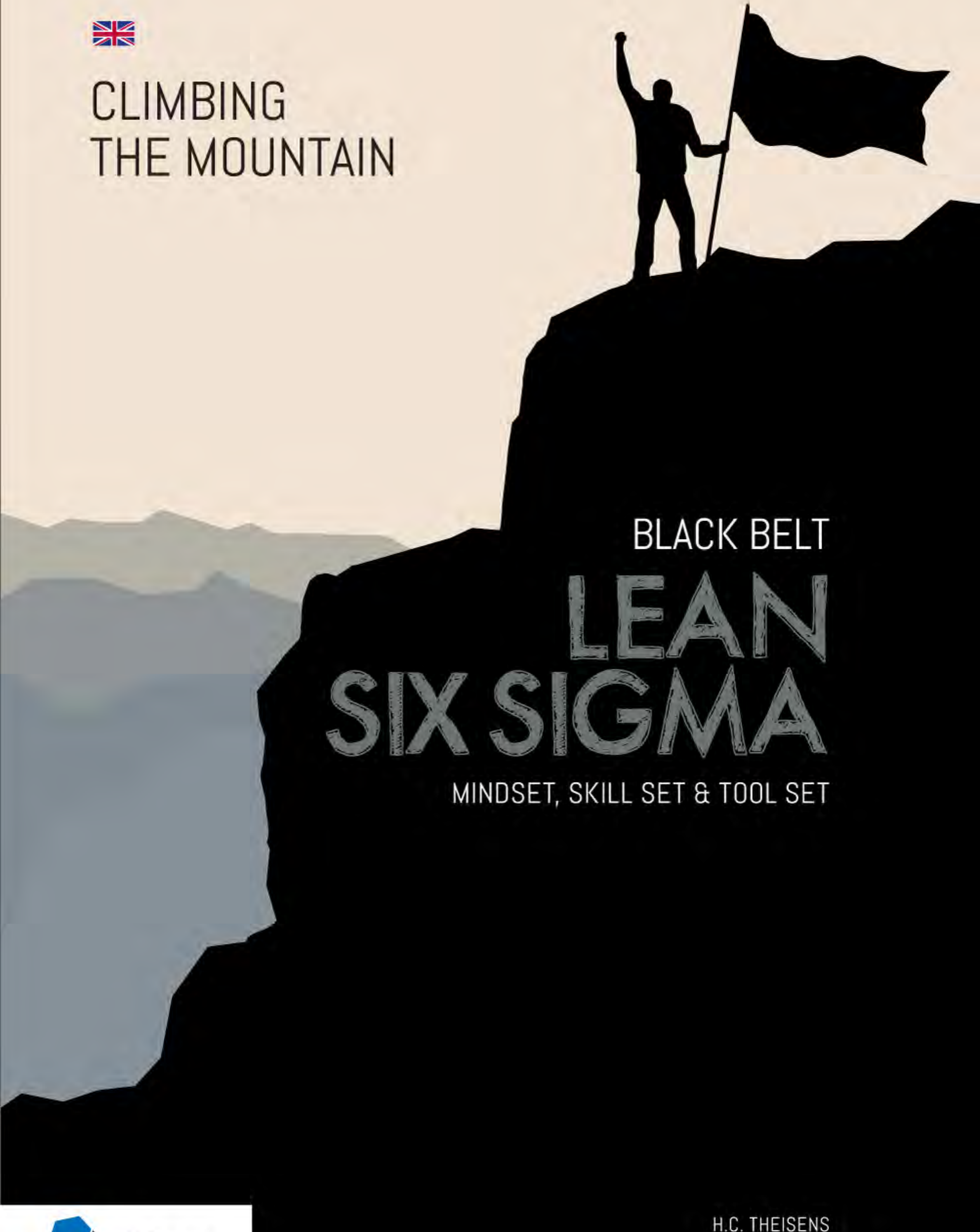
CLIMBING
THE MOUNTAIN



BLACK BELT

LEAN SIX SIGMA

MINDSET, SKILL SET & TOOL SET

H.C. THEISENS

Van Haren
PUBLISHING

LEAN SIX SIGMA BLACK BELT

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Content

Introduction

Would you consider buying a new smart phone from a certain phone provider if your friends keep complaining about connection problems or bad service? You probably would not. You also would probably not want to go to a school with a reputation for poor teaching, a hospital with a high rate of infections due to bad hygiene, or to eat in a restaurant that had served you bad food before. It does not matter what type of product or service we keep in mind; good service, good quality and a proper response time are important for all products and services that we buy. We expect a product to meet our expectations and to do so without defect.

