TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING

Department of Electrical Power Engineering and Mechatronics

QUALITY IMPROVEMENT OF THE MANUFACTURING PROCESS OF FREQUENCY CONVERTERS USING THE SIX SIGMA METHODOLOGY AND THE DMAIC CYCLE

SAGEDUSMUUNDURITE TOOTMISPROTSESSI KVALITEEDI PARANDAMINE, RAKENDADES *SIX SIGMA* METODOLOOGIAT NING KASUTADES DMAIC-TSÜKLIT

MASTER THESIS

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Tallinn, 2017

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material.
All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Thesis is in accordance with terms and requirements

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Accepted for defence

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Chairman of theses defence commission: ....
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Quality improvement of the manufacturing process of frequency converters using the Six Sigma methodology and the DMAIC cycle

Lauri Kalm, student code 153773AAAM, May 2017. – 71 pages.

TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Electrical Power Engineering and Mechatronics

Supervisor: Argo Rosin
Co-supervisor: Kaarel Lahtvee

Key words: Continuous Improvement, Lean, Six Sigma, DMAIC, manufacturing process, production, frequency converter, reliability, performance indicator

Summary:

The thesis consists of 71 pages, it contains seven tables, 19 figures, 11 charts and seven diagrams.

The purpose of this thesis is to define the factors threatening the reliability of frequency converters, perfect a company's manufacturing process and improve the business performance indicator at that company's production line. The thesis was compiled in Harjumaa, in the company ABB. It is based on an internal ABB project called „Continuous Improvement 4Q project", that the thesis' author compiled in the spring of 2017.

The thesis consists of two main parts. The first part is the theoretical part where the history and origins of Lean, Six Sigma and the DMAIC cycle are explained. Also, the DMAIC cycle's tools and equations are presented that can be used to successfully construct a Six Sigma project. The second part of the thesis consists of the „Continuous Improvement 4Q project" that the author made in ABB. There are practical examples presented of how some of the tools belonging to the DMAIC cycle are used. At the end of the project, the improvement plan's corrective actions are presented that are going to be used to get the company's business performance indicator back into stable conditions. Also, a cost saving plan is presented to show how much the company will save financially because of this project.

Sagedusmuundurite tootmisprotsessi kvaliteedi parandamine, rakendades *Six Sigma* metodoloogiat ning kasutades DMAIC-tsüklit

Lauri Kalm, üliõpilaskood 153773AAAM, mai 2017. – 71 lk.

TALLINNA TEHNIKAÜLIKOOL
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Võtmesõnad: pidev täiustamisprogramm, *Lean*, *Six Sigma*, DMAIC, tootmisprotsess, tootmine, sagedusmuundur, töökindlus, tulemuslikkuse näitaja

Referaat:

Lõputöö koosneb 71 lehest ning sisaldab seitset tabelit, 19 joonist, 11 graafikut ning seitset diagrammi.

Käesoleva lõputöö eesmärgiks on defineerida sagedusmuundurite töökindlust ohustavad faktorid, parendada ettevõtte tootmisprotsessi ning täiustada selle ettevõtte ärilise tulemuslikkuse näitajat uuritaval tootmisliinil. Lõputöö on koostatud Harjumaal, ettevõttes ABB. See põhineb ABB-sisesel parendusprojektil nimega „Pideva täiustamise 4Q projekt“, mille lõputöö autor koostas 2017. aasta kevadel.

Lõputöö koosneb kahest põhiosast. Esimene osa on teoreetiline osa, kus tutvustatakse *Lean'i*, *Six Sigma* ning DMAIC-tsükli ajalugu ning põhimõtteid. DMAIC-tsükli tööriistad ning valemid, mida ühe *Six Sigma* projekti läbiviimiseks vaja läheb, seletatakse samuti lahti. Lõputöö teises osas tutvustatakse autori poolt tehtud „Pideva täiustamise 4Q projekti“, mis koostati ettevõttes ABB – tuuakse praktilisi näiteid, kuidas osasid DMAIC-tsükli tööriistasid kasutatakse. Projekti lõpus on välja toodud täiustamisprogramm koos parandustegevustega, mida hakatakse ellu viima ning kasutama, et ettevõtte tulemuslikkuse näitaja saada tagasi stabiilsetesse tingimustesse. Samuti, esitatakse töö lõpus kulude kokkuhoiu plaan, et näidata, kui palju säästab ettevõte keskmiselt aastas rahaliselt, tuginedes antud projekti analüüsile ning tulemustele.

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TALLINN UNIVERSITY OF TECHNOLOGY
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.... 2017

ASSIGNMENT OF THE MASTER THESIS

Lauri Kalm, student code 153773AAAM

Thesis topic: Quality improvement of the manufacturing process of frequency converters using the Six Sigma methodology and the DMAIC cycle.

The assignment: Defining the factors threatening the reliability of frequency converters, perfecting a company's manufacturing process and improving the business performance indicators at the company's production line.

Initial data:

1. ABB 4Q report
2. 4Q Basic 2.0 training
3. „Lean Six Sigma & Minitab – The Complete Toolbox Guide for Business Improvement"
4. Data about the performance indicators provided by ABB's databases
5. Data about the frequency converters and production line provided by ABB's databases

List of tasks to be solved:

1. Review of the Continuous Improvement methodologies and their origins.
2. Review of different programs and tools presented in the Lean methodology.
3. Review of Six Sigma and its applications.
4. Description of distinct tools that can be used in the DMAIC cycle.
5. Analysis of the performance indicator that is over the target at ABB's Solar production line, using the tools presented in the DMAIC cycle.
6. Determination of corrective actions and improvement plan to eliminate this vital problem.
7. Estimation of possible financial savings according to the improvement plan implementation.

Supervisor:	Accepted the assignment:
Argo Rosin	Lauri Kalm ....
Senior Research Scientist	Student

1. PREFACE

This thesis was issued on the author’s initiative and the topic was chosen in collaboration with ABB. The thesis was put together in ABB and all of the main data used in the thesis was provided by ABB’s databases. The thesis is based on a „Continuous Improvement 4Q“ project and the training program that consisted of books, classes and online courses was provided by the company. Additional information was given to the author by the author’s co-supervisor Kaarel Lahtvee.

The thesis’ author would like to thank the engineers at ABB for the guidance and the coursemates at Tallinn University of Technology for the assistance with the formalization of the work. Most of all the author would like to thank co-supervisor Kaarel Lahtvee and supervisor Argo Rosin who both helped with the finishing of the thesis.

2. LIST OF ABBREVIATIONS

TPS – Toyota Production System
KPI – Key Performance Indicator
COPQ – Cost of Poor Quality
CTQ – Critical to Quality
VoC – Voice of Customer
DPU – Defects Per Unit
UCL – Upper Control Limit
LCL – Lower Control Limit
USL – Upper Specification Limit
LSL – Lower Specification Limit
MSA – Measurement System Analysis
PCBA – Printed Circuit Board Assembly
SPC – Statistical Process Control
PVS – Photovoltaic System

3. INTRODUCTION

The subject of the thesis was chosen on the author’s initiative in collaboration with ABB – the thesis was put together in the company. Since the thesis’ author is interested in learning Six Sigma and there is a requirement to do a Continuous Improvement 4Q Project in ABB, it is logical to combine the two for the purpose of profoundly understanding Six Sigma and apply for the Master’s degree.

The subject is topical because manufacturing companies are progressively trying to focus on quality and improve their knowledge about Six Sigma. Six Sigma can be used as a philosophy of management, a process-measurement methodology, an analysis methodology and a business culture – it can be used in different ways to ensure the quality of a company. Since it reflects in many various fields such as manufacturing, service, logistics and even business, it proves to be an extremely useful subject to be competent in.

There are numerous manuals, books, articles and training programs which can teach Six Sigma, but all of the aforementioned differ in many ways. The novelty of this thesis is to understand most of the tools used in the DMAIC cycle and to categorize the tools into phases so that a Six Sigma project would be constructed in the most logical and beneficial way possible. It is important to identify the useful tools among the less commonly used ones. Also, the subject of the 4Q Project, that was put together in ABB, is relevant in the eyes of the company. In 2016, the process’ performance indicator at a production line in ABB was drifting out of standard conditions and therefore an analysis of the possible root causes prove to be greatly necessary. Such an improvement project has never been done in ABB before, where an entire production line’s performance indicator is put under investigation.

The main assignments of the project are to define the factors threatening the reliability of frequency converters at the unstable production line, perfect the company’s manufacturing process at that production line and improve the business performance indicator. The thesis' assignments include the addtion of the theoretical part of Continuous Improvement, Six Sigma and the understanding of the tools used in the DMAIC cycle.

The thesis consists of two major parts – the theoretical part and a practical part where the 4Q Project is presented. The first part, the theoretical part, consists of the explanations of the history and origins of Lean, Six Sigma and the DMAIC cycle. The DMAIC cycle's tools are presented and put in logical order so that a Six Sigma project could be successfully constructed. The first chapter of the thesis' explains the origins of Continuous Improvement – different methodologies and their creators are listed. The second chapter explains what Six Sigma is in more detail – the Toyota Production System pyramid is used to help define the notion. In the next chapter, the DMAIC cycle is introduced – this is one of the longest chapters in the thesis because it holds the definitions to the different tools used in Six Sigma.

After the definitions of the different tools are given, the practical part of the thesis begins. First, the scope of the 4Q Project is explained and the details about the production line and product, that is under investigation, are given. Next, the project's different steps are introduced and at the end, the improvement actions are listed. Also, the comparison of the conditions is given, what was the performance indicator's index before and what is it after the 4Q Project's improvements are implemented. Based on the comparison and the cost saving calculations, the usefulness of the project is evaluated.

The tools used in the project are selected by the Project Leader, all of the tools belonging to the DMAIC cycle are not needed to be used. The selection depends mainly on the choices made by the project's manager – although the larger the number of tools are used, the more diversely the data can be presented.

The initial data that was needed for the completion of the project and for the thesis include the 4Q Basic 2.0 training, the ABB 4Q Report and data about the performance indicators and the frequency converters production line that were provided by ABB. The training program consisted of books, classes and courses that were all provided by the company as well. The programs that were used to construct the tables, charts and diagrams include Microsoft Excel, Minitab and an ABB's internal Six Sigma guide called the LSS Toolbox. The thesis was constucted during the spring of 2017 in the company ABB and it consists of 71 pages.

4. CONTINUOUS IMPROVEMENT AND ITS ORIGINS

Continuous Improvement as a strategy, methodology and philosophy has been around for a millennia, since the beginning of time. Going back to 2500 BC when people built the colossal pyramids along the river Nile, they were using divison of labor, standardization, gemba walks, one piece flow, teaming and collaboration, visual management, and many other fundamnetals of Continuous Improvement. The history of improvement has been long, but it is being said that the main growth and development of these strategies happened during several industrial revolutions over the past 200 years. Progression has been growing the most in the past three decades. Development of Continuous Improvement has been vast and for that reason definitions and interpretations differ accordingly. This paragraph will explain the history of how Six Sigma evolved and what are the other different methodologies that belong to the Continuous Improvement strategy. [1]

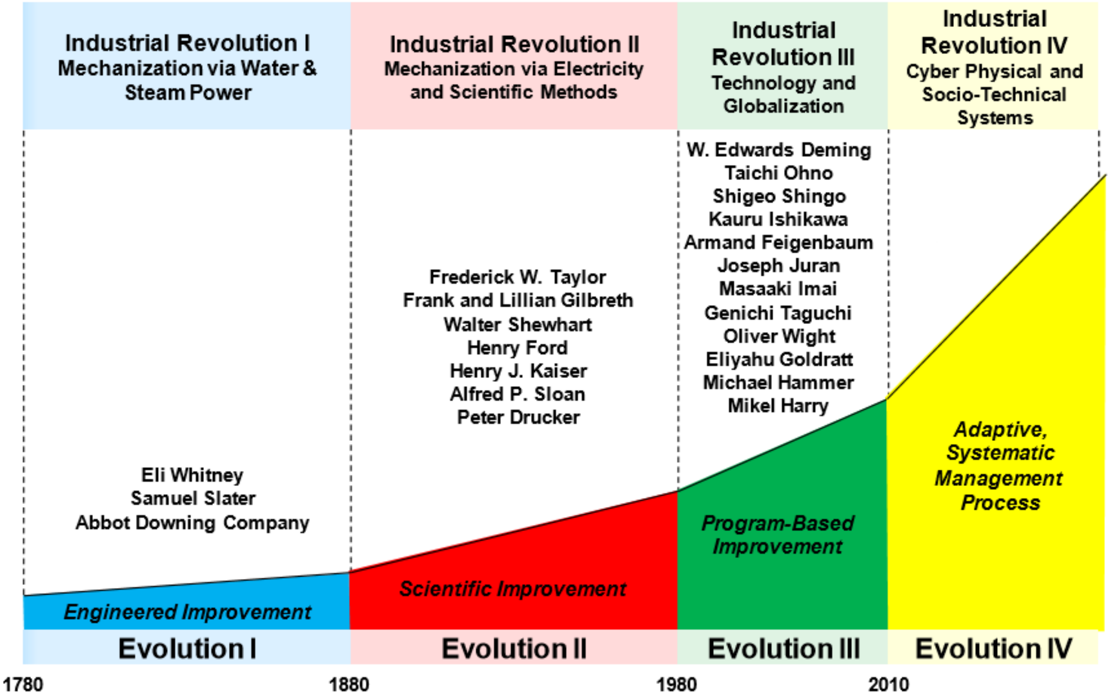


Figure 4.1. The Generations of Improvement [1]

Shown on the figure above (Figure 4.1.) is an illustration chart of the main industrial revolutions that helped shape the understandings of Continuous Improvement to what it is today. It should also be stated that Continuous Improvement is forever evolving, it has not evolved to its final state and probably never will. [1]

The first evolution of improvement occured between the 1780s and the 1880s, fueled by the industrial revolution in Europe and America – this is called the Engineered Improvement phase, where inventors achieved significant gains in productivity by harnessing the power of water and steam, and also standardization. The most important highlights and influences of this evolution include Eli Whitney's cotton gin machine invention, Samuel Slater's textile mill building and Abbott Downing Company's lean progressive assembly operation implementation. All were first glances of more detailed standardization, Lean and Six Sigma (as well as other) methodologies. [1]

The second evolution occured during the period of 1880s to 1980s with a large spike in industrial efficiency. This period is the birth time of scientific management and the discipline of industrial engineering, division of labor, progressive assembly lines, standard methods and waste reduction – this pahse is called Scientific Improvement. Some of the more important improvement highlights and influences include Frederick W. Taylor's overall approach to large-scale manufacturing – Taylor is said to be the father of scientific management, who laid down the fundamental principles of production efficiency methodologies. Other influencial people and their accomplishments include Walter Shewhart, who is known as the father of statistical quality control and who introduced the control chart as a tool for distinguishing variation. Henry Ford was one of the pioneers who adopted Taylor's methods and introduced mass production of cars. Ford is one of the originators of progressive and continuous flow manufacturing. Another influencial person was Alfred P. Sloan, Chairman and CEO of General Motors, who standardized entrepreneurial thinking by keeping risk-taking alive within a hierarchical, rule-bound and decentralized corporation. Sloan oversaw the use of rigorous financial and statistical tools to profitably manage General Motors. [1]

The main pioneers of the second evolution were firstly believed to be Taylor and Ford, who set the standards for assembly line balancing, more efficient equipment and plant layout, time studies, preventive maintenance, quality improvement, downtime reduction and continuous flow. This created a lot of competition and rivalry among the Western organizations. But as it turned out later, the leader of this evolution was undoubtedly a production system from Japan: the Toyota Production System (TPS). TPS, founded by Sakichi Toyoda, is said to be the father of all Continuous Improvement – Lean was evolved and developed from this philosophy – it was created to translate the strategies for Western organizations. [1] [2]

The third evolution took place from the 1980s till the 2010s. This was the era where TPS was ahead of Western organizations and America started to take more notes from Japan's methods. Suddenly, there was a high degree of intrest in improvement. The third evolution is called Program-Based Improvement. America's improvement was motivated by the stiff competiton form the Japanese automotive, consumer electronics, steel, machine tool, and several other industries. The most influencial people of this evolution include Taiichi Ohno, who was the inventor of the Toyota Production System (TPS). Sakichi Toyoda was the founder of TPS, but Taiichi Ohno was the main architect for all the tools, philosophies and ways of thinking. Other famous improvement pioneers were Masaaki Imai, who popularized the methodology of Kaizen in his books „Kaizen" and „Gemba Kaizen", Bill Smith, who is known as one of the fathers of Six Sigma (developed at Motorola in 1986) and W. Edwards Deming, who is said to be the father of global quality revolution. [1] [2]

The third evolution is the phase, where all the methodologies, philosophies and tools were identified and shaped. As stated earlier, Lean is said to be evolved from Toyota Production System and from Lean all sorts of improvement initiatives emerged. For example Six Sigma, Total Quality Management (TQM), Just-in-time (JIT) manufacturing, Kaizen, ISO 9000 and many other methodologies were shaped during the third evolution. It is actually not a hundred percent accurate to state that the aforementioned methodologies emerged from Lean. It would be more correct to state that all of the methodologies evolved along side each other and during the evolution of Lean. The methodologies are not literally established from Lean. [1] [3]

All of these methodologies are similar to each other to some extent and all include numerous cycle tools that can be used to improve process outputs. DMAIC (Define, Measure, Analyze, Improve, Control), DMADV (Define, Measure, Analyze, Design, Verify) and PDCA (Plan, Do, Check, Act) are just a few examples of these cycle tools. All of these tools consist of more distinct instruments that belong to each phase in that cycle and are subjects of the probability theory and statistical mathematical equations. This thesis and the project it is based on is focused on the Six Sigma methodology and the DMAIC cycle tools. [1] [2] [3]

5. SIX SIGMA

Six Sigma has become industry’s new strategy to increase profitability and enhance customer satisfaction. The phrase „Six Sigma“ has taken on several different meanings over the years. It is more of a business strategy than a quality program. Organizations that want to use Six Sigma to its maximum benefit should learn to tie Six Sigma improvements to its corporate strategy and goals for business performance. Six Sigma can be defined in four main ways:

1. A philosophy of management,
2. A process-measurement methodology,
3. An analysis methodology,
4. A business culture. [3]

Six Sigma is a disciplined, data-driven methodology for descision making and using statistical analysis to amplify the effectiveness of an organization’s best work. This methodology combines a step-by-step analytical approach to problem solving with statistical tools used in a specific sequence. The statistical methods and tools can be divided into two main categories: problem-solving processes (DMAIC: Define, Measure, Analyze, Improve, Control) and approaches for innovation in product and process design (DMADV: Define, Measure, Analyze, Design, Verify). [3]

