changes in the overall production process will be discussed and visualised.

5.1 Preparing process control

Following the constructed method, the following procedure for preparing process control at Technology Twente is proposed in Figure 5.1.

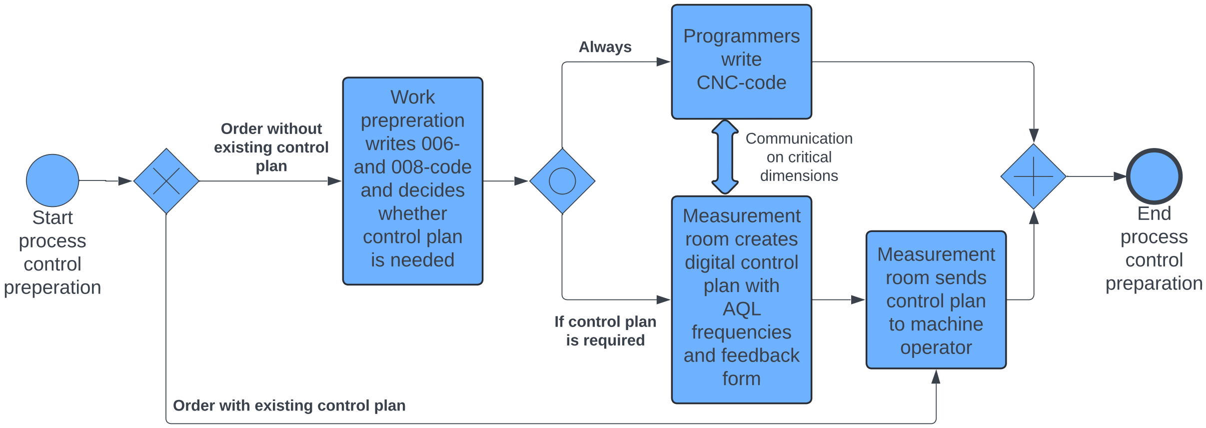


Figure 5.1: Future process control preparation

To solve the unclarity of who decides to use a control form for process control, now during the development of the 006- and 008-code, the work preparation should decide whether to use a control form. According to quality experts at Technology Twente, a control plan is needed when the product meets at least one of the following properties:

- The batch size is larger then 50
- Product has a relative large production time
- Raw material is difficult to gather
- The dimensions require a very tight accuracy (μmm order of magnitude)

To clarify the measurement frequency decision, AQL should be used when the customer does not provide clear instructions. The critical dimensions should be decided upon in communication between the programmers and the measurement room workers. As can be seen, the control form should be digitalised to save time and paper. The last proposed change is the addition of the feedback form. With this feedback form. full-team involvement is added to the process by allowing the machine operators to give feedback on process control components such as frequencies or critical dimensions.

5.2 Executing process control

Following the constructed method, the following procedure for executing process control at Technology Twente is proposed in figure 5.2.

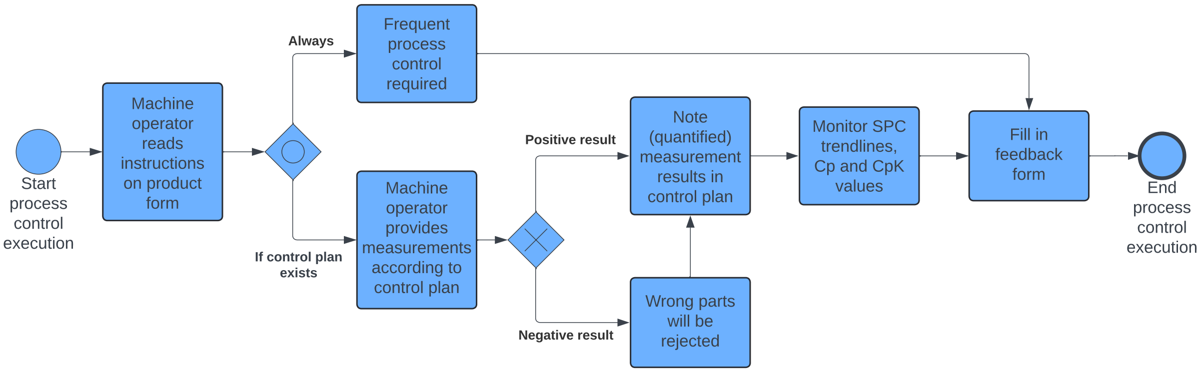


Figure 5.2: Future process control execution

Starting off, it is now clarified the machine operator is responsible for reading the instructions on the product form and executing the measurements according to the control plan. This means that at the control plan, during preparation it needs to be clearly defined where the measurements need to be done. Products that fail the inspection need to be rejected and all measurements should be noted in the digital control plan, quantified if possible. By implementing SPC, less rejections should occur lowering the wasted materials. In this phase, the feedback form can be filled in digitally to give feedback on the execution phase by the machine operator.

5.3 Archiving process control

Following the constructed method, the following procedure for archiving process control at Technology Twente is proposed in Figure 5.3.

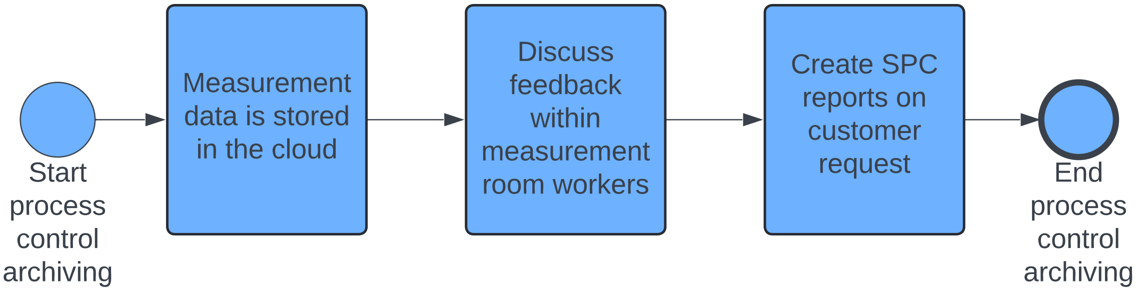


Figure 5.3: Future process control archivation

In the proposed future state, all data is digital and it can thus be stated that all data should be stored in the cloud. This then allows for later SPC reports on customer request, but also when the quality engineer requests insight when rejection rates are still high. A second huge difference is that the control forms do not need to be scanned in, but can easily be saved inside the cloud. Another change is that now in this phase, the feedback forms can be discussed within the measurement room workers, to for the next production run make possible adjustments to for instance the measurement frequency. Thus full-team involvement strategy allows for lower or higher measurement frequencies, which can respectively lower time waste or material waste.