Because of the internet, consumers can obtain a huge amount of information about the performance of products and organizations. It is very easy to compare prices of different suppliers and a product or service can be ordered at any time. If we book a restaurant we ask our friends if the food and service are good. If we have to wait two weeks for a new TV to be delivered we would probably order it somewhere else. If we call the service desk of our internet provider, we expect to talk to a person within a few minutes and they should have the knowledge to answer our question. If we buy a book, a jacket or a new laptop, we expect to receive the product within 24 hours. On top of that we expect companies to develop new models every year. Of course, we expect the price of a new model to be the same as the old model or even less. Do you, as a consumer, have any idea what this means for companies that have to develop and deliver these products? In past decades the increasing quality expectations and shorter Lead Times has had a huge impact on innovation, production, quality management and supply chain management. If a company is not able to keep up with this, it will not survive. Each year many companies, both small and large, have to close their doors because they cannot meet the increasing expectations of customers. Companies and organizations must constantly improve their knowledge of processes and quality control in response to increasing customer requirements for higher quality and shorter Lead Times.

Since process improvement has been going on for decades, process improvement techniques have been applied for decades. Different methodologies have been developed over the years like Lean Manufacturing, Kaizen, 'Theory of constraints' (TOC), 'Total Quality Management' (TQM), 'Total Productive Maintenance' (TPM) and Six Sigma. Many books have been published about process improvement and quality management by people like Deming, Imai, Taiichi Ohno and Eliyahu Goldratt. These methodologies have helped companies to make significant improvements. The methodology that is most suitable for your organization depends very much on where it stands right now and what it needs to do in order to reach a next level of performance. It is important to determine the level of Operational Excellence before an improvement program is deployed. Over past years, an integration has taken place based on best practices from improvement methodologies like Kaizen, Lean, Six Sigma and others. This book will explain these methodologies and an all-inclusive approach of the most commonly applied tools and techniques.

You may think that these methodologies are only applicable for car manufacturers or high-tech companies. It is correct that Lean and Six Sigma have made it possible for these types of companies to become better and faster. However, the same methodologies that served these manufacturers can also help service organizations, government and healthcare organizations to improve their quality, improve their response times and effectiveness, and lower their operational costs.

The ascent to the top of the mountain can be tough, as the path is full of technical and organizational obstacles. You will discover that the journey is also a very interesting, instructive and satisfying one. The roadmap and techniques described in this book will give insight and understanding of a number of powerful tools and techniques to improve processes and quality. As the entire journey of becoming World Class cannot be taken overnight, you do not have to read this book entirely at once. We recommend that you begin by identifying the current state of your organization using the CIMM framework described in paragraph [1.1.3]. This will clarify which chapters will be interesting for you to read and which approach and techniques will be useful to apply in order to reach the next level.

How to use this book

Hundreds of books have been published over the years about process improvement and quality management. You can find many different books on Lean Manufacturing or Six Sigma. This book is different because it addresses the relation between Lean and other improvement methods that have been proven to be successful over the past decades, such as TQM, Kaizen, TPM and Six Sigma. These methods, tools and techniques have been united in the 'Continuous Improvement Maturity Model' (CIMM™). CIMM is an open standard and is maintained by the 'Lean Six Sigma Academy' (LSSA). The framework describes the process of Continuous Improvement from a very early stage through to delivering World Class products and services. The CIMM framework connects Lean, Six Sigma and other improvement methods. The framework incorporates the best practices, methods and techniques of process improvement, quality management and new product development. The framework also connects the so-called 'Hard'-elements of process improvement and the so-called 'Soft'-elements of organizational development and change management.

The structure of this book is based on the LSSA Skill set for Lean and Six Sigma Black Belt [19.]. All of the techniques described in these Skill set will be reviewed in this book. The Lean elements will be discussed in chapter 1 to 6. The Six Sigma elements will be discussed in chapters 7 and 8. We also advise you to use the accompanying exercise book with exercises and answer keys. In case you would like to subscribe for LSSA certification, we advise you to review the criteria described in Appendix A and B. Those who would like to apply Lean at the Yellow or Green Belt level are advised to read the specific book within the 'Climbing the Mountain' series.