Regarding the 4Q Project that is presented in chapter 7. The Continuous Improvement 4Q Project, Six Sigma is taken more as a set of statistical engineering techniques and tools for process improvement. The objective of Six Sigma is to improve the quality of process outputs by identifying, removing, or managing the factors that influence the causes of defects the most with a focus on understanding and reducing variation (to a goal of 3,4 defects per million opportunities, a 6σ or 99,99966% level of quality). [1] [3]

One of the most common problem-solving approaches and toolkits used in Six Sigma is the DMAIC cycle. To help define Six Sigma and the DMAIC cycle, the Toyota Production System pyramid of values can be used as an example. [1] [3]

Presented on the figure below (Figure 5.1.) are the basic ideals that should be taken into account if a company desires to be successful, according to the Toyota Production System. [2]

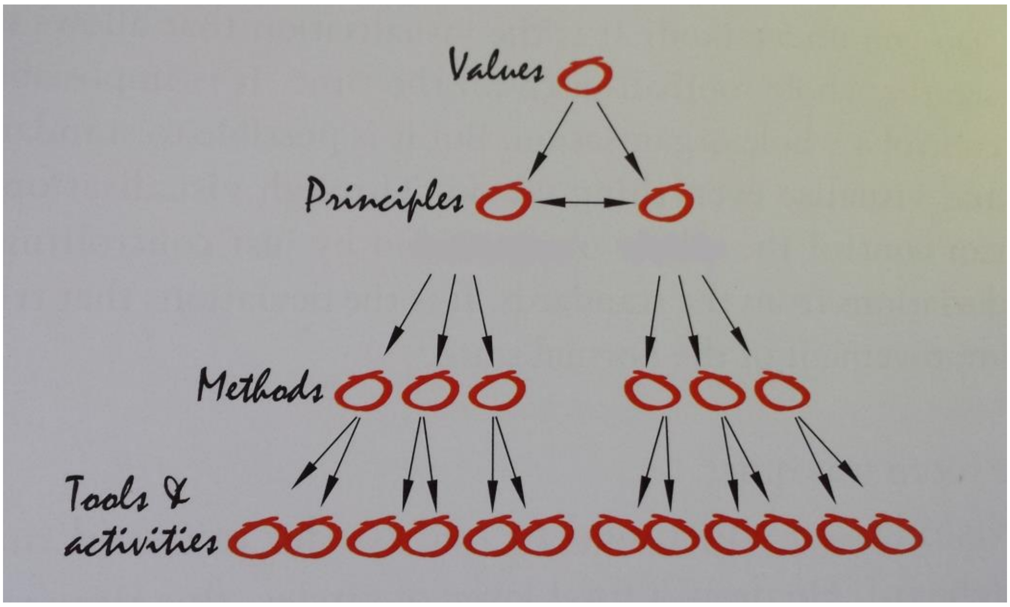


Figure 5.1. The Toyota Production System pyramid of values [2]

The Toyota Production System values pyramid suggests that the foundation of a successful company is built on values, which define how workers should act, regardless of the situation – this is not defined by tools or methodologies, it is the basic instinct of humans that should be harmonious. The tip of the pyramid can be defined with the phrase „What we want to be!". Next, principles define how descisions should be made and what should be prioritized – the Continuous Improvement strategy and Six Sigma as general psychologies should be situated on this level of the pyramid. The phrase used to help define this level of the pyramid is „How we achieve it!". [2]

Methods define how different tasks should be performed and tools and activities consist of all the different tools that are needed to realize a specific method. The DMAIC cycle as a toolkit should be situated on the method level of the pyramid and the instruments belonging to the DMAIC cycle should be situated on the ground level of the pyramid. [2]

6. THE DMAIC CYCLE

The term „DMAIC" is an acronym for the process' five sequential steps: Define, Measure, Analyze, Improve, and Control. The DMAIC process involves taking a business problem, translating it into a statistical problem, resolving the statistical problem, and returning to a practical solution that is then placed under statistical monitoring and control. [3]

1. During the Define step, the business problem is translated into a Six Sigma improvement project. A team is put together to conduct analysis and implement the recommendations. Also, a schedule is established and project responsibilites are shared out – the project sponsor, champion and leader are defined. The project sponsor is usually the senior executive who ensures that right team members are selected and keeps track of the project. The project champion is usually a middle- or senior-level executive who helps the project leader with the managing of the project. The project champion is basically the supervisor of the project leader. [3] [4]

2. During the Measure step, the characteristics of the product or process in question are identified – the points that are critical to the customer are mapped and the process operation is made clear. Evaluation is done to determine which process factors are controllable and performance standards are defined (the „as-is" conditions are determined). COPQ (Cost of Poor Quality) is determined and a target for improvement is established. [3]

3. During the Analyze step, identifying and confirming the main root causes is done. Evaluation of the current operation of the process in question is done to determine the potential sources of variation. Linking the sources of variation to control points in the process is vital, to see how the process must be set for optimal performance results (this can also be done during the end of the Measure phase, but it is usually done during the Analyze step).

Then, a number of analyzes are done with statistical tools to identify the factors that are the sources of variation. [3]

4. During the Improve step, the solution to the problem is defined, and its effectiveness is demonstrated through a pilot experiment. Screening the potential sources of variation is done to determine their effects on shifting the process mean and on reducing the total process variation. Eliminating the root causes is the main focus of this phase. [3]

5. During the Control step, the solution to the problem is prepared for integration with the routine work process, and the support systems necessary for full-scale implementation are developed. It is strongly recommended to design and implement a statistically based control system at this point and validate the measurement system to ensure it is capable of detecting significant changes. Then, a control plan is developed to maintain the improved level of process performance – standardization is done. [3]

To sum up, identification of all the process constraints that cause chronic problems in the work throughput is done during the Define phase. Measuring process time elements to find all non-value-adding components is done during the Measure phase. Using statistical tools, evaluating process bottlenecks, flow and buffer management is done during the Analyze phase. Simulating changes to the process and verifying the most promising changes with a pilot experiment is done during the Improve phase. Lastly, applying tools to sustaining the improvement gains is done in the Control phase. All of these phases consist of distinct tools and instruments that can be used accordingly. [3]

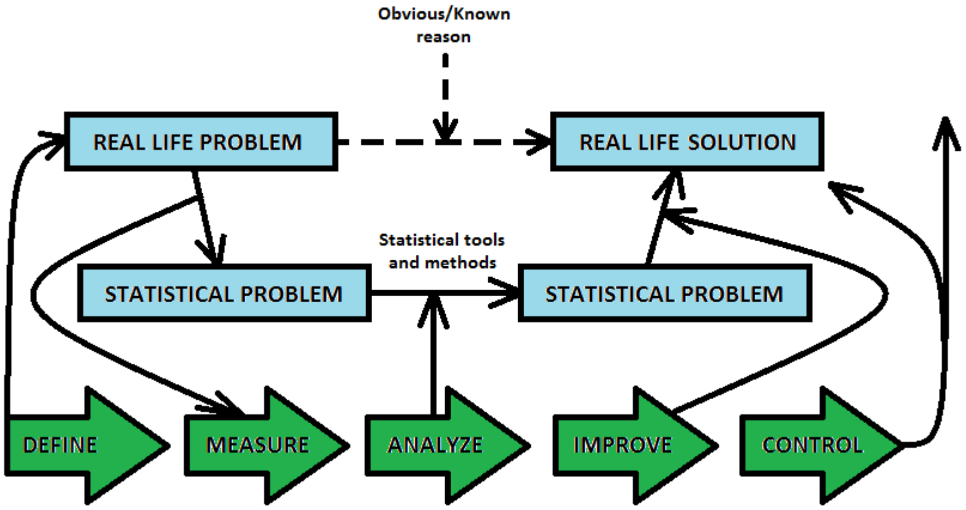


Figure 6.1. The DMAIC cycle [3]

6.1. Review of the tools used in the Define step

Define is the first step of the Six Sigma statistical problem-solving process. During this step, a problem is identified taking into account the customer’s focus. Critical to Quality considerations are made, a team charter is specified and the problem statement is defined to the performance standards. Expectations for the improvement project are set and the scope of the problem-solving strategy is kept on the customers’ primary requirements. [3] [5]

First, the inputs have to be defined and understood: the financial concerns, customer problems, process inefficiencies, product failures and flow bottlenecks have to be taken into account as indicators. The magnitude of the problem has to be determined and the risks to the company have to be considered. The importance of the project as well as the possible improvement plan should be defined so that the potential cost saving can be most profitable at the end of the project. This can be done with a number of tools. All of these tools are used taking into account the process’ KPIs (Key Performance Indicators), COPQ (Cost of Poor Quality) indicators and CTQ (Critical to Quality) factors. [3] [4] [6]

All of the tools belonging to the Define step will not be presented in this chapter, the tools that are not used in the 4Q Project, that is presented in the second part of the thesis, are not going to be introduced. The tools that are not used are for example the House of Quality, Stakeholder Analysis, CTQ Trees and the Flowchart – these tools will not be covered and further information about these tools can be found from different works that are published by Q. Brook, T. Pyzdek, P. Samuel, M. Bassard and M. George, for example. The more frequently used tools will be introduced: The Voices Triangle, Process Mapping which includes the SIPOC diagram, and Operational Definition are presented. These are the tools that the thesis’ author uses in the 4Q Project as well. Other tools are considered not to be needed for the purpose of this particular 4Q Project. [3] [4]

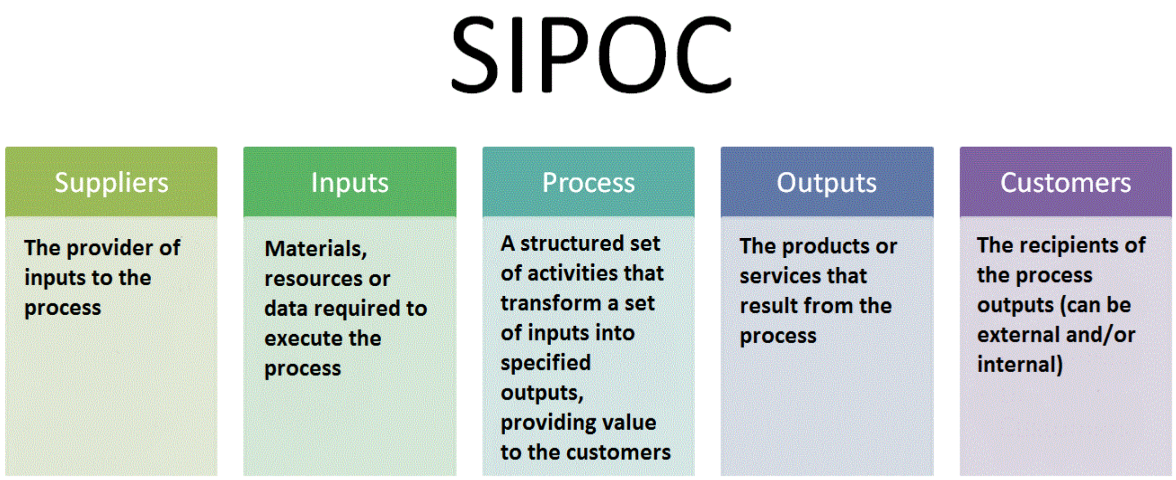
1. The Voices Triangle

The Voices Triangle which can also be described with the VoC Translation Matrix is a triangle which represents the Voice of Customer (VoC), the Voice of Business (VoB) and the Voice of Employee (VoE). Every Six Sigma project usually starts with the defining of the Voice of Customer. The Voice of Customer is sometimes also referred to as the „Finance KPIs“ or „Shareholder’s voice“. A VoC Analysis is done with brainstorming and other simple ways, no mathematical equations are usually used. To get a better perspective of how the dynamics between the process flow and final process or product are in conformity with the customer’s requirements, the VoB and VoE are taken into account similarly. This tool is used in the 4Q Project, it is presented at the end of the thesis in more detail. The Voices Triangle is used in the sence that the customers for the production line, that is under investigation, are defined via brainstorming and with the help of the SIPOC diagram. [4] [6] [7]

Figure 6.2. The Voices Triangle [7]

2. Process Mapping: the SIPOC diagram

The SIPOC diagram is a tool to describe the Input-Output process by also taking into account the requirements of the customer. „SIPOC“ is an abbreviation for the words Suppliers, Inputs, Process, Outputs and Customers. A SIPOC diagram is usually constructed starting from the Process phase. Then the customers are defined: the question „Who are the external and internal customers?“ is asked. Next, the inputs and outputs are defined that are the sources and results of the process, and finally the suppliers are determined. An example SIPOC diagram template is presented below (Figure 6.3.) where definitions of the different requirements are defined. The SIPOC diagram is also used in the 4Q Project part of the thesis. All of the suppliers, inputs, the general process, outputs and the customers are defined that are related to the production line that is investigated. [6]



SIPOC

Suppliers	Inputs	Process	Outputs	Customers
The provider of inputs to the process	Materials, resources or data required to execute the process	A structured set of activities that transform a set of inputs into specified outputs, providing value to the customers	The products or services that result from the process	The recipients of the process outputs (can be external and/or internal)

Figure 6.3. The SIPOC diagram [4]

3. Operational Definition

Operational Definition is an exact description of how to derive a value for a characteristic that is being measured. It includes a precise definition of the characteristic and how data collectors should measure it. It is used to remove ambiguity and ensure that all data collectors have the same understanding, it reduces chances of disparate results between the collectors. This tool is used in the 4Q Project presented below as well, where the definition of the KPI under investigation is described. [4]

6.2. Review of the tools used in the Measure step

Measure is the second step of the Six Sigma statistical problem-solving process. The Measure step enables an organization to understand the present condition of its work processes before it attempts to identify where the company can be improved. During this step, the CTQ (Critical to Quality) characteristics are defined in more detail, as well as the defects and errors in the process or product in question. All the factors that influence the output are evaluated, and potential effects they have on failure modes are identified. The Measure phase is based on valid data, it distinguishes the „as-is“ situation. When the logical link is made between performance measures and the measures that are critical to the customer’s satisfaction, the project team focuses on the controllable factors they discover in their analysis of the process-failure opportunities. [3]

Also, a study is usually performed to find out how much sensitivity the measurement system has to detect a change that is meaningful to customers. The measurement system can be improved to ensure it is valid and then begin collecting process-performance data to set the performance baseline for the process. The baseline is the set of indicators that defines a starting point for improvement of the process. Once the current performance is understood, a capability study is conducted to determine how good the process can become without any capital investments or major changes. [3] [4]

The inputs for the Measure step come from the prior Define step: the project charter, VoC, the Process Maps, Oprational Definition are taken into account for example. Also, the concepts, principles and methods that describe the inputs are considered: the boundary of the problem is determined and the sensitivity of the measurement is considered. A number of methods can be used to define these characteristics, for example Process Analysis, Failure Analysis, Capability Analysis and Measurement System Analysis (MSA). [3] [6]

All of the tools belonging to the Measure step will not be presented in this chapter, the tools that are not used in the 4Q Project will not be covered. For example, general line graphs and scatter plots that are sometimes used in the Measure phase to illustrate the „as-is“ situation as well as the Probability Plot and Capability Analysis are not going to be presented separately. Information about these tools can be found in different works by Q. Brook, T. Pyzdek, P. Samuel, M. Bassard and M. George, for example. Only the more frequently used tools will be introduced which the author also used during the 4Q Project: MSA (Gage R&R), the Control Chart, the Histogram and the Pareto Chart are presented – the author uses these tools in the 4Q Project because these tools prove to be useful and suitable for the scope of the project, which is presented in the second part of the thesis. [3] [6] [8]

1. Measurement System Analysis (Gage R&R)

Measurement System Analysis (MSA) is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability. It is not just a device, such as a ruler or timer, but it includes the people, standards, and procedures that surround the measurement process itself. The purpose of MSA is to find out if the measurement system that provides the data is accurate and distinguishes the sources of error in the data, as well as the scope of the variation. [4] [8]

Variation is the key enemy when it comes to a process – very simply defined, variation is deviation from expectation. When any output is closely measured, it can be found that it varies – always. The more times the output is measured, the bigger the variation might get. The measurement results vary around some average or mean. It is important then to understand if the measured results fit within the allowed limits and if there are any hidden factors in the projected graph or diagram. Variation comes from two sources: common causes and special causes. Common causes are types of variation that are just natural – they cannot be eliminated. Special causes are different: these types of variations are specific and they can be identified. Measurement System Analysis' goal is to measure the variation and define what are common causes and what are special causes that need to be focused on so that the overall variation can be reduced. Variation, common and special causes are explained in the Control Chart paragraph below in more detail as well. [4] [9]

One thing has to be taken into account as well: before performing MSA, the actual capability of the process has to be considered to detect and indicate even small changes of the characteristic under measurement. This is called measurement system discrimination. If discrimination is non-adequate, it will give no possibility to accurately measure process variation or quantify characteristic values of individual parts. Based on these reasons, measured characteristics are often grouped into data categories. Practically, this means that all parts in the same corresponding data category will have the same value for the characteristic measured. The acceptance criteria is then based on determining the number of these categories. These categories are called Distinct Categories. [4] [6] [8]

There are five parameters to investigate in an MSA: bias, linearity, stability and also repeatability and reproducibility (Gage R&R). In addition to percent errors and the number of distinct categories, the graphical analyses should also be reviewed over time to decide on the acceptability of a measurement system. [6] [8]

1.1. Bias errors are consistent types of errors that do not increase the variation that is seen in the results, but do shift the data so that results are consistently higher or lower than they should be. For example, if a ruler has 20 millimeters missing from the end, so it consistently gives results 20 millimeters too long – these kind of errors are considered as bias errors. Fixing bias errors is achieved through solutions such as routine calibration, limiting the allowable operating range of a gauge, training, using visual standards and so on. [8]

1.2. Linearity represents the change in accuracy through the expected operating range of a measurement device. When gathering data, then it should be collected within the acceptable limits where there is proven to be linearity. For example, if a scale performs differently when weighing a 10 kg item and a 100 kg item, it can be concluded that the scale's accuracy may change at various levels of measurement. The scale has a operating range of 0 kg to 300 kg, for example, but still provides false data – these kind of errors fall in the linearity category. Sources of linearity errors may come from age, wear and calibration errors. To fix linear errors, there may be calculations to account for the variations and also different ranges of measurement could be used. [4] [10]

1.3. Stability of a measurement system can be analyzed using Control Charts. Stability errors are analyzed to ensure that the measurements taken by assessors indicate the process' stability and consistency over time. Each assessor should measure the same way every time over a long period of time. Stability is the total variation of the measurements using the same parts and the same gauge. [4] [10]

1.4. Repeatability and reproducibility errors (precision errors) are the kind of faults that do not happen in the same way all the time – because of these kind of errors, more variation is added into the data. Basically, precision errors measure the variation in the measurement system itself – it measures the assessors and the tools. For example, if some people measure from the end of a ruler and others start from the point at which zero is marked – these kind of errors that cause variation are called repeatability and reproducibility errors. Repeatability errors are differences caused by the gauge itself, reproducibility errors are differences in the ways in which different people carry out the measurement process. Fixing precision errors is achieved through solutions such as developing operational definitions and working standards, training, improving gauge resolution sometimes even changing the cauge in use. Also, Gage R&R studies can be performed. [8] [10]