5.4 Proposed future production process

To the overall production process, not that much will be changed. The new BPMN of the production process at Technology Twente is visualised in Figure 5.4 on the next page.

The most important changes are already elucidated in the sections above, namely the addition of SPC, AQL, full-team involvement and digitalisation. Digitalisation has influence on the overall production process. Due to digitalisation, paper is not printed out and moved between locations in the fabric anymore. Next to that, also a feedback form is introduced and will digitally be moved between the three phases of production.

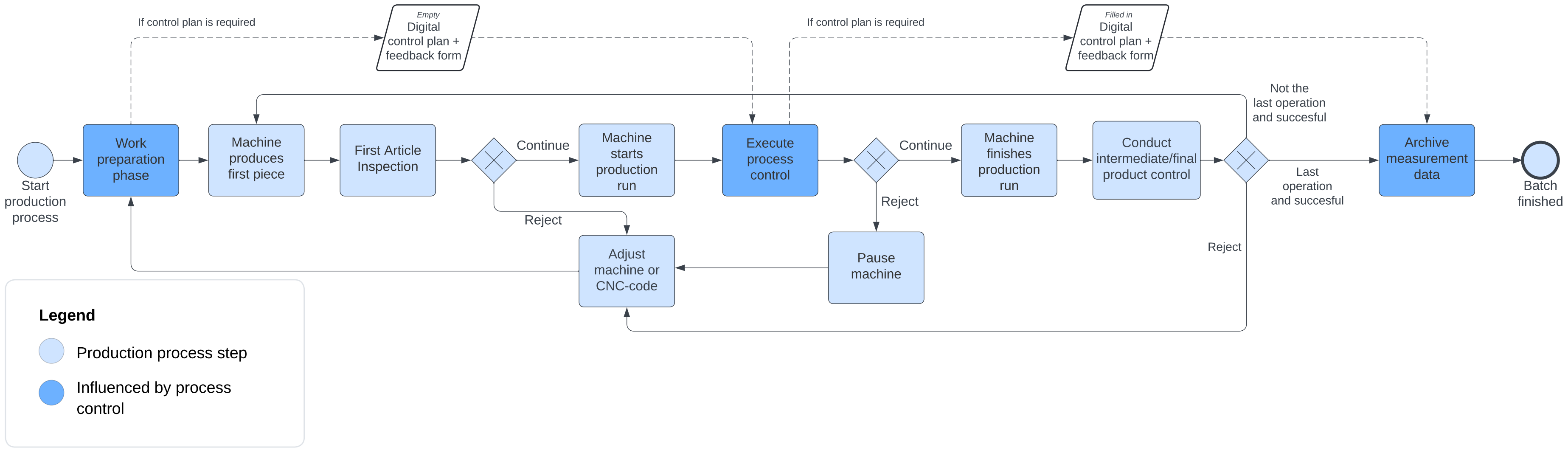


Figure 5.4: Future production process

6 Method validation - Case study

The method can be considered as validated, if the measurable action problem is solved, thus when the quality costs can be decreased with 15% to meet the tightened KPI goals. As found in the problem cluster presented in Subsection 1.2.2, this can be obtained by reducing the wasted resources; materials, time and paper. Therefore, in this subsection, the constructed method will be validated by reviewing the impact on the waste of the above resources. The reduce in waste of materials will be analysed by reviewing how implementing the method could have saved these materials. A reduction in wasted paper and time will be analysed on a qualitative basis by reviewing the proposed future states of Chapter 5.

6.1 Wasted materials

In this paragraph, the production of a large-serie batch will be evaluated. As the serie is larger than 50, following the constructed method results in SPC implementation. In this subsection, the result in wasted materials due to the absence of SPC will be analysed.

At the case company, a folder was received with 246 measurement result files from the measurement machine in the measurement room. Next to that, a pre-programmed Excel file was received in which SPC can be applied. Within this file, using the "collect data", all the measurement result files are extracted into the Excel file in chronological order. The chronological order is necessary, as otherwise SPC cannot be applied. After collecting all the data, measurement data on 17 dimensions of the product is obtained, such as lengths or diameters. However, four dimensions only contain data of a few measurements, so they are discarded as SPC is more reliable for larger series, as argued in Subsection 2.2.2. In the data set, four of the dimensions showed to have rejections. The charts of these four dimensions are demonstrated in Appendix E.

As can be seen and expected, rejections can occur suddenly as can be seen in Appendix E.1. These are errors that cannot be predicted with SPC. On the other hand, SPC can help prevent rejections with the use of charts or by calculating the C_p value, as explained in Subsection 2.2.2. To make the SPC study quantitative, a distinction is made between unpredictable and predictable rejections. Unpredictable rejections can be defined as rejections that are not in line with the current trend line of the chart. Examples are the 39th or 40th measurement of Figure 6.1. Predictable rejections are then defined as measurements that are in line with the current trend line. In Figure 6.1 below, a zoom in is made on Appendix E.1 to clarify these concepts. A rejection can be seen at the 8th measurement. The first seven measurements were done at one day. If the constructed method was used, thus if SPC was implemented before, after the seventh measurement a clear uptrend could have been noticed, allowing for adjustments to be made before the machine started producing the next day. Therefore the 8th measurement is a predictable rejection and the 19th measurement can be considered a unpredictable rejection. The reduction of unpredictable rejections will be discussed after the predictable rejections.

Based on the four analysed chart in Appendix E and the definitions of predictable and unpredictable rejections, Table 1 is constructed. As can be noticed out of 37 rejections, 15 could have been predicted with the use of trend line analysis within SPC.