This book can be used for two purposes. Firstly, it acts as a guide for Black Belts undertaking a Lean or Six Sigma project following the DMAIC roadmap ('Define – Measure – Analyze – Improve – Control'). Secondly, it is a guide for (Master) Black Belts that are involved in improving the overall performance of the organization and to lead the continuous improvement transformation process.

How to execute a Lean or Six Sigma project
Typical objectives of a Lean project are to reduce Lead time or processing times. A Lean project can also aim to reduce operational costs or improve quality. The typical Lean approach is about reducing Waste. Running an improvement project is rarely just about applying techniques only. Those who participate in Lean or Six Sigma training and have been assigned an improvement project should realize that skills like project management and managing change are critically important elements. These elements are specifically discussed in chapters 2 and 3.

Different roadmaps can be applied to manage a Lean project, such as the PDCA roadmap (Plan – Do – Check – Act), the Value Stream Map or the DMAIC roadmap. Chapter 4 is about creating a solid fundament to become a Lean organization. Techniques like 5S, standardization and implementing a quality management system are the focus in this phase. Chapter 5 is about creating a Continuous Improvement culture. Daily standup meetings and executing many small improvement projects (Kaizen events) is the approach followed in this phase. Chapter 6 is about creating stable and efficient processes by mapping the Value stream, reducing Waste and by implementing the Flow and Pull concepts. At the beginning of this chapter an overview of recommended Lean tools is provided that can be used within a Lean DMAIC approach. This overview is a good starting point to help you out. But keep in mind that each improvement project will be different and selecting the proper tools for a certain problem in a certain phase is something you learn with experience.

Typical objectives of a Six Sigma project are to improve process 'Capability' (Cpk) in order to reduce performance outside specification. The focus of these type of projects is about reducing variation. Six Sigma projects are very much data driven. This requires additional techniques which are reviewed in chapter 7. Without data available, it will be very difficult to execute a project on this level.

How to bring your organization to a higher maturity level

Those who are involved to develop the performance of the entire department or organization may use this book to develop an improvement policy and to learn which elements are important to address in order to involve the entire organization in the policy deployment process. Chapter 2 reviews the development and deployment of a continuous improvement strategy. In this chapter, we will review how to define a clear strategy (True North), Lean leadership, management of change and explain how to create a Continuous Improvement culture. Defining the current maturity level of the organization is the starting point here. The Continuous Improvement Maturity Model is discussed in paragraph [1.1.3]. At the end of Chapters 4 to 8, an assessment is presented that can be used to define the maturity at a certain CIMM-level.

The main role of the Champion, Deployment leader or (Master) Black Belt is to develop the improvement strategy and to lead the deployment of the strategy. Hoshin Kanri [paragraph 2.2.3] is a valuable tool to support the process of policy deployment. (Master) Black Belts support and coach Green and Black Belts in execution of the improvement project. Guidelines are given in the first part of this book that will help you and your organization from the very beginning until World Class performance.

Preface

What would it be like to work in an organization where everything is predictable and runs smoothly? How would it be if you as a quality employee or process owner no longer have to deal with errors or incidents? How would it be for a manager if the strategy is clear, everyone knows what his or her contribution is and there is enough time for all projects? Unfortunately, reality is very different for most organizations. Even though organizations often look beautiful from the outside, there is still a lot to improve and processes are not nearly as stable and predictable as you would like.

Many organizations currently apply Lean Six Sigma as a holistic approach for continuous improvement. This approach is supplemented with principles and techniques from other improvement methods such as Total Productive Maintenance (TPM), Theory of Constraints (TOC) or Agile. It is the combination of different methodologies that helps organizations best.

It is important to realize that applying improvement techniques is only one side of the story. The creation of a Continuous Improvement culture is also important. This covers matters such as strategy, leadership, organizational structure, change management and team development. This is also referred to as the 'Soft' side of continuous improvement, but in practice this is often the most difficult aspect. It is necessary to make people work in a different way. However, changing the organization is not easy. People, in general, do not like change unless they see the benefit of the change. Implementing an operational excellence successfully is a major challenge for management and Belts. This book has been a guidance for thousands already; it is useful as a guideline for selecting the right projects, successfully executing these projects and to lead change within an organization.