Gage R&R studies are performed for attribute data and variable data. There are four main criterias that have to be considered when performing a Gage R&R study: the study for variation percentage is based on the standard deviation, the tolerances are based on the specification limits, contribution is based on variance, and the number of distinct categories is based on the process variation. Gage R&R studies can be performed in three different ways: crossed, nested and expanded. During crossed Gage R&R, every assessor measures each part of the measuring device individually and does it multiple times. During nested Gage R&R, one assessor measures each part individually, largely because the test destroys some part of the data – one characteristic is dependant on the other. During expanded Gage R&R, there are more than two factors that affect the measuring process. In this case, it is referred to as an unbalanced design: the operator, the gauge and other factors are all measured. To sum up, a Gage R&R study measures precision error by taking one part and measuring it several times, with several different people. Gage R&R is actually not used in the 4Q Project presented below, but it is added to this paragraph because it is mentioned in the Measure phase of the project, where explanations are given, what are the reasons of it not being used. [4] [6]

2. The Control Chart

The Control Chart is a sophisticated form of a Time Series plot that enables the stability of the process, and the type of variation involved, to be understood. Control Charts detect changes in process average, process variation and one-off changes such as special causes. [8]

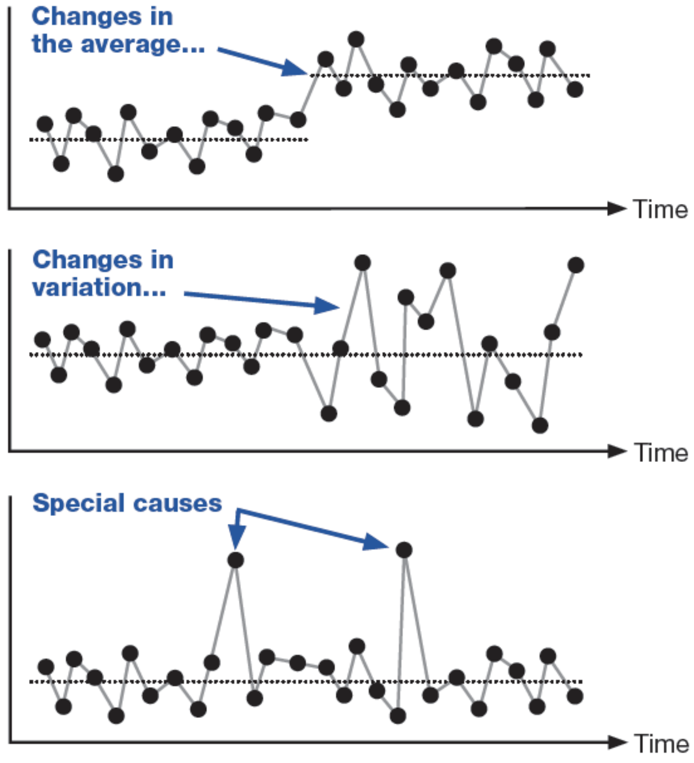


Figure 6.4. Three different types of changes in a process [8]

Control Charts, when dealing with historical data process stability assessing, are usually used during the Measure and also the Analyze phase. But in addition, Control Charts can also be used during the Contol phase, when they are used for ongoing control – the real time analysis of process performance that aims to detect and react to process changes. Before describing different types of Control Charts, the explanations of control limits and common and special causes are given. [8]

2.1. Control limits define the area of three standard deviations on either side of the centerline, or mean, of data that is plotted on a Control Chart. Control limits should not be confused with specification limits – control limits are mathematically determined, they reflect the expected variation in the data, whereas specification limits are defined by the customer. It would be ideal if the control limits and specification limits would be equal, but usually the specification limits have a narrower operating area. In a Control Chart, the tracked measurements are visually compared to decision limits calculated from probabilities of the actual process performance (standard deviations). The visual comparison between the decision limits and the performance data allows to detect any extraordinary variation in the process – variation that may indicate a problem or fundamental change in the process. The correlation between the standard deviations (six sigmas) and the control limits is presented on the example chart below (Figure 6.5.). [8] [9]

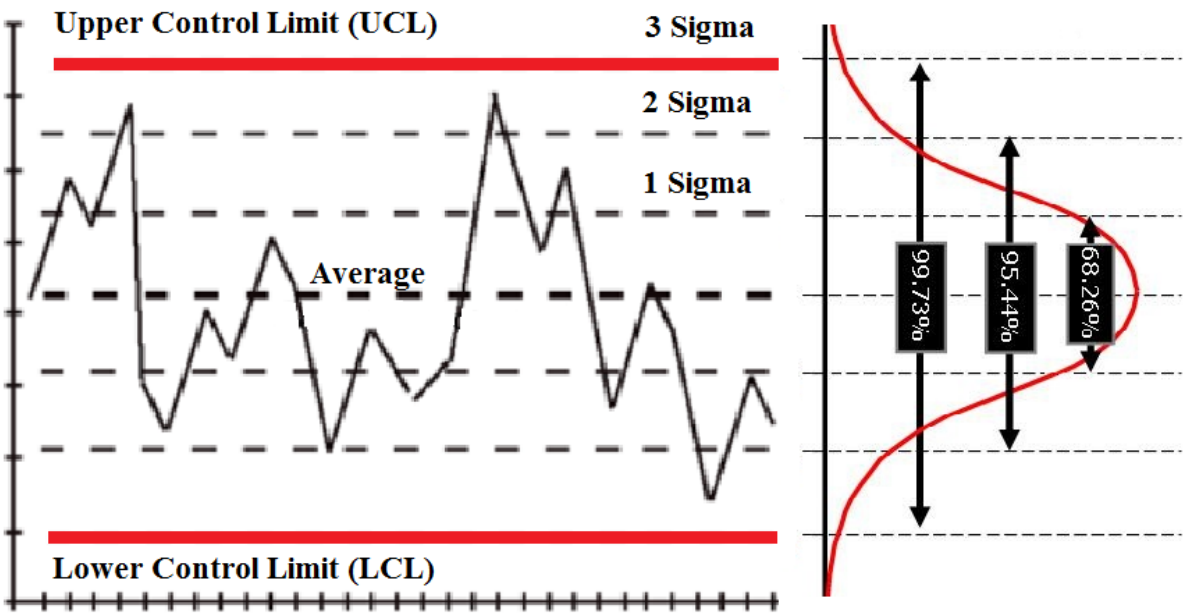


Figure 6.5. Example chart that illustrates the correlation between the six sigmas and the control limits [9]

The control limits or six sigmas are determined by the standard deviation formula which is defined as:

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{N}}, \qquad (6.1)$$

where σ – the standard deviation of a sample,

$\sum$ – the „sum of“,

x – each value in the data set,

$\bar{x}$ – mean of all values in the data set,

N – number of values in the data set.

2.2. Common and special causes are different types of variation. A stable process is one where all of the inputs are varying in a random way. Combining together, these kind of causes in the variation create a similarly random variation in the output, that is predictable within certain limits – these kind of causes are called common causes. An unstable process is one where one or more of the inputs are behaving in an extremely unpredictable way. The resulting output variation can therefore be assigned as special cause variation, and these kind of causes cannot be predicted. [8]

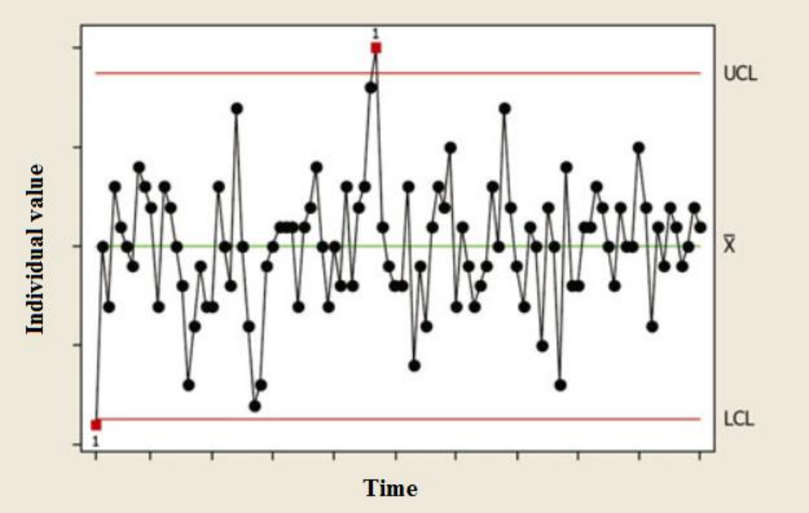


Figure 6.6. Example chart of common and special causes [4]

As seen from the chart above (Figure 6.6.) the area that fits within the control limits (UCL and LCL) are all common causes. These values fall within the six standard deviations. The two values that are out of the control limits, presented as „1“, are special causes. [4]

There are a range of Control Charts to choose from depending on the application and type of data. However, all of the different types of Control Charts work in roughly the same way.

First, the performance of the process is plotted as a Time Series plot. Secondly, the level of variation in the process is assessed. Thirdly, control limits are calculated and drawn on the plot based on the measured variation. The fourth step is that each point on the chart is assessed against a number of tests. Finally, any data points that fail the tests are highlighted and investigated – the special causes are defined and examined. Depending on the scope of the project's problem, in some cases the special causes are not examined – in some projects it is expected to generally reduce variation. In these kind of cases focus goes on the common causes – the goal is to reduce the overall variation, or mean. [8] [11]

The different types of Control Charts are separated into two major categories, depending on what type of process measurement is being tracked: continuous data Control Charts and attribute data Control Charts. [4] [11]

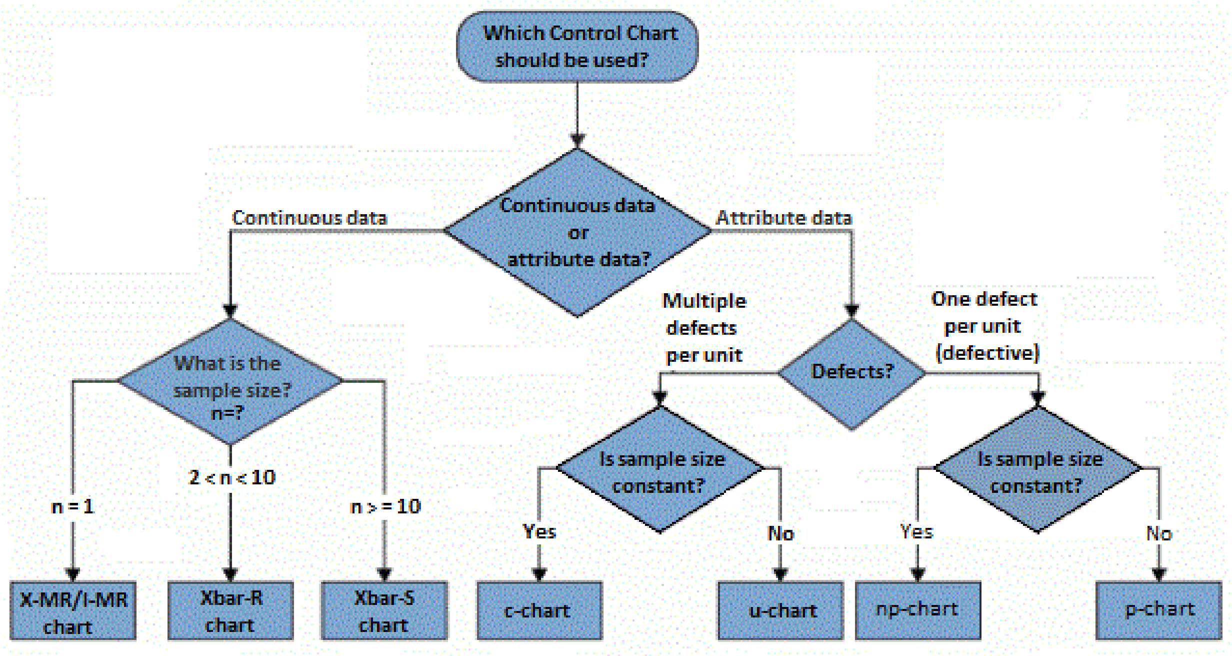


Figure 6.7. Categorization of different Control Chart types [4]

As seen on the figure above (Figure 6.7.) the range of Control Charts to choose from is vast, depending on the data type, variation and sample size. There is also an additional chart called the Run Chart which is missing from Figure 6.7. This chart can be categorized under the Control Chart types as well, it is for continuous data and when the sample size is equal to one (it is a different type of the X-MR/I-MR chart). [6] [8]

All of the chart types are not going to be introduced in this paragraph, an example is brought on the basis of the c-chart. When using a c-chart, an important characteristic is that the number of samples of each sampling period is essentially the same. As seen from Figure 6.7. as well, it is used with attribute data and when multiple defects per unit occur. [4] [8]

For example, a contactor manufacturing company would like to monitor defects in the manufacturing process of their new mini-contactors product. Technicians recorded the number of defects in the manufacturing process for each subgroup of 10 mini-contactors per hour. To monitor the number of defects, a c-chart was constructed. The example is presented below (Figure 6.8.) [4]

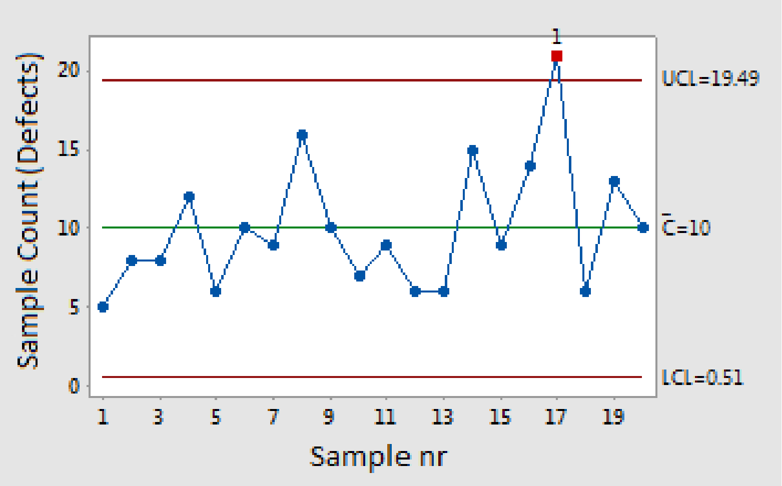


Figure 6.8. Example c-chart of the manufacturing process' defects of mini-controllers [4]

As seen from the c-chart, the technicians found 10 defects in each mini-controller (sample) on average. It is also seen that sample number 17 is out of the control limits – a special cause. The technicians should try to identify the root causes that may have contributed to the unusually high number of defects, and especially, examine why mini-controller (subgroup) number 17 had so many defects. Also, they can take the mean as a reference point if they descide that 10 defects per mini-controller on average is too many. The Control Chart is one of the most important tools used in the 4Q Project presented at the end of the thesis. It is used in the Measure phase and the Control phase also to distinguish the changes in the process. [4]

3. The Histogram

The Histogram summarizes the overall performance of a process and shows the shape of the distribution. It describes the most common number of defects per sample and the standard deviation's relation with the distribution of the sample. The golden rule when analyzing histograms is not to read too much into them, instead, the results should be summarized. Histograms are used to represent categorization of continuous data and the recommended minimum sample size for a Histogram is said to be 25, so that the observed data would be expedient. The Histogram answers three main questions: “What is the most common system response?”, “What distribution does the data have?” and “Does the data look symmetric or is it skewed to the left or right?”. The Histogram is sometimes also constructed during the Analyze step – this depends on the project structure and the decision made by the Project Leader. [6] [8] [11]

For example, a PCBA manufacturing company would like to monitor the distribution of the frequency of defects occuring during the manufacturing process of PCBAs. Engineers measured that during the PCBA manufacturing process of a hundred samples, they usually cause six to thirteen faults per PCBA, with an average of 10 faults. The engineers at the PCBA manufacturing company also figured out how frequently these errors occur, so that they could plot the data on the Histogram. Distinct results were achieved, the example is presented below (Figure 6.9.) [4]

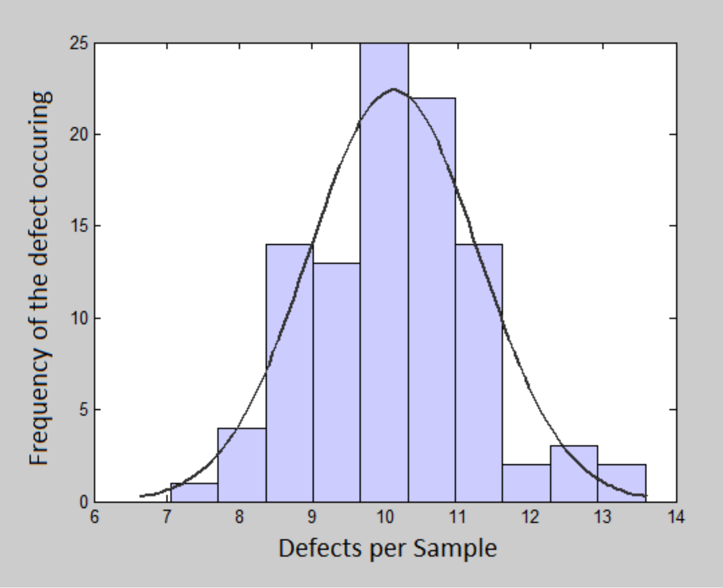


Figure 6.9. Example Histogram of the defects per PCBA distribution [4]

As seen from the example Histogram above (Figure 6.9.), the distribution curve helps define the shape of the process and determine the problematic areas. The Defects per Sample points out the number of defects caused to a PCBA during the manufacturing process. For example, it can be seen that the most common number of defects per PCBA is 10 with an occurrence of 25 times. There seem to be no special causes and out-of-limit occurrences. Data like this provided by the Histogram can be used for further analyses in the next phases of a project. The Histogram is also used in the thesis' 4Q Project part to help describe the most common number of faults. [4]

4. The Pareto Chart

The Pareto Chart is used to graphically summarize and display the relative importance of the differences between groups of data that are being investigated. It is a quality chart of attribute data that helps identify the most significant types of defect occurrences. The Pareto Chart shows both frequency of occurrences (as a bar graph) and cumulative total of occurrences (as a line graph) on a single chart. It describes the types of occurrences and the frequency of the occurrences on the same graph with the addition of the total percentage. Pareto Charts can also be constructed and used during the Analyze step of the DMAIC cycle. [4] [12]

The Pareto Chart is subject to the 80/20 Principle. Reasons for failure are often found to conform to the 80/20 princple which states that 80 percent of the failures are generally caused by around 20 percent of the main root causes. [8]

For example, a toy company would like to monitor the complaints of the defects that are being sent in by the customers. The toy company set a fixed time period – one month – and collected the complaints from the customers. The data points collected represent 219 different complaints. The engineers at the toy company categorized the complainst and concluded that there are five main root cause categories why customers send complaints. The frequency of the problems occurring is presented on the table below (Table 6.1.). [4]