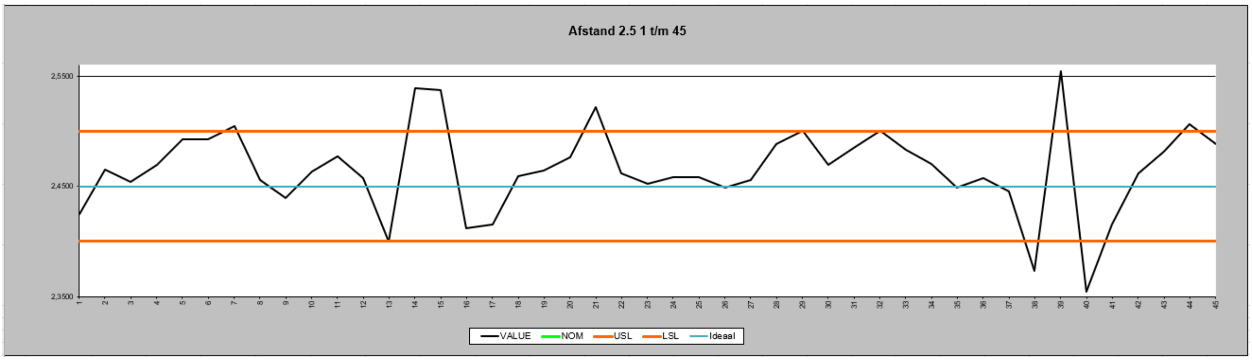


Figure 6.1: Distance 2.5, measurements 1 to 45

	Distance 2.5	**Distance 1.5**	**Distance 0.8 li**	**Distance 0.8 re**
Predicatble rejections	10	4	0	1
Unpredictable rejections	15	6	1	0
Total rejections	25	10	1	1

Table 1: Total rejections

Another way to implement SPC is by calculating the C_p and C_pk value as explained in Subsection 2.2.2, to see whether the production process is in stable state. Looking at Appendix E.2, it can be noticed that after the rejection at the 111th measurement, the spread starts increasing. Next to that, during the whole process the measurements are not that organised along the ideal. As said, the requested dimension is 1,5 mm. The UTL is 1,6mm and the LTL is 1,4mm. As the first rejection occurs at the 111 measurement, an analysis is done on the first 110 measurements and all measurements. Next to that, the first till 178 and 246 measurements are analysed as this can give insight in the change of the C_p and C_pk values over time. This results in table 2 below.

	Measurements 1-110	**Measurements 1-178**	**Measurements 1-246**
Standard deviation	0,0216	0,0331	0,0565
Average	1,4524	1,4594	1,4852
C_p Value	1,5408	1,0067	0,5895
C_pK value	0,8074	0,5984	0,5025

Table 2: C_p & C_pk values

In Table 2, it can be seen that for the first 110 measurements, the process was fulfilling C_p value standards as described in Subsection 2.2.2. However, as time progresses the overall C_p value started decreasing drastically. If SPC was implemented at Technology Twente, corrections could have been made when C_p values decreased. Next to that, it could have been noticed that the C_pk value was already below standards. Monitoring the C_p and C_pk values would have reduced the unpredictable rejections discussed above, since that if the process had less spread and was closer to the mean, as sudden peaks could then still result the measurement to be within the tolerance limits.

6.2 Wasted time & paper

The other two wasted resources that the constructed method is aimed to reduce are paper and time. In this section, it will reflected upon to what degree paper and time waste is reduced by implementing the constructed method at Technology Twente, by evaluating both the whole production process and later per phase.

The reduction of paper waste occurs at all phases of the production process. From now on, the control plan will not be printed out by the measurement room, but will be kept digital. Next to that, the feedback form introduced will also be implemented digitally. Thus the paper waste will be reduced to zero paper wasted by implementing the constructed method and this will also reduce the time of printing and moving the paper. This last reduction is not measurable, as it is difficult to estimate the time to print out paper and the time to move paper in-between the stations during production.

Discussing the wasted time, lots of opportunities present itself in all different phases of the production process that are influenced by process control. Starting off with the preparation phase, solving the unclarities in decisions will save the workers from different departments lots of discussion time. The person who makes the decision to use a control plan is now clear as well as how this decision is made is also clear. Measurement frequency and dimensions are clarified.

In the execution phase, it is clarified the machine worker needs to provide the measurement results, either by himself at the work floor if possible or in the measurement room. Also, quantified measurement results are required enabling later SPC possibilities. By directly filling in the digital measurement data, direct SPC charts and values can be identified, saving time.

At the archiving phase, the control plan does not need to be scanned in for archiving, but this can be done automatically, which saves a lot of time. By discussing the feedback of the machine operators in this phase, adjustments on the production process can be made to later save time or save materials after respectively reducing or increasing the measurement frequency. As data is quantified if possible and digitalised in the previous phase, SPC reports on customer request can also be created in less time.

6.3 Chapter conclusion

As stated in the introduction of this chapter, the method can be considered as validated when it can be shown the method contributes in lowering the wasted resources. Summarising the waste reduction of the three resources:

- Material waste
  - With the use of SPC, rejections could have been prevented.
  - 15 out of 37 rejections can be identified as predictable and could have been prevented with a trend line analysis.
  - 22 out of 37 rejections can be identified as unpredictable and cannot be claimed to be fully prevented. However, by evaluating the C_p and C_pk value during production, adjustments could have been made earlier on, that results in sudden differentiation's to less likely fall outside the tolerance limits.

- Paper waste
  - Paper waste is reduced from x papers used and thrown away to zero by implementing the constructed method, as it insists to digitalise the whole process control process.
- Time waste
  - Discussion time is saved, by solving the unclarities during preparation, execution and archiving phase.
  - Not printing out and scanning in the control plan saves time.
  - Quantifying data directly saves time when performing SPC

For a batch size of at least 50 products, a decrease of at least 15% in wasted materials is shown. For the wasted paper, a reduction from x papers to 0 was achieved. However, a quantification in time reduction was not possible, making the claim of the method being fully valid yet not possible.