I want to thank everyone who helped with reviewing this book. In total, around 25 experts from various companies and organizations made a valuable contribution in the past years. I would also like to thank the people who have contributed to the development of the 'Continuous Improvement Maturity Model' that has already helped many organizations in determining their improvement strategy. This model has been the basis for this book.

ir. H.C. Theisens
Master Black Belt Symbol B.V. (the Netherlands)

"It always seems impossible until its done."

— Nelson Mandela —

1 World Class performance

World Class Performance is the highest level that an organization can reach within its own sector by developing new products and services that exceed customer expectation in a very short time-to-market. In order to achieve World Class Performance, organizations need to develop and produce products and services that are the best in the world. Its production and delivery process should perform at the level of Operational Excellence and the organization should continuously improve its processes.

World Class Performance is not something that you can realize in a few months. Unfortunately, there is no golden roadmap to success. Working to become World Class is a long and bumpy journey with successes and setbacks. There will be roadblocks on the winding way to the top of the mountain. It is very unlikely that all people involved will reach the summit. Some will fall behind while others will drop off. Although this is not a joyful perspective, it is a path that must be followed if you want to stay competitive in the future as most of your competitors work on Continuous Improvement.

1.1 Continuous Improvement

"We can't manage to deliver on time; We suffer a lot from errors and internal rejection; The involvement of employees in continuous improvement is not up to standard; We suffer a lot from disruptions in our supply chain; Our customers' requirements are becoming increasingly complex; We have no control over the work in process; We would like to involve our suppliers in our continuous improvement process."

Maybe you recognize some of the aforementioned issues within your organization or maybe other issues are at play. Each organization has the challenge to provide products and services with maximum value for their customers at the lowest possible cost and with the shortest delivery time. In order to achieve this, organizations must constantly work to improve their processes and develop the organization. Continuous Improvement is not only about improving the processes, but also about developing the organization and the employees. In this section we will review the culture, values, principles and roles within a Continuous Improvement organization.

1.1.1 Continuous Improvement history

In the last few years, the Lean and the Six Sigma philosophies have merged to Lean Six Sigma as a holistic view and approach for continuous improvement. Lean Six Sigma is a combination of Lean Manufacturing and Six Sigma and uses a combined set of both Lean and Six Sigma tools. It also embraces best practices from other improvement methods like Total Quality Management, Total Productive Maintenance and Theory of Constraints. Lean Six Sigma includes a common goal of Lead Time reduction, operational cost reduction and overall quality improvement. Combining the synergies of Lean and Six Sigma provides organizations with greater speed, less variation and more bottom-line impact. Lately, many organizations have also added Agile to their continuous improvement strategy.

The origin of managing quality goes back thousands of years. The construction of the great pyramids of Cheops in 2560 BC could not have taken place without Quality Management. Even today, people are still amazed at how the 5.5 million tons of limestone, 8,000 tons of granite and 500,000 tons of cement were used in the construction of the Great Pyramid (Romer, 2007). The accuracy of the pyramids is such that the four sides of the base have an average deviation of only 58 millimeters in length (Cole, 1925). The base is horizontal and flat up to ±15 mm (Lehner, 1997). The ratio of the circumference to the height is equal to 2π with an accuracy higher than 0.05%. "Although the ancient Egyptians could not define the value of π precisely, we can conclude that they actually used it in practice" (Verner, 2003).

The four industrial revolutions
In the past two centuries, development has progressed rapidly and four industrial revolutions can be distinguished. The first industrial revolution (1780-1850) is characterized by the steam engine. In 1777, James Watt's first steam engine was set up in a quarry in Cornwall. With the arrival of the steam engine, it became possible to replace work done by people, animals or windmills with a machine. This period marks the transition to new production processes.

The second industrial revolution (1850-1970) is also known as the technological revolution. The best-known example of the second industrial revolution is Ford's production line. Henry Ford designed his first running assembly belt in 1913 for the T-Ford which unleashed a revolution in manufacturing. It was Henry Ford's goal to "Set the world on wheels" and produce an affordable car for the general public, with the simplest design at the lowest possible cost. This assembly line became the benchmark for mass production methods worldwide. The introduction of the diesel engine in 1894, as an alternative to the steam engine, made an important contribution to the further development of production lines. Furthermore, the First and Second World War had a major influence on the development of mass production.