Table 6.1. Example table of the frequency of the problems occurring [4]

Defect Category	Number of Occurrence	Frequency	Cumulative Frequency
Category 1 (Cat. 1)	80	36,5%	36,5%
Category 2 (Cat. 2)	62	28,3%	64,8%
Category 3 (Cat. 3)	36	16,4%	81,2%
Category 4 (Cat. 4)	23	10,5%	91,7%
Category 5 (Cat. 5)	18	8,3%	100,0%

As seen from the table above (Table 6.1.), Category 1 is the most frequent and Category 5 is the least frequent. For Category 1, the cumulative frequency is the same as the frequency precentage, for the next categories, the according frequency precentages are summarized till a hundred percent. The cumulative frequency, as stated before, is presented as a line graph on the chart – this line helps to determine the most vital root causes that need to be handled and improved. The „Vital Few" and „Useful Many" categories are distinguished. The data presented in the table is plotted on the Pareto Chart so that the results can be presented graphically as well. [4] [12]

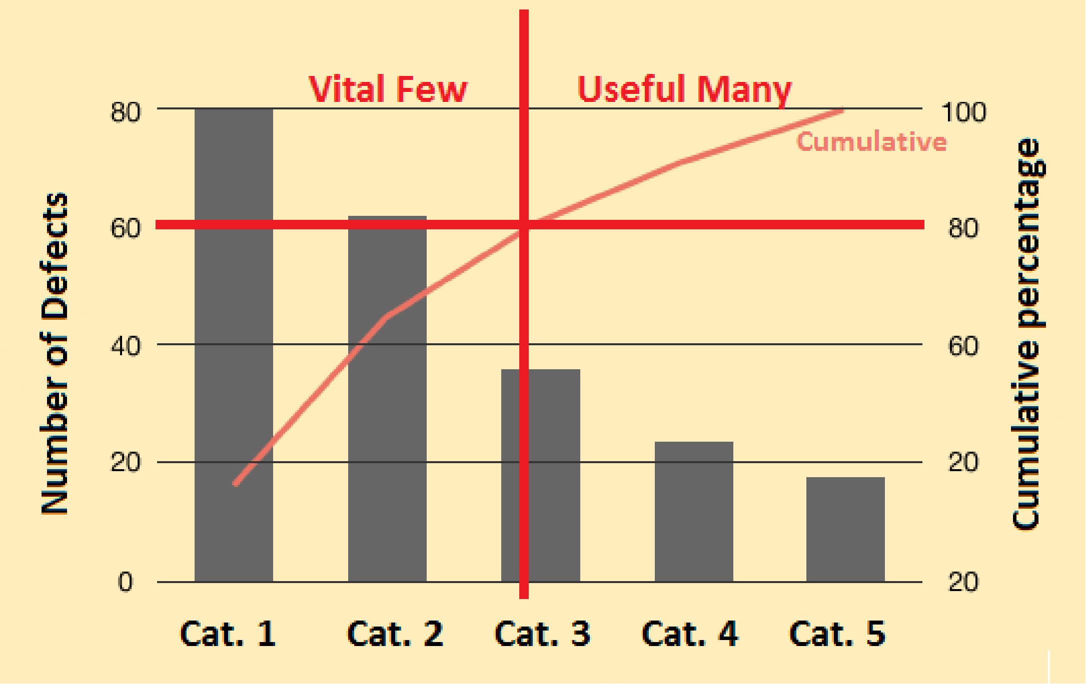


Figure 6.10. Example Pareto Chart of the different types of customer complaints [12]

As seen from the chart above (Figure 6.10.), all five of the root cause categories are presented with the according frequencies. From the crossing point of the cumulative percentage line and the 80 percent horisontal characteristic, a vertical line is drawn. This vertical line separates the „Vital Few" root causes from the „Useful Many" root causes. The „Vital Few" root causes of the customer complaints, in this case the first and second root causes (Cat. 1 and Cat. 2), are the main root causes that need to be focused on and improved. Everything right of the vertical red line do not need to be focused on at first. The Pareto Chart is used in practice as well, presented in chapter 7. The Continuous Improvement 4Q Project. It is used to illustrate the different root cause categories that have to be analyzed in the Analyze step of the 4Q Project at hand. [8] [12]

6.3. Review of the tools used in the Analyze step

The Analyze step is the phase where analysis of process-performance data is done to localize sources of controllable variation. Also, determination of the root causes and addressing the areas where process improvement can be done, is focused on. The Analyze step adds statistical strenght to the anaylsis. Statistical analysis identifies a problem's root cause by determining which factors contribute to the variation. When the analysis is complete, the dominant sources of controllable variation are identified. This helps in identifying the area on which to focus on when building a soulution during the Improve step. [3] [6]

The Analyze phase is less of a logical flow, ant it rather provides more of a toolbox of techniques. First, the process is analyzed, then, theories and ideas are developed. Next, data analysis is performed and finally, the root causes are verifyed and the cause and effect has to be understood. The inputs for the Analyze phase are the results measured in the Measure step, the variation analysis that is going to be used and also the different set of tools. [3] [13]

There is a large number of tools that can be used in the Analyze phase – not all are going to be covered in this paragraph. The tools that are not used in the 4Q Project below are not introduced: the Tree Diagram, the Seven Wastes (TIMWOOD), the Spaghetti Diagram, Hypothesis Analysis, Analysis of Variance (ANOVA), the Affinity Chart, the Measles Chart, Dot Plots, Box Plots, Time-series Analysis, Bottleneck Analysis, Failure Mode and Effects Analysis (FMEA), Confidence Intervals, Correlation and Regression Analysis and Design of Experiments (DOE) for example are not going to be explained. Also, the differences in the distribution shifts and the differences between α-risks and β-risks are not going to be described. Information about these tools can be found in different works by Q. Brook, T. Pyzdek, P. Samuel, M. Bassard and M. George, for example. These tools are not needed because the analysis can be performed with the following tools described below. [3] [4] [6]

The more commonly used tools are presented: Cause and Effects Analysis which include the Fishbone diagram and the Cause and Effect Matrix and the 5 Whys. These are the tools that are also used in the 4Q Project. (The author also used the Pareto Chart during the Analyze phase of the project.) [8] [13]

1. Cause and Effects Analysis: the Fishbone diagram

Fishbone diagrams are usually used during brainstorming, to identify root causes. However, they can also be used throughout the Analyze phase as a great tool for structuring a team's thoughts. There are many different versions of Fishbone diagrams, with different branch names. There are no right or wrong ones – just the appropriate branch categories should be chosen that are suitable for the according project. A Fishbone diagram is constructed starting with the formulation of the main question or root cause. This is placed to the „head" of the fishbone. The rest of the fishbone consists of one line drawn across the diagram, attached to the problem statement, and several lines, or "bones," coming out vertically from the main line. These branches are labeled with different categories. The categories for manufacturing industries are Machine, Method, Material, Measurement, Environment and People. These categories are put to the ends of the main „bones". Next, the potential root causes of these categories are examined and determined. An example of a manufacturing Fishbone diagram template is presented below (Figure 6.11.). The Fishbone diagram is used in the 4Q Project also. It is used to help define the possible root causes. [4] [8] [14]

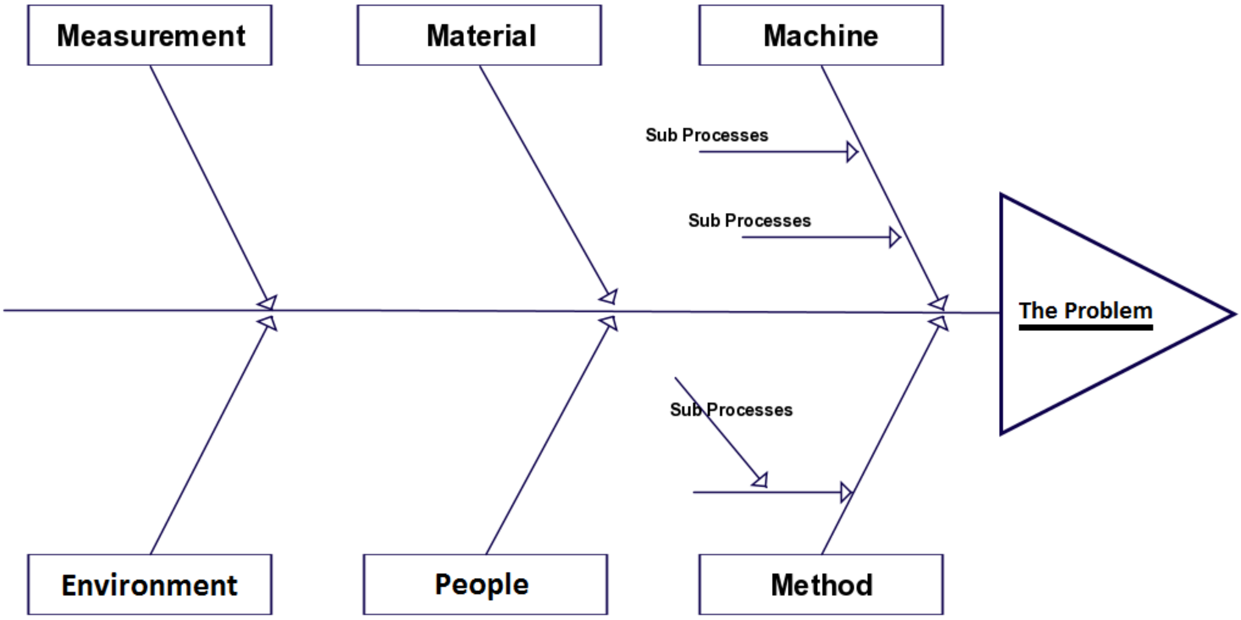


Figure 6.11. Example Fishbone diagram template with manufacturing industries categories [4]

2. Cause and Effects Analysis: the Cause and Effect Matrix

Having identified the inputs and outputs during Process Mapping and having distinguished the more probable root causes of the process' problem with the help of the Fishbone diagram, a Cause and Effect Matrix can be used to identify which of the process' inputs are most important in relation to the customers requirements. A Cause and Effect Matrix prioritizes process inputs against process outputs from the customer perspective. The Cause and Effect Matrix can also be constructed during the Improve phase – the thesis author used this tool during the Improve step in the 4Q Project, but it is introduced here, in the Analyze paragraph of the theoretical part, because it is usually defined along side the Fishbone diagram. [8] [14]

To complete a Cause and Effect Matrix, first, the process outputs have to be identified. Secondly, each process output has to be rated in terms of its importance to the customer. Thirdly, the process steps have to be identified, as well as the process inputs. Next, the correlation between each process input and output have to be rated. Based on these characteristics, estimated scores are given to all of the points – the scores given usually vary from „1“, „3“ and „9“. A low score means that the input has little effect on the output, and vice versa. Finally, each correlation value is multiplied by the same outputs importance and the results of each row are added up. The process inputs that have the highest scores should be focused on and controlled. [8]

Table 6.2. Example Cause and Effect Matrix [4]

		1	2	3	4	
	Process Outputs	Output nr 1	Output nr 2	Output nr 3	Output nr 4	TOTAL SCORE
	Process Inputs					
1	Input nr 1	1	3	9	9	243
2	Input nr 3	1	1	9	9	81
3	Input nr 5	3	1	3	3	27
4	Input nr 9	1	3	3	3	27
5	Input nr 2	1	3	3	1	9
6	Input nr 8	3	1	1	1	3
7	Input nr 4	1	1	1	1	1
8	Input nr 7	1	1	1	1	1
9	Input nr 6	1	1	1	1	1

As seen from the example Cause and Effect Matrix above (Table 6.2.), Input nr 1 turned out to be the most vital one with the biggest added up score of 243. This sort of tabled data can be taken as a reference point when choosing the most relevant and critical root causes that need to be improved in the Improve step. Based on this example, the inputs that definitely need to be focused on, are Inputs nr 1, 3, 5 and 9. [4] [8]

3. The 5 Whys

The 5 Whys can be used to investigate a specific failure for finding a problem’s real root cause. It is usuallt used parallel to the Fishbone diagram. It is a tool that does not involve data segmentation, hypothesis testing, regression or other advanced statistical tools, and in many cases can be completed without a data collection plan. Asking “Why?” several times can peel away the layers of symptoms which can lead to the root cause of a problem. Very often the ostensible reason for a problem will lead to additional questions. And although this technique is called “5 Whys” it can be found that in many cases it is enough to ask the question fewer times and sometimes it is needed to ask more times than five before the root cause can be determined. The 5 Whys is usually used when problems involve human factors or interactions. It is one of the simplest tools presented in the DMAIC cycle. This tool is not used in the 4Q Project in a straightforward manner, it is used during the formulation of the different Fishbone diagrams. [4] [8] [15]

6.4. Review of the tools used in the Improve step

The Improve step focuses on the previously agreed upon opportunity for business improvement. This phase includes identifying the process factors that statistically solve the problem by shifting the mean or reducing the variance, demonstrating the ability to control a process by setting the level of these parameters, validating optimal set points for continuously operating the process, and developing an implementation solution that ensures sustainable and predictable performance in the face of failure opportunities. Eliminating the root causes and developing and piloting solutions are the main objectives of the Improve step. [3] [8]

The inputs for the Improve phase include data discovered from the Analyze step, experimental design, variables sorting, sequential search and a large number of tools that can be used. The only tools that were used in the 4Q Project during the Improve phase include the Cause and Effect Matrix, which is defined in the last paragraph, and the SMART Actions. The short definition of SMART Actions is given in the 4Q Project. This paragraph will not hold definitions of any other tools. [3] [8]

The tools that also belong to the Improve step but were not used in the 4Q Project are for example Opportunity Storming, Multi-vari Analysis, Response Surface Method, Evolutionary

Operation (EVOP), Statistical Tolerance Analysis, 5S, SCAMPER, Matrix Analyses, Single Minute Exchange of Dies (SMED), Total Productive Maintenance (TPM) and One Piece Flow. These tools are not needed for analysis during the 4Q Project because a sufficient result can be achieved with only the use of the Cause and Effect Matrix and the SMART Actions. Information about the tools that are not used can be found in different works published by Q. Brook, T. Pyzdek, P. Samuel, M. Bassard and M. George, for example. [3] [6] [8]

6.5. Review of the tools used in the Control step

The Control step is the final phase of a Six Sigma project. The objectives of the Control step are to produce a project-control plan that delivers sustained optimal performance, disseminate improvement results across the entire organization, institutionalize the improvements so that they become part of the daily work routine and institute a performance-monitoring system to ensure that corrective action is taken if the process deviates from its designed parameters. The main goal is to maintain the (piloted) improvements and standardize. The work performed during the Control step primarily affects the process owner and the implementation team. The actions performed during this phase include determining practical conditions, identifying training needs of front-line workers to ensure that process-performance consistency is achieved, mistake-proofing the process and preparing statistical controls to keep the performance of critical process factors optimal. After implementing ongoing measurements, standardizing the solutions and quantifying the improvements, it is allowed to close the project. [3] [6] [8]

The inputs to the Control phase include data and piloting results that came from the Improve step, Work-Content Analysis and also Principles of Standardization. The set of tools that can be used during the Control step is large – not all of the tools are going to be presented in this paragraph. Process Re-engineering, Change Management, the Control Plan and Response Plan, Action Logs, KPI Trees, Standardized Work, Poka-Yoke, Visual Management (Visual Factory) and Process Sigma Calculations are not going to be presented because these tools are not used in the 4Q Project. The tools used in the 4Q Project include Statistical Process Control (SPC) and Cost-Benefit Analysis – these tools are introduced because they are also used in the 4Q Project part. Information about the tools that are not used can be found in different works published by Q. Brook, T. Pyzdek, P. Samuel, M. Bassard and M. George, for example. [3] [4] [8]

1. Statistical Process Control (SPC)

Statistical Process Control (SPC) is a technique for applying statistical analysis to measure, monitor and control processes. It can be used in the Measure and Analyze phases as well to describe the process' variation and the „as-is" situation. In the Control phase it is used more to determine the changes and improvements through charts. The major component of SPC is the use of the Control Chart which is described in chapter 6.2. Tools used in the Measure step, point number 2. The Control Chart – this chapter and point also include the definitions of the control limits and Figure 6.7. describes the categorization of different chart types as well. The basic assumption made in SPC is that all processes are subject to variation. This variation may be classified as one of the two types: special and common cause variation, as stated in chapter 6.2. point number 2. The Control Chart as well. [4] [6] [8]

SPC provides the ability to determine process capability and identify whether the process has changed and corrective actions are required. Control Chart information can be used to determine the natural range of the process and to compare it with the specified tolerance range. If the natural range is wider, then either the specification range should be expanded, or additional improvements will be necessary to narrow the natural range. [11]

In order to work with any distribution, it is important to have a measure of the data dispersion. Often, focus goes on the average values, but understanding dispersion is critical to the management of industrial processes. For example, if a person is asked to walk through a river and told that the water depth is one meter, more information would be wanted by the person but he or she would probably make the trip. But if the person is told that the water depth range is from zero to ten meters then the person would re-evaluate the trip. Dispersion helps to distinguish these kind of data differences. [9] [11]

Dispersion measures the consistency of the process, usually a Xbar-R chart is used at this point. Problems on the dispersion chart should be addressed first. When control limits on the average chart are calculated in the standard way (three sigmas from the average), out-of-control variables on the dispersion chart will also lead to out-of-control factors on the average chart. These out-of-control factors on the average chart are not an indication of changes in the process average, however, they are a logical result of changes in the dispersion. SPC is also used in the 4Q Project below. It is used to demonstrate how the improvement actions affect the DPU index in the last part of the project. [4]

2. Cost-Benefit Analysis

Cost-Benefit Analysis is a decision-making tool to compare costs (negative results) and benefits (positive results) of a proposed change to a process. The costs can include labor, equipment, materials and time, and the benefits often include increased customer satisfaction, increased revenue, cost avoidance and reduced cycle time. Cost-Benefit Analysis weighs the real costs of a potential solution under consideration against the potential benefits of the solution. Additional examples of costs: capital investment needed, implementation costs (time of the project team, process improvement costs), start-up costs (training, lost production during switch from the old to new process), operation costs (additional cost of running the new process compared to the old process) and so on. Cost-Benefit Analysis can also be conducted during the earlier stages of the improvement project, but it is more commonly used during the Improve step or the Control step to determine the possible savings. [9] [12]

When conducting a Cost-Benefit Analysis, the steps involved for possible solutions include considering all costs associated with getting the solution up and running, quantifying benefits of a fully implemented solution and comparing the real costs of solution against the potential benefits. A similar tool to the Cost-Benefit Analysis is also used in the 4Q Project as well – it is presented in the chapter 7. Continuous Improvement 4Q Project – Control. [10]

7. THE CONTINUOUS IMPROVEMENT 4Q PROJECT

Six Sigma professionals exist at different levels – each with a different role to play. At a project level, there are Yellow Belts, Green Belts, Black Belts and Master Black Belts. The people who have the accrording certification, conduct projects and implement improvements. The most basic is the Yellow Belt. People who work on Yellow Belts – their everyday work will reflect a quality vs profit relationship. This belt is considered to be the first level in the Six Sigma belts sequence. [8] [16]

The next step in the Six Sigma belts is the Green Belt. People with this certification are often referred to as the worker bees because they do the majority of the work during projects. They are the ones who gather all the necessary information and do a majority of the experiments and tests throughout the project. The main goals of a Green Belt are to ensure the success of the training techniques and lead smaller improvement projects. [16]

One of the higher levels in the Six Sigma belts is the Black Belt. These are the people who are in charge of the Six Sigma projects within their respective companies. The projects they head up typically are expected to save the company at least 100 000 euros. This is why the people constructing Black Belt projects usually do the work regarding the project full time. [16]

The highest level one can achieve regarding the Six Sigma belts, is the Master Black Belt. The people certified with this title are highly trained Black Belts who will do the work full time, even after the project is completed. The Master Black Belt will make sure everything continues running smoothly and all of the training that the company learned, stays in the company. They execute the practices throughout the company, not just within the project. Usually, Master Black Belts are the main Six Sigma coaches and trainers in the company. [16]

The Continuous Improvement 4Q Projects that can be constructed in ABB are considered to be types of Six Sigma Yellow Belts. They are constucted to help workers prepare for Six Sigma Green Belts and Black Belts (and even Master Black Belts).