7 Conclusions and Recommendations

7.1 Conclusion

It can be concluded that machining SMEs can optimise the efficiency and effectiveness of their process control procedure, by implementing the method that was constructed in this thesis, visualised in Figure 7.1. The definitions of the method chunks that are numbered per phase of the cycles, can be found in Section 3.5. The constructed method, PCOM-MSME, is the solution to the main research question as the method makes process control more efficient and effective. The claim that the core problem and action problem of Technology Twente are solved, cannot be fully made, since it is not yet possible to see a decrease in quality costs of at least of 15%. Only a minimum of 15% reduction in wasted materials after method implementation was proven, if the batch size is larger than 50.

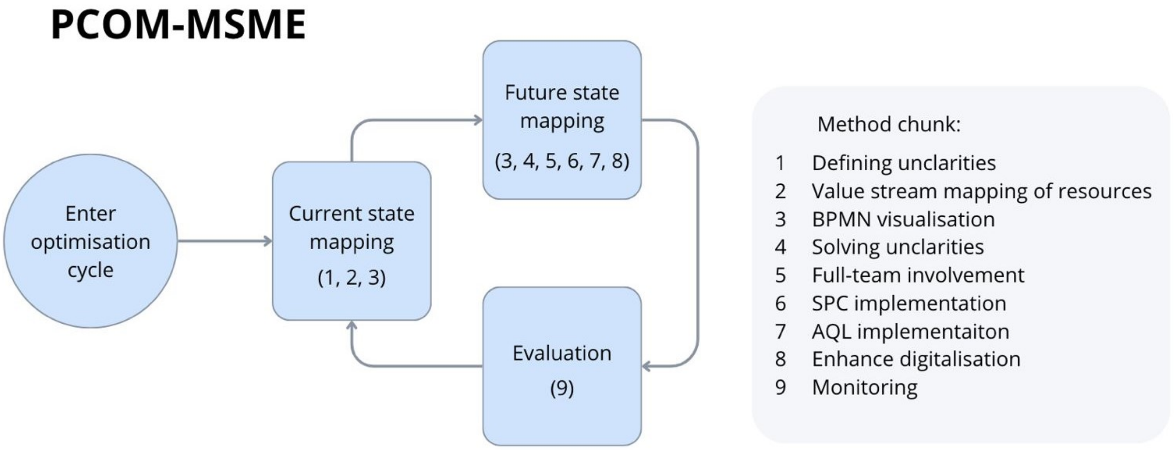


Figure 7.1: PCOM-MSME, a method for process control optimisation at machining SMEs

As a validation, the method is implemented at Technology Twente, a machining SME. By implementing the constructed method in Chapters 4 and 5, in Chapter 6, it was demonstrated that the number of wasted resources; materials, paper and time, can be reduced. To allow for further implementation at Technology Twente, in Section 7.2, recommendations are given.

7.2 Recommendations

Following the conclusion, it is recommended for Technology Twente to implement the method constructed in the thesis and to further evaluate the proposed future state as further validation. Apart from this thesis, a small report was written for Technology Twente, with more practical solutions, In this section, an overview of specific recommendations to Technology Twente for optimising their process control will be given for when Technology Twente decides to further implement the method:

- Implement digitalisation software like High-QA to digitalise the control plan generation
- Implement Bluetooth measurement devices to allow machine workers to automatically fill in the digital control plan
- Use the SPC Excel sheet out of 2007 or the Excel sheet from ASML for series larger than 50
- Use AQL to determine measurement frequencies
- Format the control plan such that it forces machine workers to quantify their measurement data when possible
- Closely monitor the digitalisation of process control

7.3 Limitations

In Subsection 3.1.1, the requirements for the constructed method are established. As can be noticed, the more requirements that are established, the more situation specific the method becomes. A limitation of the thesis and the constructed method is that the amount of requirements a researcher can generate severely influences the situation specificness of the constructed method. Next to that, it also reduces the validity as to some degree subjectivity plays a role. This limitation was tackled by conducting as much interviews at multiple machining SMEs, to fully understand what requirements a method for machining SMEs can be.

As discussed, the validation part of the thesis has some drawbacks. Due to time constraints, it is not possible to fully implement and analyse the constructed method. Therefore, the quantitative part of the validation was done on historical data with the reasoning that if the method was constructed before, SPC would have been implemented and would have saved more than 15% of the wasted materials.

Next to that, when the method was implemented at a product at Technology Twente that would not have met any of the in Section 5.1, the result would be that SPC would not have been necessary. Therefore, implementing the method on the production of a product that would not have needed SPC implementation, quantitative validation would not have been possible.

The last limitation lies within the qualitative validation. It is possible to validate that for instance full-team involvement contributes to reducing the wasted resources, but it is difficult to make this quantifiable.

7.4 Further research

For this thesis, the MPSM cycle was used to develop a method for process control optimisation. As stated in subsection 3.1.1, this solving approach limits the research to developing an optimisation approach rather then developing a method for setting up process control for a machining SME.

In further research, the DSRM cycle, design-science research method, can be utilised to, with situational method engineering to develop a method for setting up process control for a machining SME. Than for even further research, these two methods can then be used together as a package for machining SMEs.

As explained in Section 3.4, the final constructed method does not need to be tailored yet as the method was already assembled specific to the situation. Therefore, in further research, the current constructed method can be be further tailored when changes in the machining industry occur, by following the tailoring approach that was discussed and also visualised in Appendix C.3.

The last further research suggestion flows from the conclusion. To fully claim the core problem to be solved and the constructed method is validated, the reduction in quality costs need to be analysed after a longer time period after implementation.