In an ABB's Continuous Improvement 4Q Project, the first two phases of the Six Sigma DMAIC cycle – Define and Measure – are put together and labeled only as the Measure step, as seen on the table below (Table 7.1.). But in this thesis, the Define and Measure phases are presented separately, as would in an ordinary Six Sigma project, to present the tools that are used in the project more distinctly. The Continuous Improvement 4Q Project is tracked with a table that is usually situated at the very beginning of the project (Table 7.1.).

Table 7.1. Continuous Improvement 4Q Project status tracking table

Current Status				
Status Replace **O** with **X** to indicate that the project is complete for that quadrant.	**X**	**Q1 Measure**	Q1 Q2 Q4 Q3 Any necessary containment done, project set up and data collected. The current state investigated and understood.	Q1 Q2 Q4 Q3 Root Cause Analysis (RCA) complete and verified.
	X	**Q2 Analyze**		
	X	**Q3 Improve**	Q1 Q2 Q4 Q3 New work methods and processes standardized. Issue closed.	Q1 Q2 Q4 Q3 Long Term Solution developed, piloted and implemented that eliminate the root causes.
	X	**Q4 Sustain**		

The Continuous Improvement 4Q Project is constructed with the help of the following programs: Microsoft Excel, Minitab and an ABB's internal Six Sigma Toolbox guide called the LSS Toolbox, which helps with the calculations and construction of some of the Control Charts, Pareto Charts, Fishbone diagrams and some of the other types of charts.

Before the different phases of the 4Q Project are introduced, the scope of the project is explained in more detail. The project that was assigned to the thesis' author at the beginning of 2017 is the investigation of the quality of a frequency converter's production line. In ABB, there are different KPIs for every production line to help monitor the quality of the production process and control whether the process is in stable conditions. At the end of 2016 it was concluded that one of the KPIs at a specific production line was over the set target – the Defects Per Unit (DPU) index in 2016 was 31% higher than it was supposed to be (more information about the DPU index is presented in the 7.1. Continuous Improvement 4Q Project – Define chapter also, where Operational Definition is explained).

The production line that is put under investigation, produces frequency converters that go up to 1000kW. The products name is the PVS800 – it is a central inverter for converting, adjusting and conveying power generated by a solar generator to the electrical power system. The inverter is built in an air-cooled cabinet for indoor use.

Some specifications of the PVS800 frequency converter: the input DC voltage range for the inverter is from 600V to 850V, with the maximum DC voltage of 1100V; the maximum DC current is 1710A. Also, the maximum output power is 1200kW and the nominal AC current is 1445A for the 1000kW inverter's output side. A cabinet like this has about 7000 different components and materials in it. The DPU target set – [redacted] – means that only every [redacted] inverter cabinet produced can have one minor production defect in it. Considering the fact that there are over 7000 details that can have errors, the DPU index target is considered to be quite impressive. Nontheless, the fact that the KPI was over the set target of even a small amount, it is labeled as a critical „red flag" case and a Continuous Improvement 4Q Project is needed to be conducted to find out the root causes why the process was out of standard limits. The project's name is „PVS800 DPU index was over the target in 2016". An example picture of the frequency converter cabinet is presented below (Figure 7.1.).

Figure 7.1. Example picture of the PVS800 frequency converter cabinet

7.1. Continuous Improvement 4Q Project – Define

The 4Q Project starts with the Project Description – the defining of the problem is explained and the responsible personnel are assigned. The Project Leader is the thesis' author, the Project Champion is the thesis' co-supervisor Kaarel Lahtvee as also seen from the table below (Table 7.2.) and the Project Sponsor is the Production Line Manager. The Define part also include the SIPOC diagram and the Operational Definiton.

1. Project Description

Table 7.2. PVS800 DPU index was over the target in 2016 4Q Project description

<table>
<tr><td colspan="2">What is happening?
PVS800 DPU index was over the target in 2016.</td><td colspan="2">Why this is a problem?
The number of defects per one unit is over the allowed target. This may lead to additional undetectable defects and field failures that add additional cost.</td></tr>
<tr><td colspan="2">When does/did the problem happen?
This issue was raised in 2016 by the Process owner and the situation is still the same in 2017.</td><td colspan="2">Who is involved with the problem?
All the Line-workers, Foremen, Engineers and the Production Line Manager who are involved with the PVS800 production line.</td></tr>
<tr><td colspan="2">Where does/did the problem happen?
This problem occurred on the PVS800 production line.</td><td colspan="2">How do we know we have a problem?
PVS800 KPI (DPU) in 2016 was over the target.</td></tr>
<tr><td colspan="4">Organizations needed for the investigation?
PVS800 production line and the Solar Process Engineering Department.</td></tr>
<tr><td colspan="4">Project target and major assumptions
Achieve target DPU for PVS800 (lower the DPU 31% – from [redacted] to [redacted] or better).</td></tr>
<tr><th>Name</th><th>Job Title</th><th>Project Responsibility</th><th>Contact details</th></tr>
<tr><td>Lauri Kalm</td><td>Process Engineer</td><td>Project Leader</td><td>Mobile: +372 56 801 342
email: Lauri.Kalm@ee.abb.com</td></tr>
<tr><td>Kaarel Lahtvee</td><td>Process Engineer</td><td>Project Champion</td><td>Mobile: +372 56 801 295
email: Kaarel.Lahtvee@ee.abb.com</td></tr>
</table>

2. Size of Problem

When the Project Description is determined, next, the Size of Problem is defined. The Size of Problem states that data from the ABB's database suggests that from January of 2016 till December of 2016 there were 546 PVS800 cabinets produced in the Jüri Factory and from that amount there were [redacted] defects. The main goal is to find the root causes of these defects. It is important to propose and implement corrective actions and that the DPU index is brought down to standard conditions.

3. The SIPOC diagram

When the Project Description and Size of Problem are both defined, then the SIPOC diagram is constructed – the SIPOC diagram is presented in the Appendix (Annex 1.). The SIPOC diagram is constructed to represent a more general illustration of how production in the PVS800 production line is managed.

4. Operational Definition

After the SIPOC diagram, the Opperational Definition is defined. The Operational Definition: Before data is presented, it is important to explain some of the meanings of the abbreviations presented in the 4Q Project. The main abbreviation is the KPI (Key Performance Indicator) used for the 4Q Project: DPU (Defects Per Unit). Defects Per Unit is the number of defects per unit, found in final control of the production line. DPU is the primary measurement for cabinets, and every defect is taken into account. The reporting frequency is weekly and the measurement method is via ABB's database. The target is set by the Factory General Manager who makes the descision based on the guidelines from Steco (Steering Committee). The target set for the DPU index in 2016 was [redacted].

These four tools and pointers conclude the 4Q Project's Define step. The VoC is determined partly in the Project Description and partly via brainstorming at a project meeting. Tools like the House of Quality and the Flowchart for example are chosen not to be used or needed at this point of the project. The SIPOC diagram and the other tools that are used are sufficient enough to move on to the Measure step.

7.2. Continuous Improvement 4Q Project – Measure

In the Measure step, the baseline is set and the first analyses of the „as-is“ situation are done. First, the historical data is shown on a general graph that presents the 12 month summary of the production line’s DPU, and the defects are presented on a pie-chart in more detail. The Control Chart, Histogram and Pareto Chart are also used to present the data in different ways. Usually, a Measurement System Analysis (Gage R&R) is necessary to be conducted as well, to estimate the variation in the measured data, but this was not done for this 4Q Project since it was considered not to be needed.

1. General graph of the DPU data

The graph consists of the DPU data from 2016 – the number of cabinets procuded each week is presented as well as the number of defects. The DPU index trendline and the target are both presented on the graph as well. The general graph of the DPU is presented in the Appendix (Annex 2.). When analyzing the graph, it is seen that there are DPU index increases in May, July, August, Spetember and December. Further analysis revealed that the peaks are not related, for example, in May and July, the DPU increase was caused by wiring defects, in August the peak was caused by broken electrical components and in September the peak was caused by damaged or wrongly assembled mechanical parts. This data is received from the ABB’s database and it is a clear indicator that the three main root causes are wiring defects, broken elekctrical components and damaged or wrongly assembled mechanical parts. These are the three main root causes that need to be analyzed.

2. Gage R&R

It would usually be necessary at this point to evaluate whether the data entering process from final control has been objective enough. However, further analysis revealed that the data inserting does not affect the common root causes of the cabinets. The only difference is whether the data inserted to the ABB’s database has been labeled as an internal or external fault. This does not affect the scope and main goal of this 4Q Project because the main goal is to lower the DPU index and find corrective actions to the main root causes regarding wiring, electrical components and mechanical parts. GageR&R is not needed at this point because the data entering has been sufficient enough for the scope and purpose of this 4Q Project.

3. Pie-chart of the common failures

Below (Figure 7.2.) is a pie-chart that illustrates the common failures in the PVS800 production line and shows the percentages of how the defects are devided between the [redacted] defects that occurred in 2016. It is seen that 37% of all the defects consist of wiring failures, 32% of all the cabinet defects consist of broken electrical components and the third biggest failure categoy is the damaged or wrongly assembled mechanical parts, which create an 11% fraction of all of the different defects.

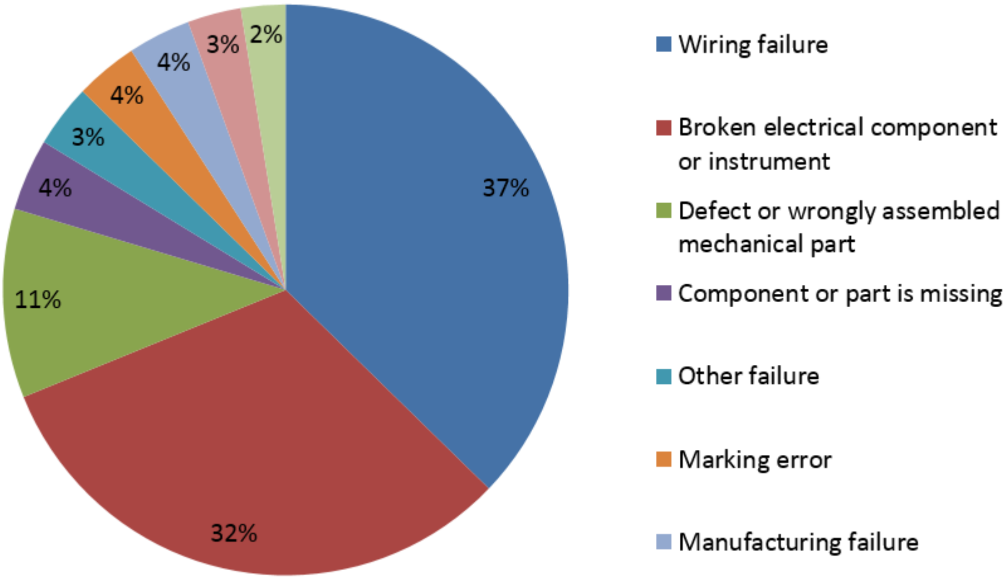


Figure 7.2. Common failures of the PVS800 production line in 2016

4. The Control Chart

A Control Chart is also plotted to illustrate the control limits of the DPU index and to determine the baseline graphically. Since the DPU index is categorized as attribute data and there may be more than one defects per sample (cabinet), the correct Control Chart to use would be the u-chart. The number of cabinets produced in one week and the average number of faults occurred that same week are taken into account – because of this, the UCL differs accoringly – this is because the sample size is unequal (shown below on Figure 7.3. as well). The chart is constructed this way because the DPU index is measured using the same principle – „per week“.

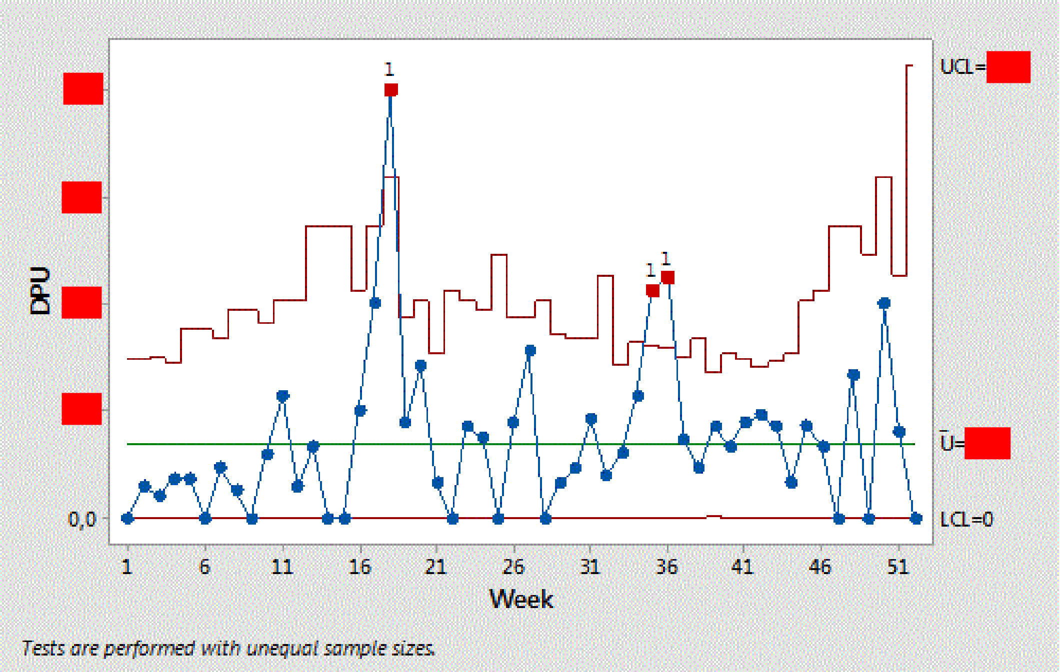


Figure 7.3. U-chart of the DPU [n(sample size) = produced cabinets in each week]

To get a more objective result, the u-chart is modified to fit the examined process. Since the tests are performed with unequal sample sizes (the number of cabinets produced each week differs), the average amount is found of how many cabinets are produced per week – the amount is [redacted]. Taking into account the average number of cabinets produced each week, the correct baseline can be found below (Figure 7.4.).

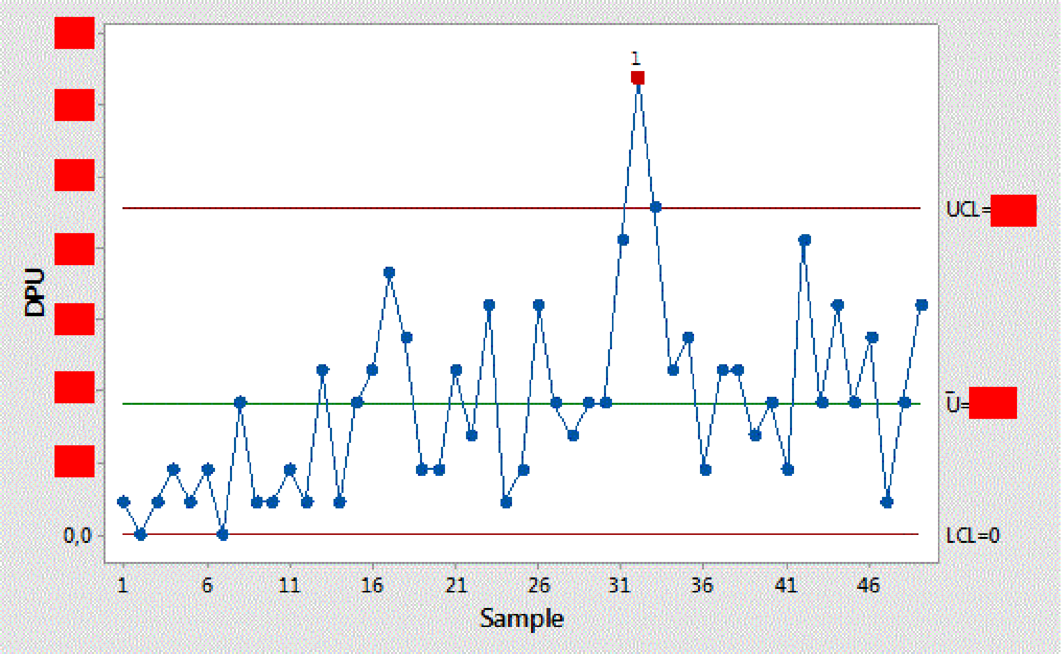


Figure 7.4. U-chart of the DPU with the fixed sample size of [redacted] cabinets produced per week

As seen from the modified u-chart above (Figure 7.4.), the sample size of cabinets produced each week is fixed. One control point is equivalent to [redacted] cabinet's DPU. There is one point out of the control limits – a special cause. The goal of the 4Q Project is not to concentrate on the special cause(s), but rather focus on narrowing the control limits. It would be ideal, if the upper control limit would be the same as the target: [redacted]. This indicates that overall variation has to be reduced.

5. The Histogram

A Histogram is also constructed to illustrate the volume of defects each individual cabinet had. The Histogram describes the most common number of defects per cabinet, the standard deviation and distribution of the sample. As seen from the Histogram below (Figure 7.5.), zero faults per cabinet is the most common result – this is the way it should be. Special cases are presented as well, there are cabinets with four and six defects but the amount is relatively small – this is not the main focus of the 4Q Project. The main goal is to analyze the more common causes – why there are one or two defects per cabinet and what the defects are.

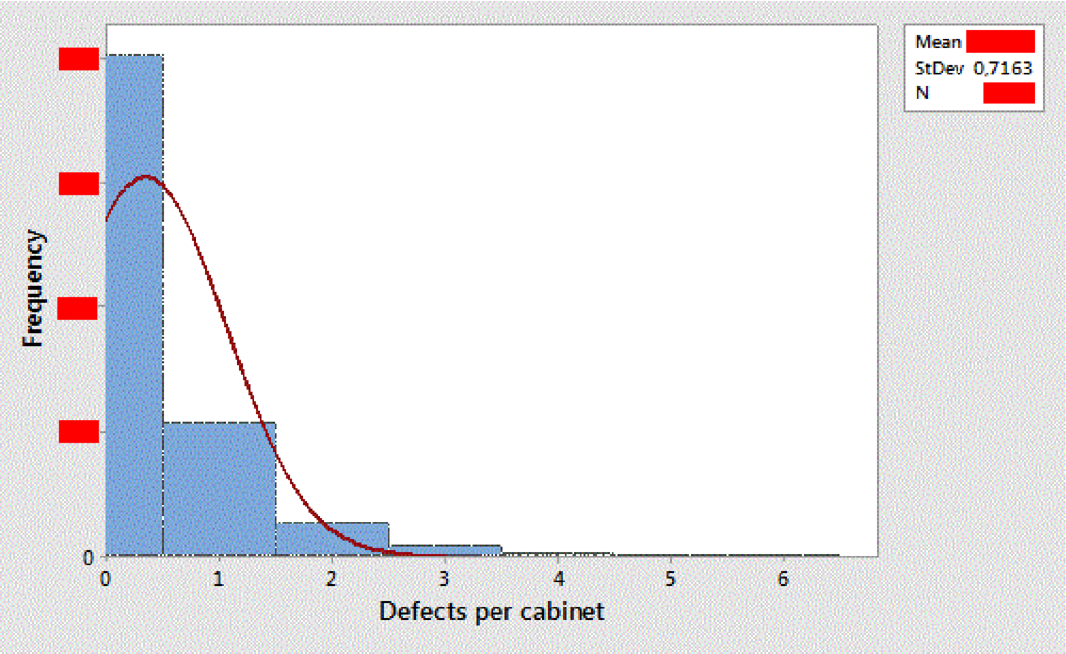


Figure 7.5. Histogram of the defects per cabinet

6. The Pareto Chart

The Pareto Chart is also a good tool and method to describe and confirm the fact that the three common failures stated earlier are the most vital. Below (Figure 7.6.) is the Pareto Chart of the main failure causes that surfaced in 2016.

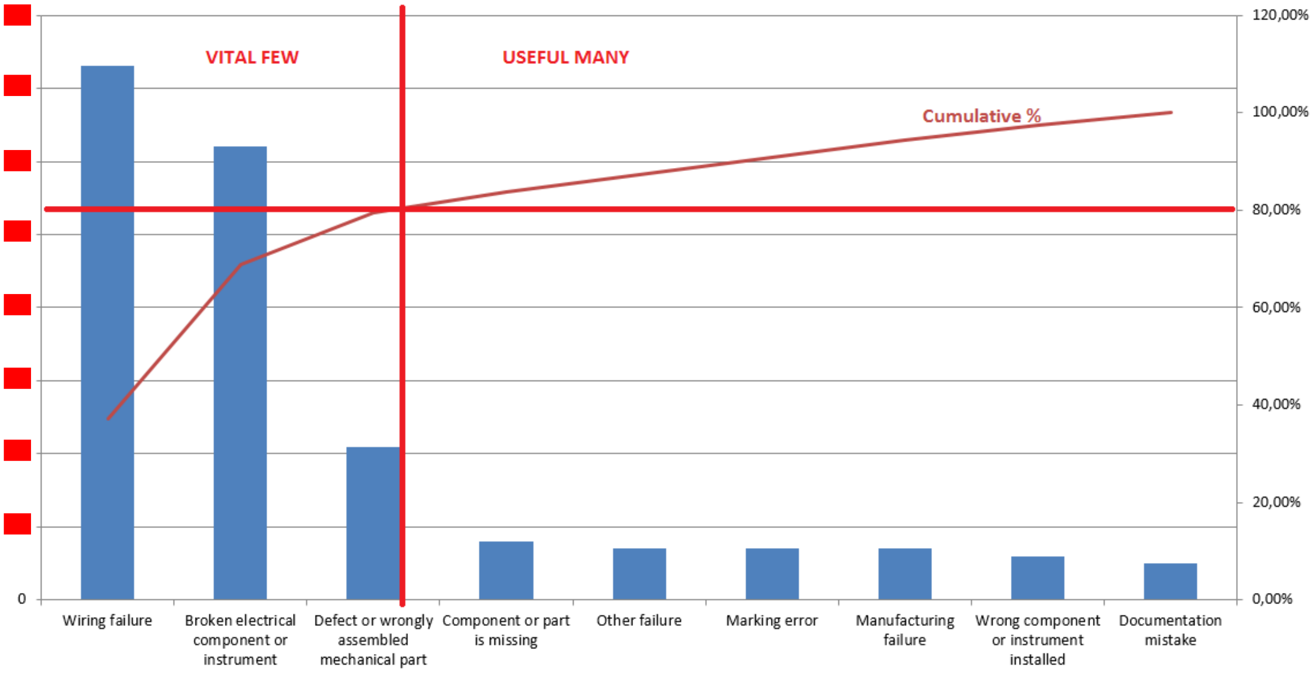


Figure 7.6. Pareto Chart of the common fault categories

As seen from the chart (Figure 7.6.), the “VITAL FEW” area is the area where the main causes are situated. The argument set earlier, that the three main root cause categories are wiring failures, broken electrical components and damaged or wrongly assembled mechanical parts, proves to be objective after constructing the Pareto Chart. These are the three main subjects that have to be analyzed in the Analyze step.

7.3. Continuous Improvement 4Q Project – Analyze

The Analyze step of the 4Q Project consists of different Fishbone diagrams and analyses done with the help of Pareto Charts. These tools are used to help define the area on which to focus on when building a soulution during the Improve step. Also, the verifying of the root causes is done.

1. Pareto Chart Analyses

To get more detailed results, the main fault categories are broken into subcategories and analyzed separately. Three different Pareto Charts are constructed and the subcategories are broken down into categories of components (except for wiring failures where the root causes do not depend on the components).

Regarding the root cause categories, data from the database is most versatile about the wiring problems – there are different categories. The data about the broken electrical components and damaged or wrongly assembled mechanical parts is more straightforward. Because of this, separate Pareto Charts are not presented about the last two – the charts are not filled with different causes. Only the Pareto Chart about the wiring defects is presented.

The information about the broken electrical components that was gathered from the first Pareto Chart suggests that there are four main components that fail the most: RDCU-boards that have connection pins broken, NAMU-boards, G10 power supplies and modules that fail during HiPot testing. The information about the damaged or wrongly assembled mechanical parts that was gathered from the second Pareto Chart suggests that there are three main components that are damaged the most: (DC) busbars, doors and Q1-switches; and one component group that is most often assembled incorrectly: busbar bolts. The most frequently occurred wiring errors are presented on the Pareto Chart below (Figure 7.7.).

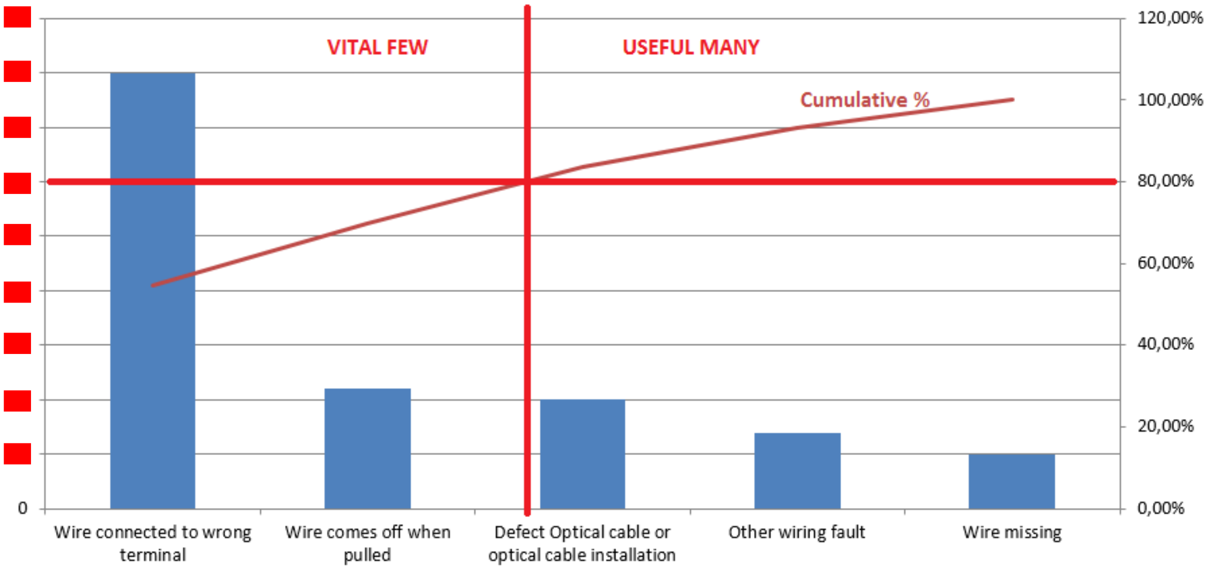


Figure 7.7. Pareto Chart of the wiring failures subcategory

As seen from the chart (Figure 7.7.), the "VITAL FEW" area is where the main causes are placed. The main wiring errors that need the most focus are "Wiring connected to wrong terminals" and "Wire comes off when pulled". These are the main root causes that need to be removed or improved. Since the second and third root causes are almost of similar size, the optical cable installation process will be taken into investigation and improvement also.

As stated earlier, the main components that have wiring issues are not going to be categorized separately, because the root causes do not depend on the components. These common root causes apply to all of the components and boards, for example, modules, G30 power supplies, NAMU-boards and so on.

2. Detailed Fishone diagrams

To find the possible root causes of the main failure categories, detailed Fishbone diagrams are constructed. The fishbone diagrams are created in a way that all the basic categories (Method, Machine, People, Environment, Measuring and Material) are taken into account. The diagrams are presented in a more simplified form. Usually, to evaluate which of the possible root causes are most vital, Matrix Analyses are done as well. This is not done for these Fishone diagrams because the Project Leader consulted with the former Process owner and workers at final control to verify the chosen categories. The Project Leader felt that there was no need to do additional analyses with the help of Matrix Analyses to categorize the more vital root causes. The detailed Fishbone diagrams are presented accordingly, based on the three main root cause categories.

2.1. Broken electrical components

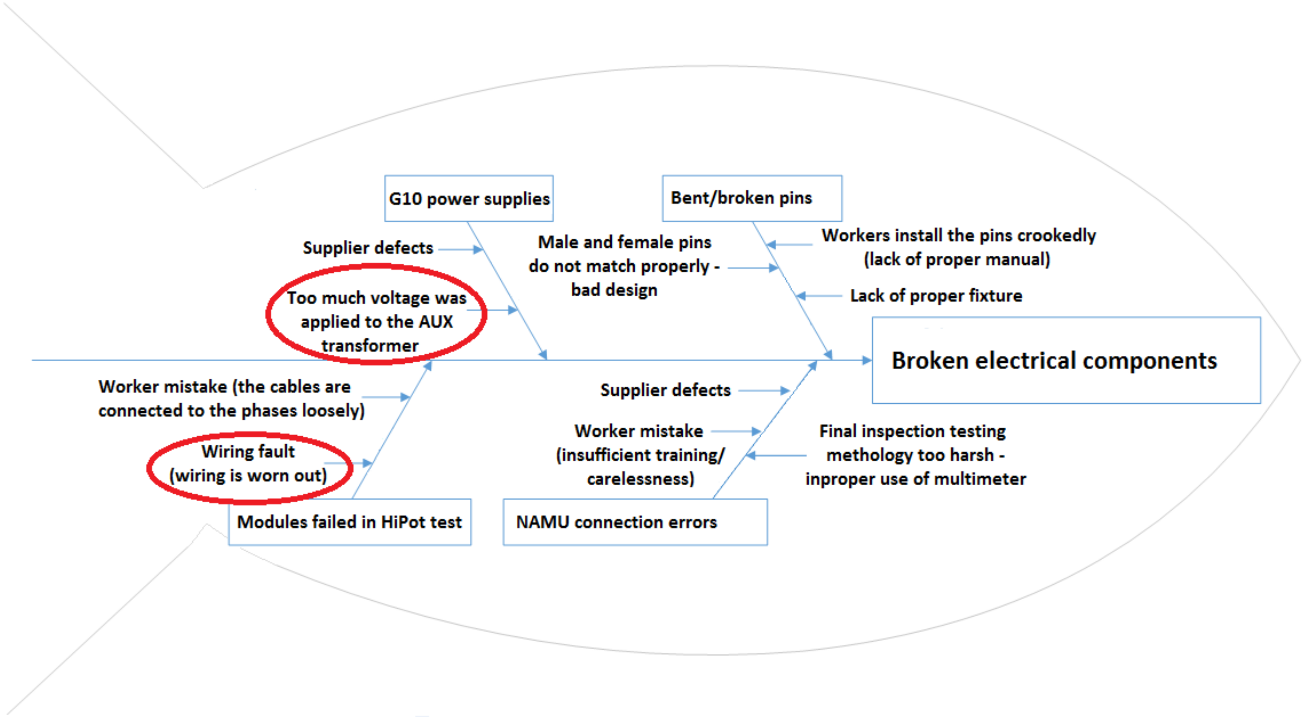


Figure 7.8. Fishbone diagram of the broken electrical components root cause category

As seen from the diagram above (Figure 7.8.), several root causes are defined. The defects regarding the G10 power supplies most probably originate from the tester's mistake, when there is too much voltage applied to the auxiliary section transformer. Regarding the failed modules at the HiPot test, this issue is being investigated already by other individuals and a separate 4Q Project is being done to eliminate this issue. The analysis done so far suggests that the main problem is in close contact with the testing wires and connection crocodiles that need a better maintenance plan.

Regarding the NAMU-board connection errors, the most probable root cause is related to the final control testing methology. But, since this is not one of the more vital root causes, this issue will not be labeled as "critical". Regarding the broken pins on RDCU-boards, this is a vital case but also an old one. The supplier has been contacted and design changes have been proposed in the past, but since this is an older product, revision changes will not be taken into account and the main root cause of the issue (male and female pins do not match properly) will not be handled.

2.2. Damaged or wrongly assembled mechanical parts

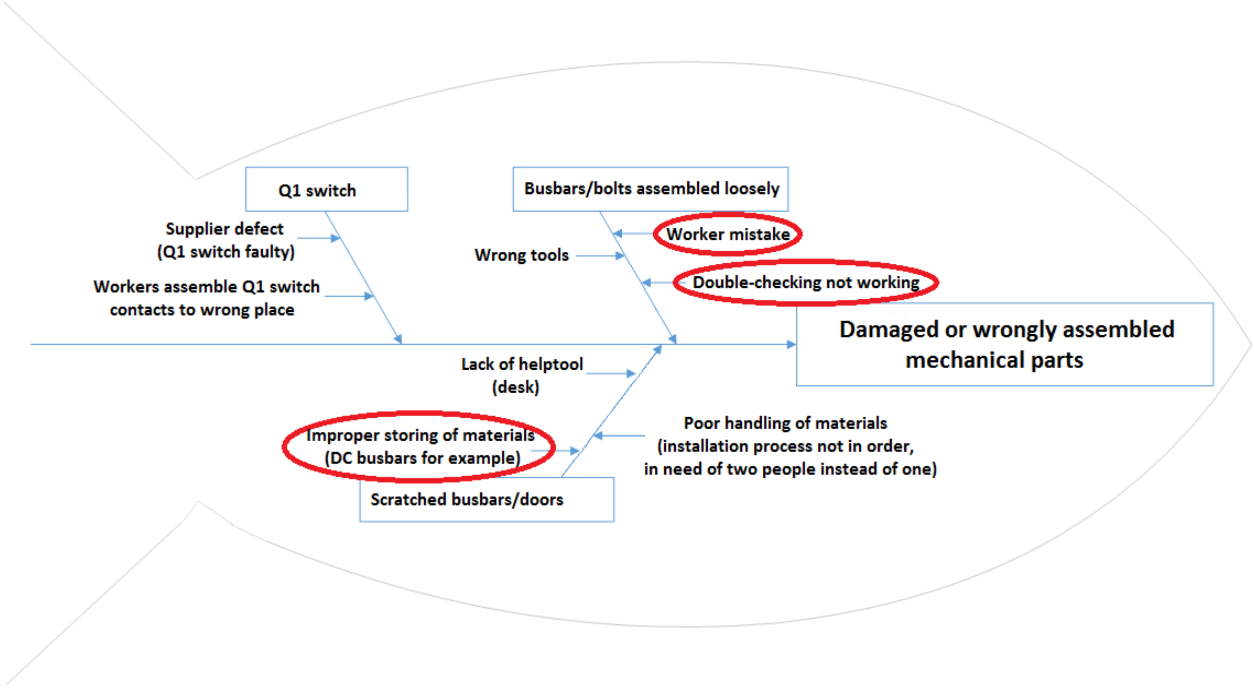


Figure 7.9. Fishbone diagram of the damaged or wrongly assembled mechanical parts

As seen from the diagram above (Figure 7.9.), the main issues are connected with the busbars and bolts that are assembled too loosely and the mechanical damages appearing on doors (and busbars). The possible main root causes for the loosely assembled busbars and bolts are closely related with worker-mistakes and unstandardized work. Regarding the scratches and other mechanical damaged on doors and busbars, the main root cause is in close contact with the improper storing of the materials. Investigation with the Senior assembler revealed that these are the main points that need to be assessed.

2.3. Wiring failures

As seen from the diagram below (Figure 7.10.), there are several critical root causes that need to be focused on regarding the wiring issues. The supplier of the wires has to be contacted so that the markings would be better – this may resolve the issues regarding the wires that are connected to wrong terminals. Also, the pulling test has to be checked and standardized – torques should be defined and some kind of Poka-Yoke device should be taken into use.