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Appendices

A Quality 4.0 transition framework

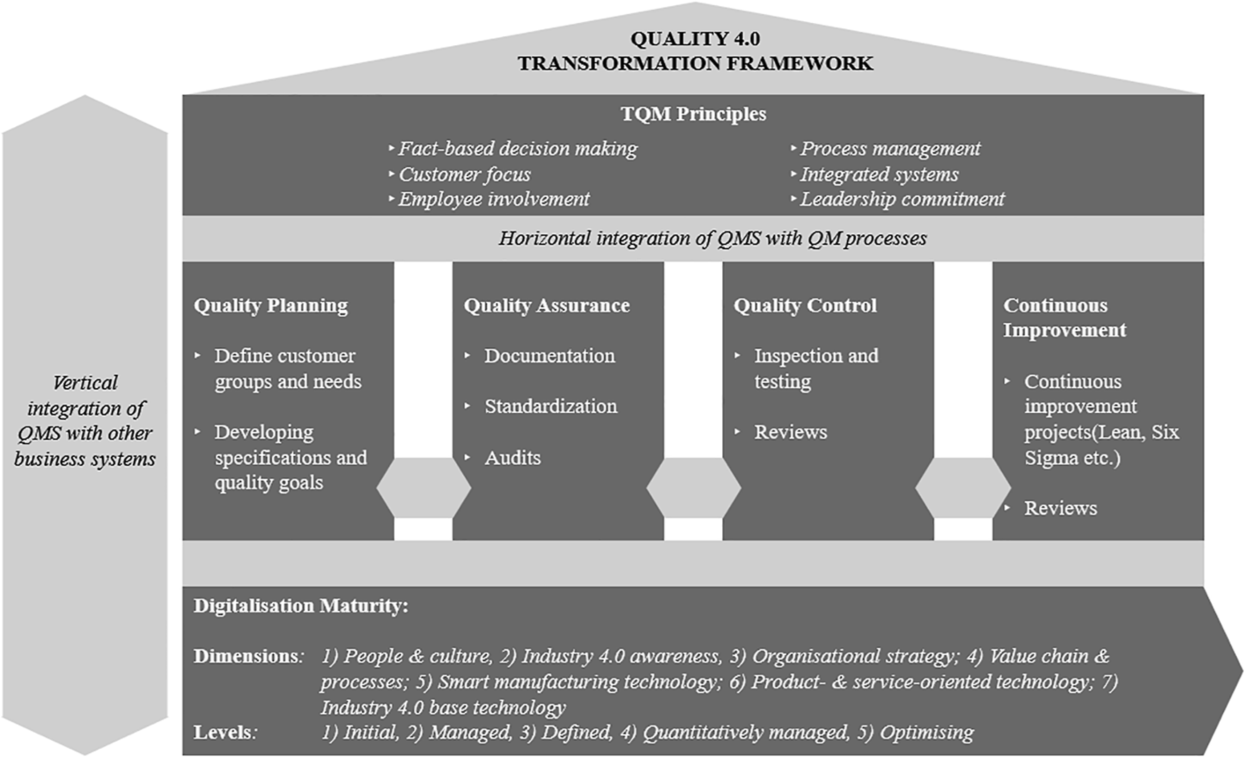
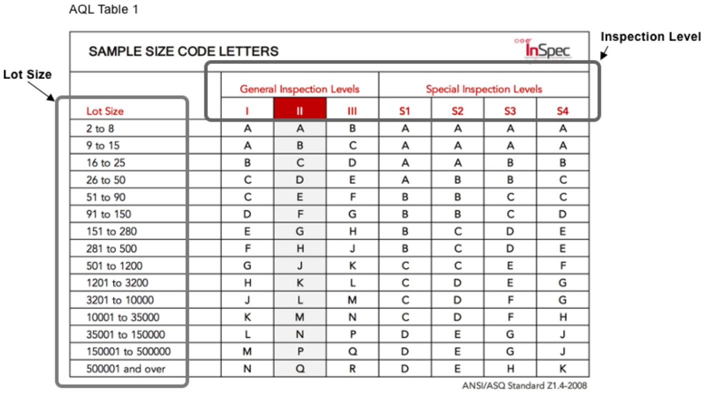


Figure A.1: Quality 4.0 transformation framework (Prashar, 2023, Figure 2)

B AQL Tables

B.1 Sample size code letters



AQL Table 1

Lot Size

Inspection Level

SAMPLE SIZE CODE LETTERS

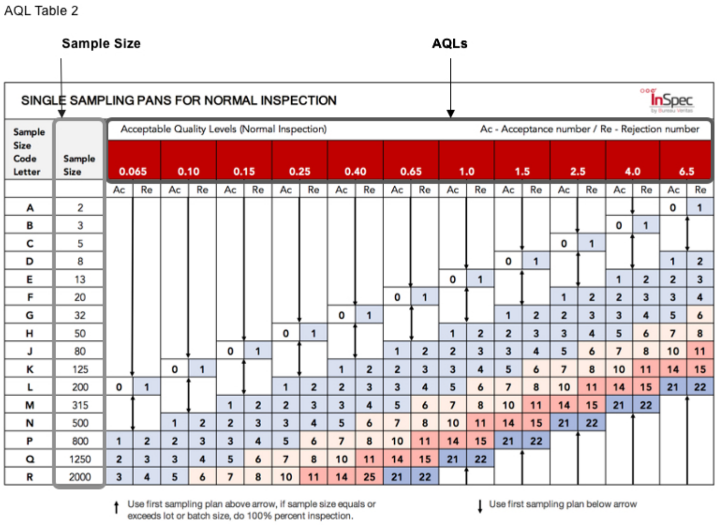
InSpec

Lot Size	General Inspection Levels I	General Inspection Levels II	General Inspection Levels III	Special Inspection Levels S1	Special Inspection Levels S2	Special Inspection Levels S3	Special Inspection Levels S4
2 to 8	A	A	B	A	A	A	A
9 to 15	A	B	C	A	A	A	A
16 to 25	B	C	D	A	A	B	B
26 to 50	C	D	E	A	B	B	C
51 to 90	C	E	F	B	B	C	C
91 to 150	D	F	G	B	B	C	D
151 to 280	E	G	H	B	C	D	E
281 to 500	F	H	J	B	C	D	E
501 to 1200	G	J	K	C	C	E	F
1201 to 3200	H	K	L	C	D	E	G
3201 to 10000	J	L	M	C	D	F	G
10001 to 35000	K	M	N	C	D	F	H
35001 to 150000	L	N	P	D	E	G	J
150001 to 500000	M	P	Q	D	E	G	J
500001 and over	N	Q	R	D	E	H	K

ANSI/ASQ Standard Z1.4-2008

Figure B.1: AQL Sample size code letters, ANSI ASQ Z1.4 standards (Bureau Veritas, n.d., Figure 1)