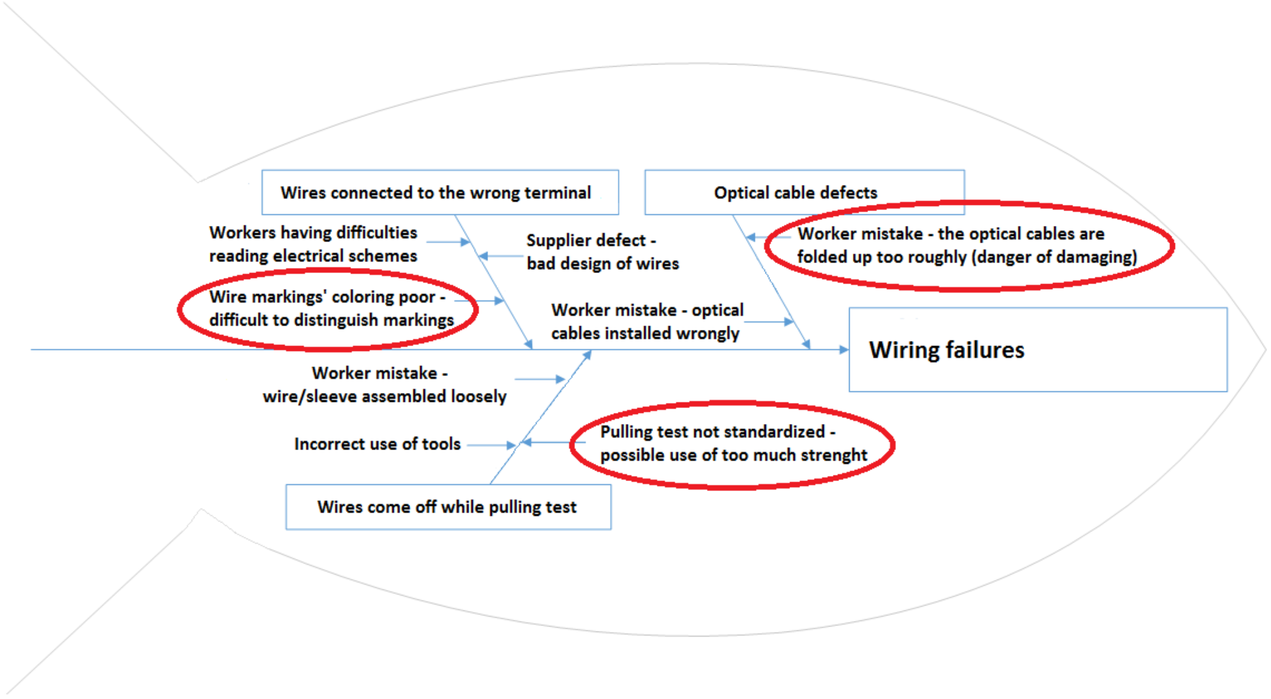


Figure 7.10. Fishbone diagram of the wiring failures root cause category

3. Verifying the root causes

After an analysis like above – when using different Pareto Charts and Fishbone diagrams to help find the root causes – verifying of the results has to be done. To verify that the data and the main root cause defining is correct, the data from the database is double checked, the Senior assembler is consulted and the data is also verified by the former Process owner. Such verifying is especially necessary since there is no using of the Measurement System Analysis nor the Correlation and Regression Analysis.

7.4. Continuous Improvement 4Q Project – Improve

During the Improve step of the 4Q Project, all of the possible solutions are listed – this is done via brainstorming with the former Process owner and some of the line-workers. Also, a Cause and Effect Matrix is used to help prioritize the possible solutions. The best solutions are picked out and the SMART Actions list is constructed. There are pictures and comments to help present the corrective actions that are implemented in the improvement plan.

1. All the possible solutions

First, all the possible solutions are listed that are achieved via brainstorming. For the three main root cause categories there are three possible solutions proposed for each.

1.1. Broken electrical components

1.1.1. Make testing manual changes to prevent shorted G10 power supplies: to prevent final control workers from applying too much voltage to the auxiliary transformer.

1.1.2. New maintenance plan for HiPot test wire sets and connection crocodiles: prevent failures and short circuit faults for modules during HiPot testing.

1.1.3. Make RDCU-board installation process change: notify workers and introduce proper manual to prevent bent or broken pin errors on RDCU-boards.

1.2. Damaged or wrongly assembled mechanical parts

1.2.1. Make double-checking process change to prevent loose busbars and bolts: update assembly manual.

1.2.2. New Kanban procedure and storing for DC busbars: to prevent scratches and other mechanical damages.

1.2.3. Make storing and transportation process change for doors: to prevent scratches and other mechanical damages.

1.3. Wiring failures

1.3.1. Make optical cable installation procedure change: update folding process to prevent optical cable defects.

1.3.2. Pulling test standardization: test pulling and also torques of wires-to-plugs attachments to prevent error: “Wires come off when pulled”.

1.3.3. Make wire markings more readable: renegotiate with the wire supplier that the wire markings would be more distinct and readable. Also, propose wire colouring changes to prevent the main error “Wires connected to the wrong terminal”.

2. Cause and Effect Matrix

To categorize and choose the best solution, a Cause and Effect Matrix is construced. Other sort of matrixes, for example the Value vs Complexity Matrix, Prioritization Matrix and Pugh Matrix could also be constructed, but the Project Leader decided to base the choosing of the best solutions on the Cause and Effect Matrix below (Table 7.3.).

Table 7.3. Cause and Effect Matrix of the proposed solutions

	Occurrence	**Easy to fix**	**Investment**	**Investment paying off**	**Estimated change to DPU decrease**	*Total score*
Make wire markings more readable	**5**	**3**	**5**	**5**	**5**	*1875*
New Kanban procedure and storing for DC busbars	**4**	**3**	**5**	**7**	**4**	*1680*
Pulling test standardization	**4**	**3**	**5**	**5**	**5**	*1500*
New maintenance plan for HiPot test wire sets and connection crocodiles	**3**	**3**	**4**	**7**	**4**	*1008*
Make storing and transportation process change for doors	**3**	**3**	**5**	**7**	**3**	*945*
Make double-checking process change to prevent loose busbars and bolts	**4**	**3**	**5**	**5**	**3**	*900*
Make RDCU- board installation process change	**4**	**3**	**5**	**3**	**4**	*720*
Make optical cable installation procedure change	**3**	**3**	**5**	**3**	**4**	*540*
Make testing manual changes to prevent shorted G10 power supplies	**3**	**4**	**5**	**3**	**3**	*540*

As seen from the table above (Table 7.3.), the upper headings (or x-axis) present the criterias that affect the choice-making of the best solutions the most. The selections on the left side (or y-axis) represent the main corrective actions of the improvement plan. The indexes are multiplied and the total score is taken into account – then the descisions are made which solutions are categorized as “best solutions”. Explanations of how the indexes were chosen:

2.1. Occurrence (the frequency of the defect occurring)
  2.1.1. 5P – over 20 faults.
  2.1.2. 4P – 10 to 20 faults.
  2.1.3. 3P – zero to 10 faults.

2.2. Easy to fix (estimated time needed for the implementation)
  2.2.1. 5P – ~one hour.
  2.2.2. 4P – ~one day.
  2.2.3. 3P – ~one week.

2.3. Investment (estimated cost of the corrective action)
  2.3.1. 5P – close to zero euros per year.
  2.3.2. 4P – close to 1000 euros per year.
  2.3.3. 3P – more than 1000 euros per year.

2.4. Investment paying off (estimated rating if the corrective actions’ savings outweigh the cost of the implementation: the number of defets, the hours needed for rework and the cost of the material are taken into account)
  2.4.1. 7P – saving of more than 1000 euros per year.
  2.4.2. 5P – saving of zero to 1000 euros per year.
  2.4.3. 3P – saving of zero euros per year.

2.5. Estimated change to DPU decrease (estimated rating of the corrective actions impact to the DPU decreasing)
  2.5.1. 5P – number of defects is lowered by ~50%.
  2.5.2. 4P – number of defects is lowered by ~20%.
  2.5.3. 3P – number of defects is lowered by ~10%.

3. Best solutions

Based on the Cause and Effect Matrix, the best solutions can be chosen by the Project Leader. There are six best solutions chosen, that are going to be focused on for the SMART Actions:

- 3.1. Make wire markings more readable,
- 3.2. New Kanban procedure and storing for DC busbars,
- 3.3. Pulling test standardization,
- 3.4. New maintenance plan for HiPot testing,
- 3.5. Make storing and transportation process change for doors,
- 3.6. Make double-checking process change for bolts/busbars.

Even though the best solutions have now been defined and chosen, all of the solutions will be implemented and dealth with accordingly, if there is time. The best solutions will be handled as higher priority cases and dealth with beforehand.

4. SMART Actions

SMART is an acronym for Specific, Measurable, Achievable, Relevant and Time-Bound. These are the characteristics all the best solutions have to be equivalent to. The tasks and chosen solutions are assigned to different people involved with the project who have to complete the assignments during the time period. Below is the table (Table 7.4.) that represent the best solutions and the responsible people behind the tasks, with the appointed times.

Table 7.4. SMART Actions table with the target and completion times

Action	Owner	Target Date	Complete Date
Make wire markings more readable	Lauri Kalm	10.04.2017	27.04.2017
New Kanban procedure and storing for DC busbars	Lauri Kalm, Einar Nahkur	17.04.2017	21.04.2017
Pulling test standardization	Lauri Kalm	10.04.2017	-
New maintenance plan for HiPot test wire sets and connection crocodiles	Kalev Starkopf, German Kruglov, Margus Onga, Lauri Kalm	06.03.2017	10.03.2017
Make storing and transportation process change for doors	Einar Nahkur, Lauri Kalm	17.04.2017	17.04.2017
Make double-checking process change to prevent loose busbars and bolts	Lauri Kalm	17.04.2017	-

5. Results from the SMART Actions and implementation plan

5.1. Make wire markings more readable

The wire markings are difficult to read and easily worn off. Analysis revealed that this is one of the main reasons why assemblers connect wires to the terminals backwards. There is one set of wires where the wire markings are covered with white „stockings“ so that the markings would be more readable. The corrective action is that all of the cabinet’s wire sets are done the same way – with white „stockings“, so that the wire markings would be more distinct and the assemblers would not install the wires backwards because of poor markings.

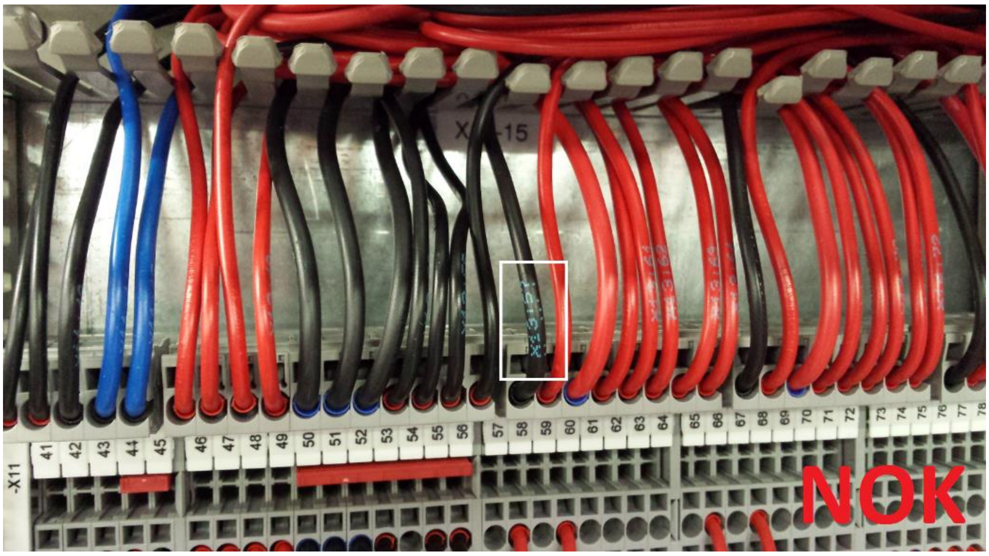


Figure 7.11. Picture of the former „as-is“ situation with wires with poor markings (NOK)

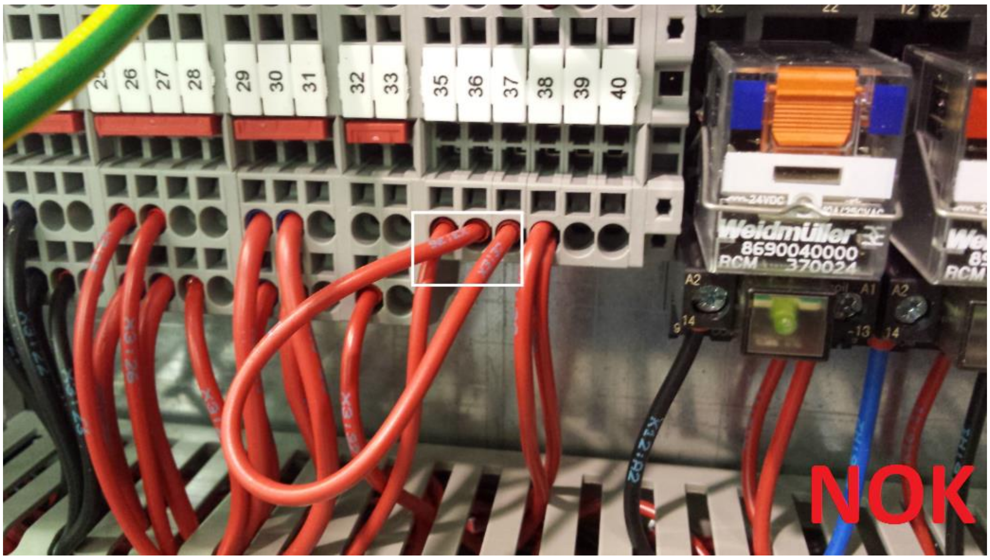


Figure 7.12. Picture of the former „as-is“ situation with wires with poor markings (NOK)

Figure 7.13. Picture of the former „as-is“ situation with wires with poor markings (NOK)

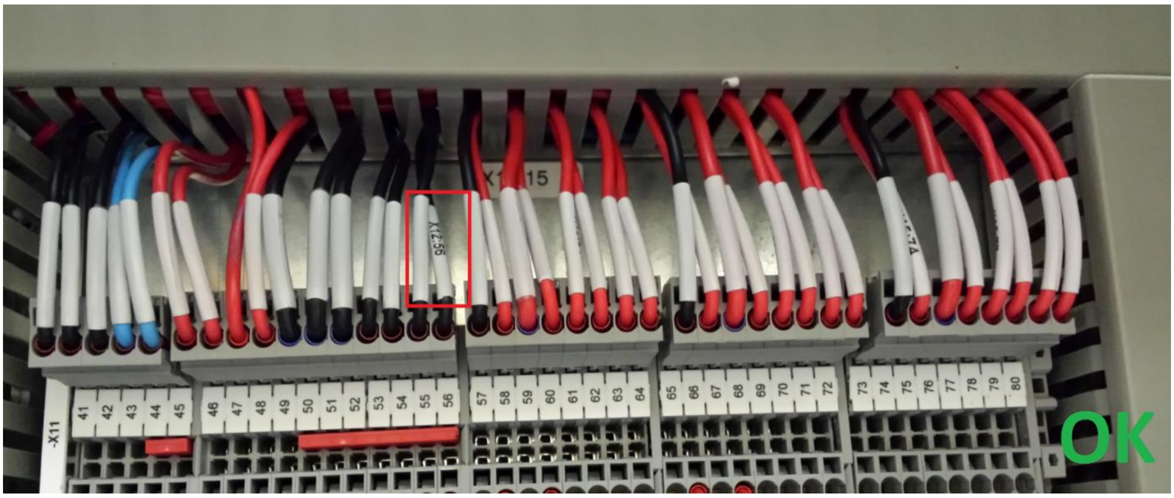


Figure 7.14. Picture of the improvement – new markings on the wires (OK)

5.2. New Kanban procedure and storing for DC busbars

There are numerous faults of busbars that are damaged and scratched mechanically. This is caused by improper storing of busbars in Kanban boxes and from the fact that the busbars’ edges are too sharp.

The first idea was to improve the storing of the busbars by applying protective bubble wrap around the busbars or to put protective layers between the busbars. This is not implemented because the cost of the improvement action would be too high and the time expenditure would be too long. Instead, the supplier of the busbars is contacted and a corrective action is inquired from them. The supplier has to eliminate the sharp edges of the busbars so that the scratches caused because of friction would be minimal. After the implemented change the scratches should reduce significantly because the sharp edges are smoothened.

Figure 7.15. Picture of the former „as-is“ situation with busbars with sharp edges (NOK)

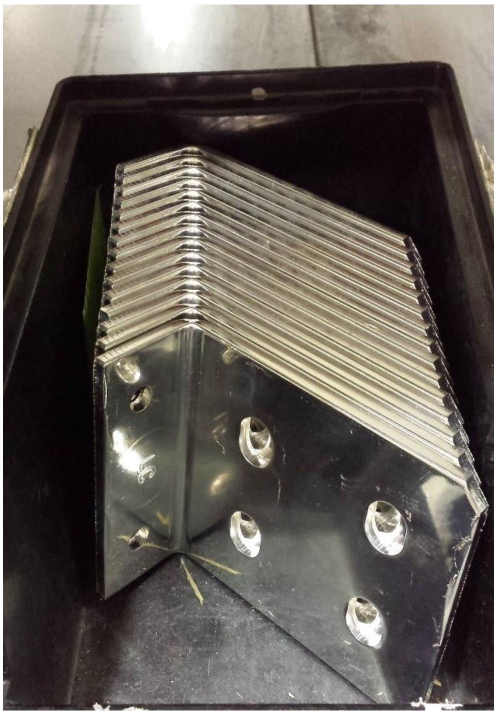


Figure 7.16. Picture that shows the storing of the busbars (not going to be changed)

Figure 7.17. Picture of the improvement – sharp edges removed from busbars (OK)

5.3. Pulling test standardization

For this solution there is no time to implement according corrective actions. This issue will be eliminated within another improvement project in the future.

5.4. New maintenance plan for HiPot testing

To reduce the danger of modules failing at HiPot testing, the maintenance plan is updated: wire sets will be changed once every three months now, as seen from the outtake as well (Figure 7.19.). Before, the wire sets were changed only once a year or once every two years.