B.2 AQL Rejection numbers



AQL Table 2

Sample Size

AQLs

SINGLE SAMPLING PANS FOR NORMAL INSPECTION

InSpec by Bureau Veritas

Acceptable Quality Levels (Normal Inspection)

Ac - Acceptance number / Re - Rejection number

Sample Size Code Letter	Sample Size	0.065		0.10		0.15		0.25		0.40		0.65		1.0		1.5		2.5		4.0		6.5	
		Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re
A	2																			↓		0	1
B	3																	↓		0	1	↑	
C	5															↓		0	1	↑		↓	
D	8													↓		0	1	↑		↓		1	2
E	13											↓		0	1	↑		↓		1	2	2	3
F	20									↓		0	1	↑		↓		1	2	2	3	3	4
G	32							↓		0	1	↑		↓		1	2	2	3	3	4	5	6
H	50					↓		0	1	↑		↓		1	2	2	3	3	4	5	6	7	8
J	80			↓		0	1	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11
K	125	↓		0	1	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15
L	200	0	1	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22
M	315	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑	
N	500	↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑			
P	800	1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑					
Q	1250	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑							
R	2000	3	4	5	6	7	8	10	11	14	25	21	22	↑									

↑ Use first sampling plan above arrow, if sample size equals or exceeds lot or batch size, do 100% percent inspection.

↓ Use first sampling plan below arrow

Figure B.2: AQL Rejection numbers (Bureau Veritas, n.d., Figure 2)

C Situational method engineering

C.1 Process-driven requirement selection

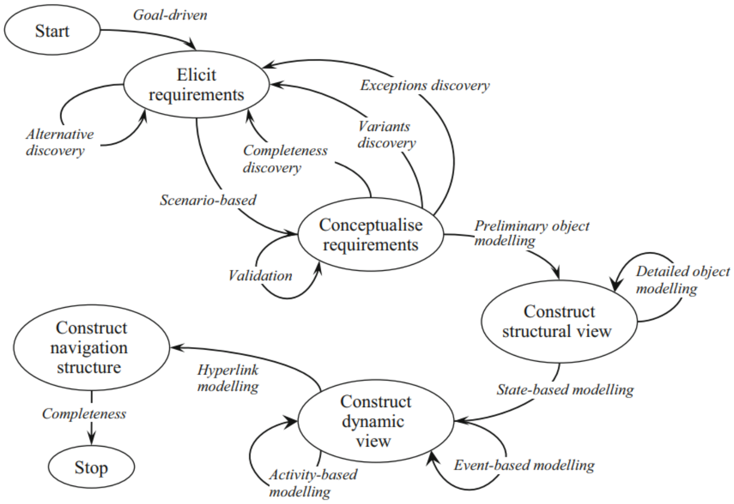


Figure C.1: Process-driven requirement selection (Ralyté, 2002, figure 7)

C.2 PC-driven method chunk selection

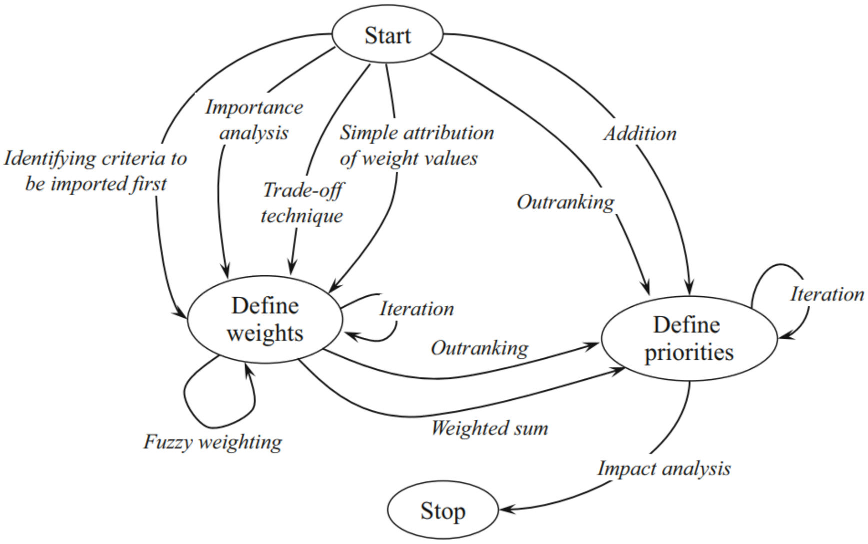


Figure C.2: PC-driven method chunk selection (Kornyshova et al., 2007, figure 2)