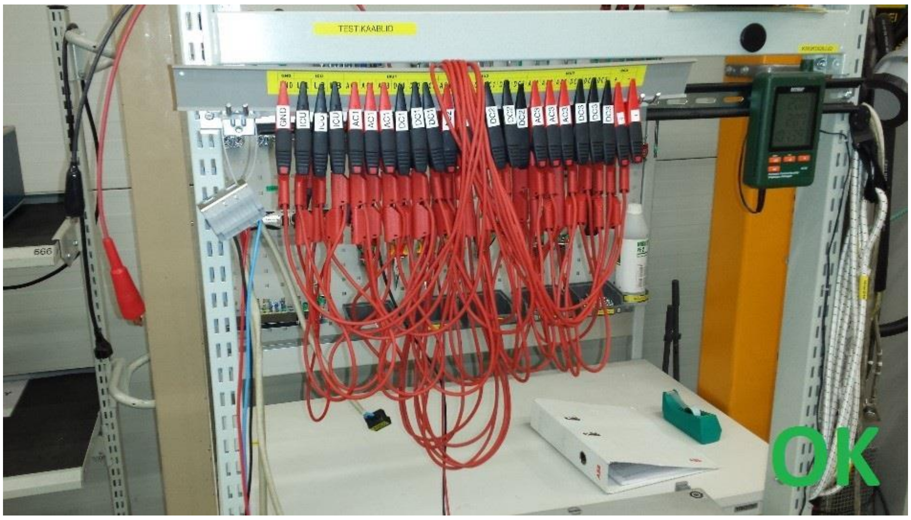
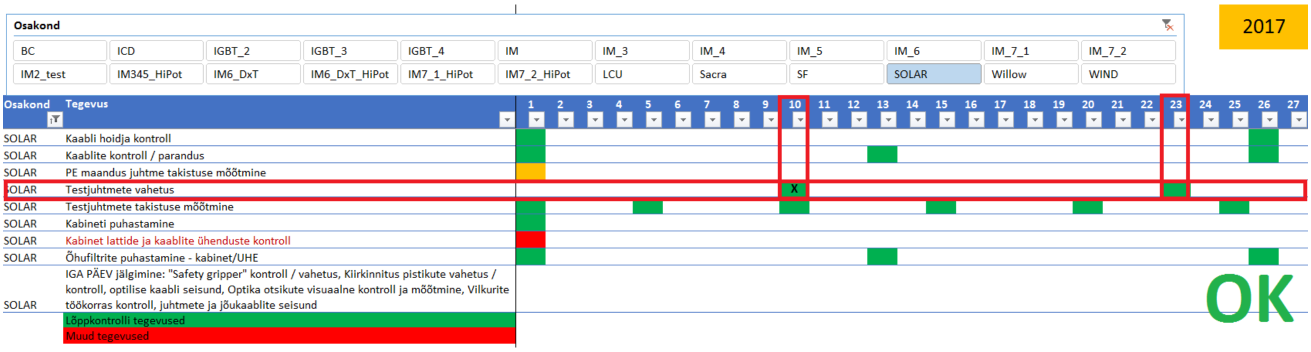


Figure 7.18. Picture of the improvement – new wires ordered once every three months (OK)



Osakond

BC | ICD | IGBT_2 | IGBT_3 | IGBT_4 | IM | IM_3 | IM_4 | IM_5 | IM_6 | IM_7_1 | IM_7_2
IM2_test | IM345_HiPot | IM6_DxT | IM6_DxT_HiPot | IM7_1_HiPot | IM7_2_HiPot | LCU | Sacra | SF | SOLAR | Willow | WIND

Osakond	Tegevus	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
SOLAR	Kaabli hoidja kontroll	🟩																									🟩	
SOLAR	Kaablite kontroll / parandus	🟩												🟩													🟩	
SOLAR	PE maandus juhtme takistuse mõõtmine	🟨																										
SOLAR	Testjuhtmete vahetus										X													🟩				
SOLAR	Testjuhtmete takistuse mõõtmine	🟩				🟩					🟩					🟩					🟩					🟩		
SOLAR	Kabineti puhastamine	🟩																										
SOLAR	Kabinet lattide ja kaablite ühenduste kontroll	🟥																										
SOLAR	Õhufiltrite puhastamine - kabinet/UHE	🟩												🟩													🟩	
SOLAR	IGA PÄEV jälgimine: "Safety gripper" kontroll / vahetus, Kiirkinnitus pistikute vahetus / kontroll, optilise kaabli seisund, Optika otsikute visuaalne kontroll ja mõõtmine, Vilkurite töökorras kontroll, juhtmete ja jõukaablite seisund																											

🟩 Lõppkontrolli tegevused
🟥 Muud tegevused

Figure 7.19. Picture of the improvement – outtake from the new maintenance plan (OK)

5.5. Make storing and transportation process change for doors

To reduce mechanical damages on doors, the supplier is contacted. It is implemented that the supplier would send the doors in bubble-wrap – this was not done before. Also, the green trolleys that transport the doors are fitted with a thin layer of softening plastic so that the doors would not get scratched. These two corrective actions should reduce the amount of doors that get mechanically damaged durig transportation.

Figure 7.20. Picture of the former „as-is“ situation with danger of doors getting mechanically damaged (NOK)

Figure 7.21. Picture of the improvement – doors are now sent in bubble-wrap (OK)

5.6. Make double-checking process change

Like for the Pulling test standardization solution, there is no time to implement corrective actions for this solution. This problem will also be eliminated within another improvement project in the future.

7.5. Continuous Improvement 4Q Project – Control

During the Control step of the 4Q Project, SPC is done – the „to-be“ Control Chart is plotted and the Two-Sample Poisson Rate Test is performed to present the p-value. Also, cost saving calculations are made. Since there was little time to analyze the changes that would take effect after the implementations, the amount of data is too insufficient to make trustworthy conclusions – therefore estimation calculations are made of how much the number of defects per each root cause category would decrease, based on the made improvement actions. Based on the estimation calculations and the data provided by the ABB’s database, there were 42 cabinets manufactured in one of the last months in the Jüri Factory, and from this amount, there were 12 defects. The 12 defects include seven wire pulling test faults, two transformer wire faults, two faults where wires were connected to the wrong terminal and one wrongly installed label fault. As seen from the data, the wire pulling test defect is still an issue. Also, there are still two „wires connected to the wrong terminal“ faults which imply that this root cause still needs to be dealth with as well, even though the percentage has decreased.

1. SPC – the Control Chart

Like for the Control Chart constructed in the Measure phase of the 4Q Project, the sample size of the 42 cabinets produced is fixed to the sample size of [redacted] cabinets per week, so that the data would match the former chart. The „to-be“ Control Chart is fitted with the control limits that are calculated after the corrective actions have been implemented. Since there was little time to make a thorough observation of the performance indicator change, there are only four data points that present the data. This is usually considered to be too few for attribute data. Nontheless, the plotted chart can be taken as an indicator to see if the improvement plan’s corrective actions are affecting the process and if the control limits have expanded or narrowed. The Control Chart is presented below (Figure 7.22.).

As seen from the u-chart below (Figure 7.22.), the control limits have narrowed and the mean has lowered 22% after the implementation. This data is a clear indicator that the corrective actions have affected the process for the better. The only problem is with the probability that the process will stay in stable conditions. For the purpose of this thesis, this result is sufficient enough, but for the purpose of the 4Q Project in ABB, there are additional data gatherings needed to ensure that the process has indeed improved.

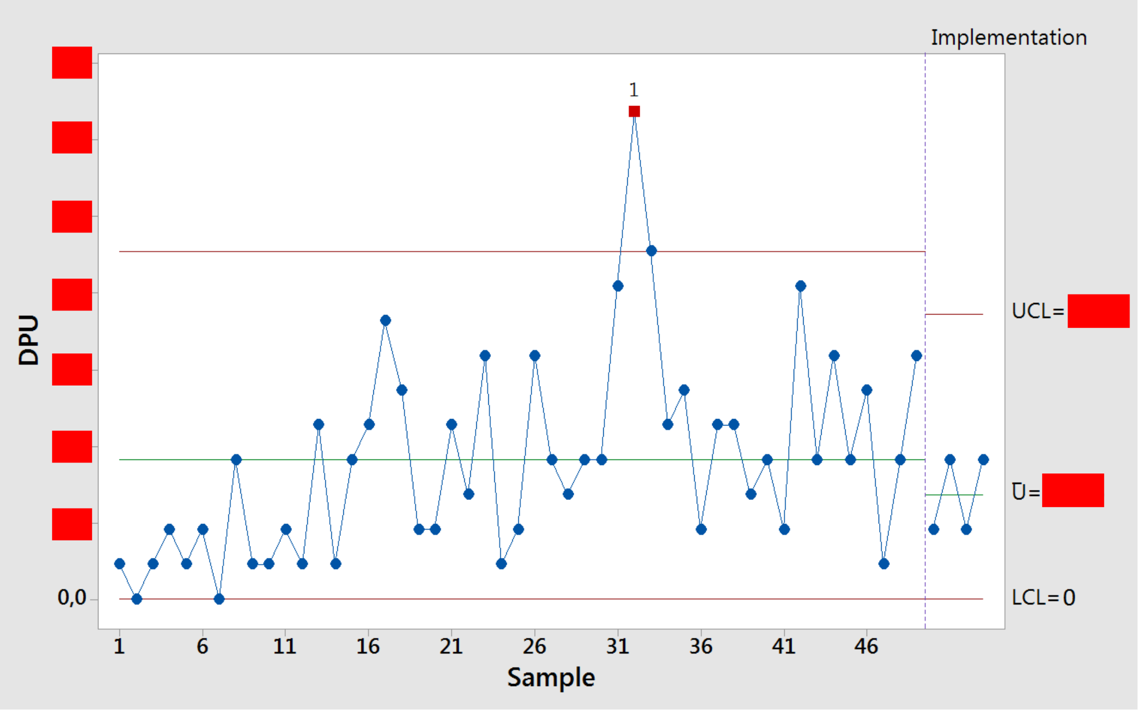
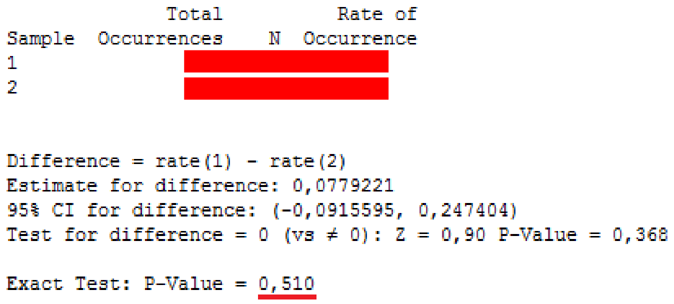


Figure 7.22. U-chart of the DPU with the new control limits after the implementation

2. Two-Sample Poisson Rate Test (p-value)



```
                Total                Rate of
Sample   Occurrences      N   Occurrence
1                 [redacted]
2                 [redacted]


Difference = rate(1) - rate(2)
Estimate for difference: 0,0779221
95% CI for difference: (-0,0915595, 0,247404)
Test for difference = 0 (vs ≠ 0): Z = 0,90 P-Value = 0,368

Exact Test: P-Value = 0,510
```

Figure 7.23. Snip from the Two-Sample Poisson Rate Test done in Minitab

To see if the rate of occurrence for before and after the changes differ, the p-value is found. As seen from the snip (Figure 7.23.), the calculated p-value is 0,510. Therefore, the data is consistent with the null-hypothesis and the population defect rates do not differ significantly between the two measured values. This is not a good indicator and suggests that additional analyses and improvements need to be made.

3. Cost saving calculations (Cost-Benefit Analysis)

To evaluate the savings of the 4Q Project, the four improvement actions that were implemented are all taken into account. The working time saved because of the decreased DPU index is taken into consideration and the savings of the materials are taken into account also, regarding busbars, doors and modules. No investments were needed for the implementation of the corrective actions, except for the wire sets that are changed every three months, to ensure that modules do not fail during HiPot testing. When the saved working hours, the prices of the materials and the needed investment are all determined, the cost saving can be calculated. Since the salary of the factory workers and the prices of the materials cannot be published, the result is reflected in a more general way.

Table 7.5. Table of the estimated cost savings

	Per Year (euros)
Saving because of saved working hours	100
Saving because of saved materials	7733
Investment	-5780
Winnings	**2053**

As seen from the table above (Table 7.5.), the saving for the workings hours came up to around 100 euros per year, the saving for the unscrapped materials came up to around 1953 after the investment was calculated off. The total saving of the project is therefore about 2053 euros per year. A 2000-euro cost saving result of an improvement project like this is considered to be a rather weak result. But, for a learning project it can be considered acceptable, especially considering the fact that the main goal of the project was to reduce the overall variation and the DPU index – this kind of an objective does not reflect in the faniancial savings that outstandingly.

The Control phase turned out to be successful – the Control Chart reflects a result that shows that variation did indeed decrease. The problem with the result is that there are not enough data points to base the analysis on. The cost saving calculations show that the project produces a saving, even though the winnings are not substantial. The results can be taken as indicators that the process is improving and if new projects are done with additional corrective actions then the DPU index can be shifted back into stable conditions.

8. CONCLUSION

The main goal of this thesis was to improve the performance indicator at a production line in ABB. By analyzing and improving the performance indicator, the different threats to a frequency converter's production process were determined. By improving the production line's performance indicator and determining the threatening factors, the production line's overall manufacturing process was improved and variation was reduced. The goal at hand was achieved with the help of the Six Sigma methodology and the tools used in the DMAIC cycle.

First, the DMAIC tools were defined. The thesis' first part consists of a 28 page theoretical part, where the history of Continuous Improvement is introduced. The general meanings of Six Sigma and the DMAIC cycle are defined and the tools used in the DMAIC cycle are also presented. The tools were selected from different literature sources and categorized based on the frequency of their occurrences in the 4Q Project. There are three main tools presented in the Define chapter, four main tools presented in the Measure chapter, three in the Analyze chapter and two main tools introduced in the Control chapter of the thesis.

The second part of the thesis consists of a 26 page practical part, where the 4Q Project, that was compiled in ABB, is introduced. As stated above, the purpose of the project was to define the factors threatening the reliability of a frequency converters production line and improve the business performance indicator which was the DPU index. The project starts with the Define phase, where the project description is given and the overall information is presented, for example with the help of Operational Definition. The Measure step of the project consists of the presenting of the „as-is“ situation. A pie-chart, Control Charts, Histogram diagram and Pareto Chart were contructed to illustrate the conditions of the production line. All of the charts concluded the same thing, that the three main root cause categories that threaten the PVS800 production line, are wiring failures, broken electrical components and damaged or wrongly assembled mechanical parts – this is the conclusion of the Measure phase.

The Analyze phase consists of Pareto Analyses and Fishbone diagrams that give a more detailed approach to finding the root causes of the three main defects. After the analysis, the Improve phase was compiled. During this step, the remaining root causes were categorized to help find the most vital ones. A Cause and Effect Matrix was also constructed and the root causes were taken into account so that the improvement actions could be listed. The four main corrective actions that were implemented consisted of changes done to the wire markings, development done to the busbars so that the sharpness of the edges would be reduced, a new maintenance plan for the wire sets at HiPot testing and changes done to the door transportation process. There were also a few improvement actions that could not be implemented because of lack of time – these actions are taken into implementation during future improvement projects.

The Control step of the 4Q project consists of the analysis of the effect of the implemented corrective actions. A Control Chart was contructed to show the change of the control limits and the DPU index. Also, the cost saving calculations' results were presented. The result of the Control Chart was acceptable – the process' mean reduced 22%. However, there was not enough time to gather a sufficient number of data points which indicate that actually the result of the chart cannot be taken as a hundred percent proven outcome. The data was gathered from only one month after the improvement changes were implemented and the number of cabinets produced – 42 – is not high enough. But, the fact that variation did decrease and the DPU index reduced even for a small amount of cabinets – this can be taken as a clear indicator that the corrective actions do affect the process for the better.

The cost saving calulactions concluded that due to the projects improvement plan the company will save around 2000 euros per year. As stated earlier, a 2000-euro cost saving result for an improvement project like this is considered to be a rather weak result. But, considering the fact that the main goal of the project was to reduce overall variation and the DPU index, then even a small amount of winnings is considered to be positive.

Overall, the thesis' author evaluates the work to be successful – the goal stated in the assignement was not achieved a hundred percent, but the results in the analysis revealed that the process is improving towards the set objective. The DPU index decreased by 22% – from [redacted] to [redacted]. This work can be taken as an indicator that the corrective actions do improve the process, but additional work still needs to be done so that DPU will reduce an additional 9%.

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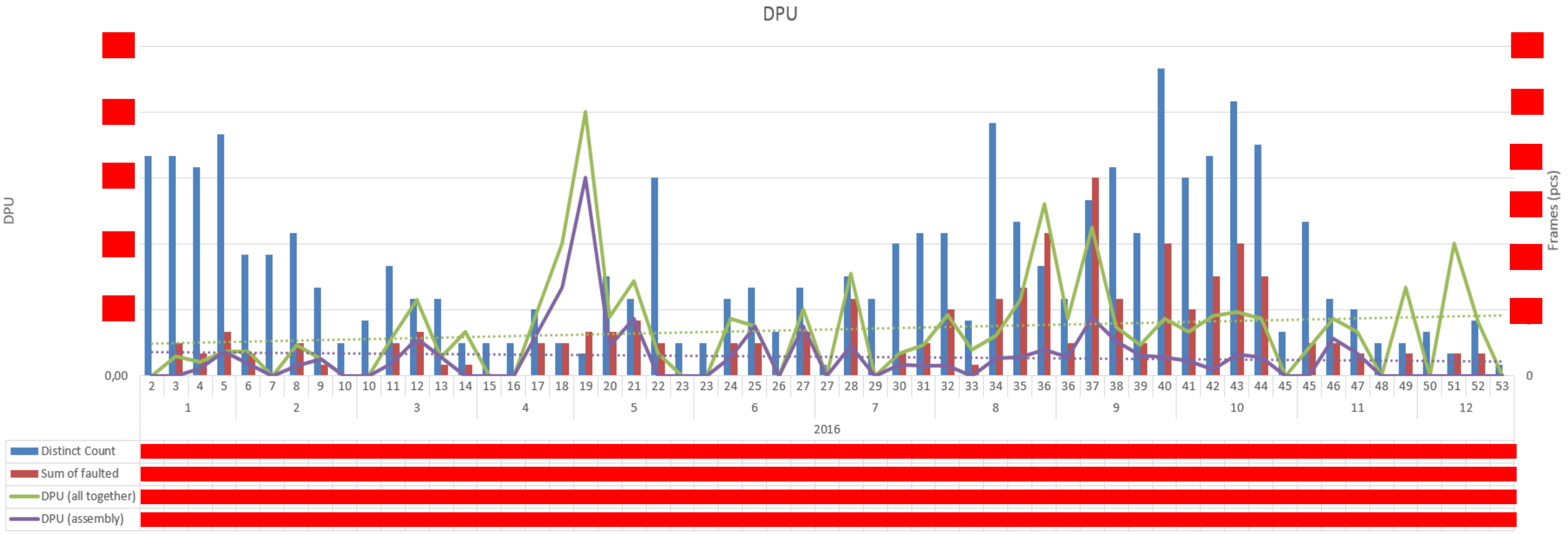
APPENDIX

Annex 1.

S	I	P	O	C
End Client	Order	An order is placed by the client.	Cabinets	Testing
Frame supplier	Invoice	The order is handled by the Sales team and sent to the Planning team.	Testing data	Packing
Material supplier	Materials	The Planning team plans the schedule and then forwards the order to production.	Entries in Chronos	Production Manager, Drives Sales deptartment
Sales, Planning, Engineering departments	Know-how (human resources, technical drawings, manuals etc.)	Production takes place in the subassembly production line and the main assembly production line.	KPI	End Client
		After assemblying the cabinet goes into testing where numerous tests are performed depending on the client's demands.		
		After testing the cabinet goes into packing and shipment to the customer.		

Annex 2.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1 2 3 4 5 6 7 8 9 10 11 12
2016
Distinct Count [redacted]
Sum of faulted [redacted]
DPU (all together) [redacted]
DPU (assembly) [redacted]