C.3 Method tailoring

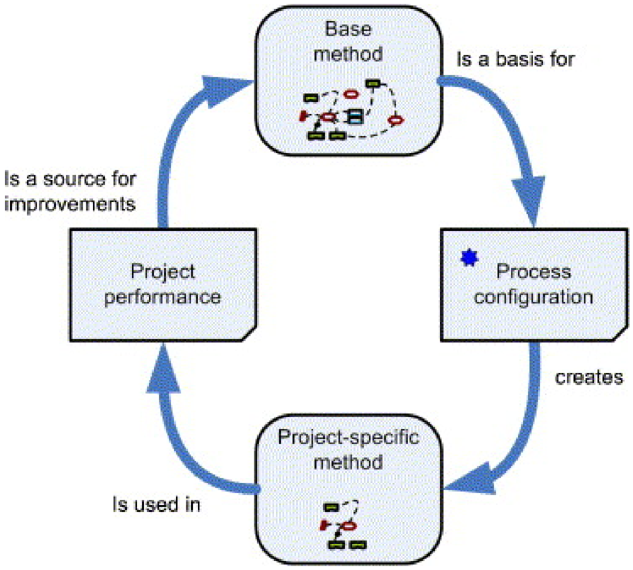
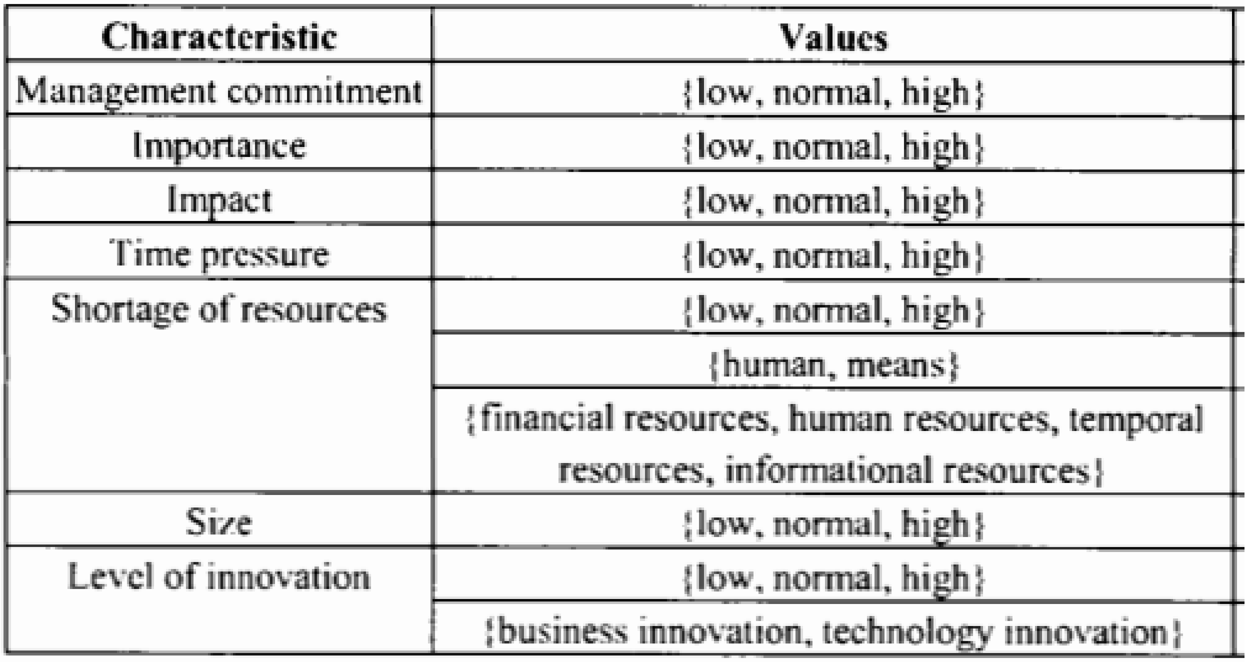


Figure C.3: Continuous evolution approach for method tailoring (Bajec et al., 2007, figure 3)

D Project Characteristics tables

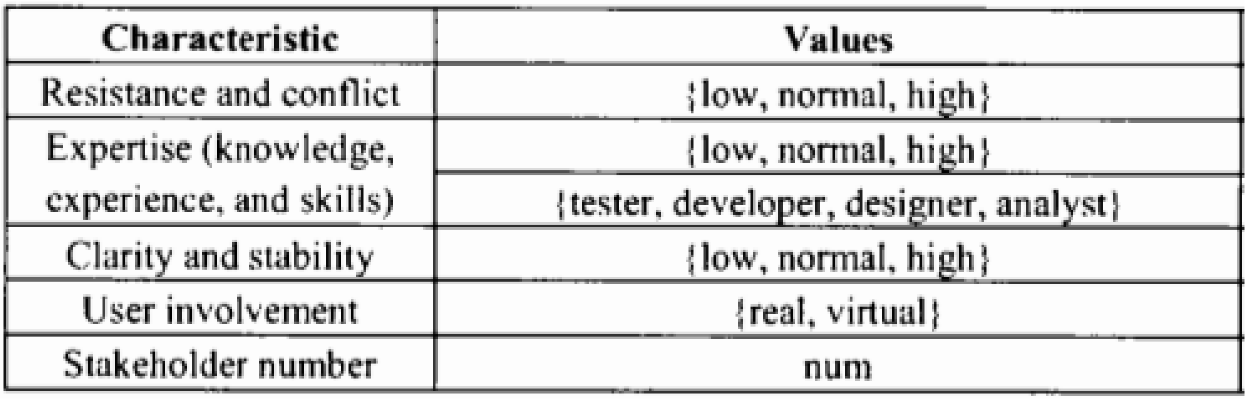
D.1 Organisational project characteristics



Characteristic	Values
Management commitment	{low, normal, high}
Importance	{low, normal, high}
Impact	{low, normal, high}
Time pressure	{low, normal, high}
Shortage of resources	{low, normal, high}
	{human, means}
	{financial resources, human resources, temporal resources, informational resources}
Size	{low, normal, high}
Level of innovation	{low, normal, high}
	{business innovation, technology innovation}

Figure D.1: Organisational project characteristics table (Kornyshova et al., 2007, table 1)

D.2 Human project characteristics



Characteristic	Values
Resistance and conflict	{low, normal, high}
Expertise (knowledge, experience, and skills)	{low, normal, high}
	{tester, developer, designer, analyst}
Clarity and stability	{low, normal, high}
User involvement	{real, virtual}
Stakeholder number	num

Figure D.2: Human project characteristics table (Kornyshova et al., 2007, table 2)

D.3 Method chunk selection with MCDA

Methodology	**Method chunk**	**Size (0,3)**	**Level of innovation (0,3)**	**Expertise (0,2)**	**Clarity & Stability (0,2)**	**Weighted sum**
Project description	Constructed method	Low	High, Business & Technology	High & Analyst	High	1
Six Sigma (DMAIC)	Define	x	x	x	x	1
	Measure	x		x	x	0,7
	Analyse	x		x		0,5
	Improve	x	x			0,6
	Control	x	x	x		0,8
Six Sigma (SPC)	SPC	x	x	x	x	1
Lean	Identify value	x			x	0,5
	Value stream mapping	x			x	0,5
	Create flow	x				0,3
	Establish pull	x	x			0,6
	Continuous improvement	x			x	0,5
TQM	Customer-focus	x				0,3
	Full-team involvement	x	x		x	0,8
	Continuous improvement	x			x	0,5
	Data-driven decision making	x		x		0,5
BPM	Analyse	x		x	x	0,7
	Model	x		x	x	0,7
	Implement	x	x			0,6
	Monitor	x		x		0,5
	Optimise	x	x			0,6
AQL	AQL	x	x	x	x	1

Table 3: MCDA analysis and weighted sum

E SPC charts

E.1 SPC chart distance 2.5

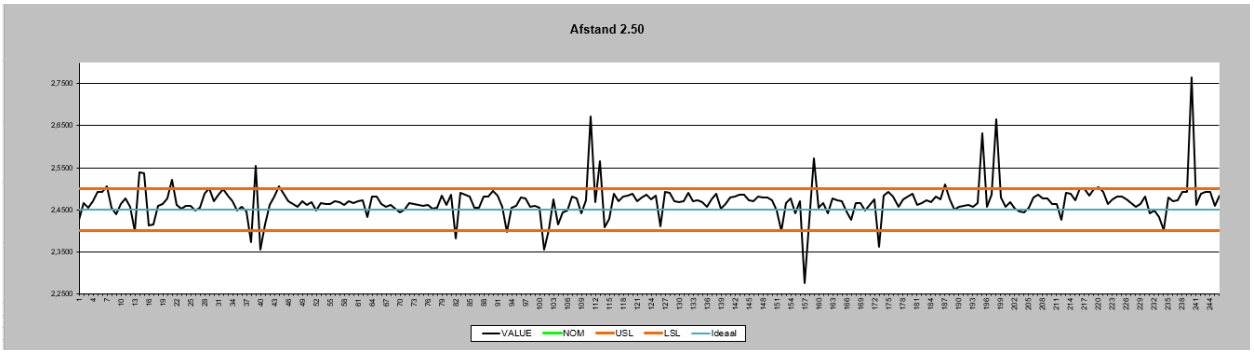


Figure E.1: Distance 2.5

E.2 SPC chart distance 1.5

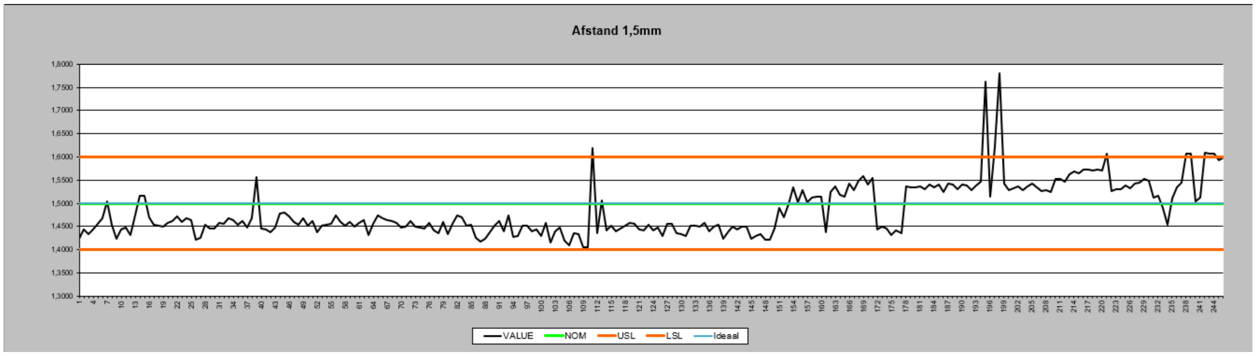


Figure E.2: Distance 1.5

E.3 SPC chart distance 0.8 li

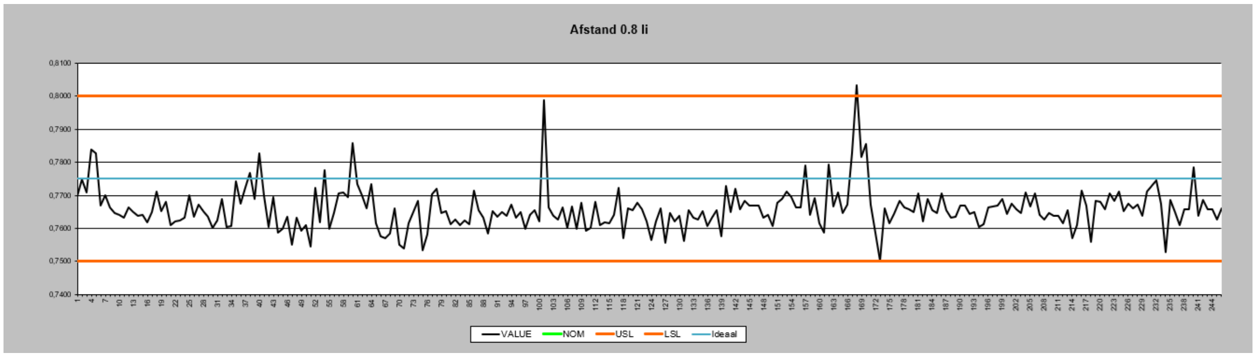


Figure E.3: Distance 0.8 li

E.4 SPC chart distance 0.8 re

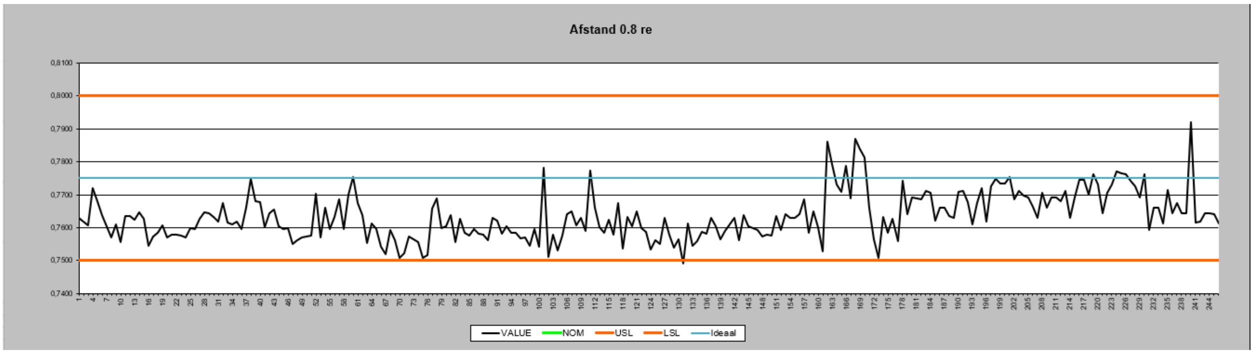


Figure E.4: Distance 0.8 re