The third industrial revolution (1970-2010) is characterized by the introduction of the computer in the 1950s. Digitization made it possible to transfer data from analogue data carriers to digital data carriers. This allowed information to be shared and consulted easily and anywhere in the world. Partly because of this, it became possible for companies to globalize their business. Production and delivery could take place worldwide, so that economies of scale were realized. Examples of the third industrial revolution are the use of 'Programmable Logic Controllers' (PLCs), 'Computer Aided Design & Manufacturing' (CAD / CAM), mechatronics and robotics. The first applications of robotics have been made in the Automotive industry, where, among other things, welding activities and assembly work is carried out by robots.

Currently we are at the beginning of the fourth industrial revolution (i4.0). The digital revolution, 'Internet of Things' (IoT), technology platforms and artificial intelligence play an important role in this era. The development of new technologies introduces a service mentality in the industry, similar to the development of Smartphones and Apps. Systems, machines and goods will communicate with each other about logistics, operations and performance while the human interference with the product will be reduced. Disciplines such as planning, engineering, delivery, maintenance, quality and service are further integrated. Industry 4.0 will drastically change the world in the coming decade and will require new business models. This is a threat to those who stand still while offering opportunities for those who are moving.

History of Total Quality Management (TQM)
The concept of quality, as we think of it now, first emerged during the Industrial Revolution. Previously, products had been made from start to finish by the same person or team of people, with handcrafting and tweaking the product to meet 'quality criteria'. Mass production brought huge teams of people together to work on specific stages of production where one person would not necessarily complete a product from start to finish. In the late 19th century, pioneers such as Frederick Winslow Taylor and Henry Ford recognized the limitations of the methods being used in mass production at the time and the subsequent varying quality of output. Henry Ford (1863 – 1947) was the founder of Ford Motor Company and sponsor of the development of the assembly line technique of mass production. Many would say that Lean started with Henry Ford. Initially this was more a Lean initiative than a quality management initiative. Each T-Ford was supplied in any desired color (as long as it was black) and was supplied with a tool box in the trunk. Later, Ford emphasized standardization of design and component standards to ensure a standard product was produced. Management of quality was the responsibility of the Quality department and was implemented by inspection of product output to 'catch' defects.

Walter Andrew Shewhart (1891 – 1967) was an American physicist and known as the father of statistical quality control. He has set the basis for the control chart and bringing the production process into a state of ‘Statistical Process Control’ (SPC). He is also the founder of the PDCA circle (then called PDSA). The application of statistical control evolved during World War II where quality became a critical component of the war effort.

Sir Ronald Aylmer Fisher (1890 – 1962) was an English statistician. According to some, he created the foundations for modern statistical science. His important contributions to statistics include the ‘Analysis of Variance’ (ANOVA) and ‘Design of Experiments’ (DOE).

After World War II, the Japanese welcomed the input of Americans Joseph M. Juran (1904 – 2008) and W. Edwards Deming (1900 – 1993). Juran was a management consultant and engineer. He wrote several influential books on quality management. This was illustrated by his ‘Juran Trilogy’, which is composed of three managerial processes: quality planning, quality control and quality improvement. He was one of the first to write about the Cost of Poor-Quality (COPQ). He is also known for the ‘Vital few versus Useful many’ statement, also known as the Pareto tool or ‘80/20 rule’. Deming was an American statistician after whom the Deming Prize for quality is named (1951). Deming proclaimed the PDCA circle for solving problems from Shewhart. Deming is regarded as having had more impact upon Japanese manufacturing and business than any other individual of Japanese heritage. He was only just beginning to win widespread recognition in the U.S. at the time of his death in 1993.

Quality management in the United States came much later as a direct response to the quality revolution in Japan. By the 1970s, U.S. industrial sectors such as automobiles and electronics had been broadsided by Japan’s high-quality competition. The U.S. response became known as ‘Total Quality Management’ and consists of continuously improving the ability to deliver high-quality products and services to customers. TQM typically relies heavily on the previously developed tools and techniques of quality control. TQM enjoyed widespread attention during the late 1980s and early 1990s before being overshadowed by ISO 9001, Lean Manufacturing and Six Sigma. Many of its principles and tools, however, are still present in today’s quality management programs.

History of Kaizen

Masaaki Imai (born 1930) is a Japanese organizational theorist and management consultant, known for his work on quality management. Masaaki Imai wrote the groundbreaking book ‘Kaizen: The Key to Japan’s Competitive Success’ (1986). Through this book, the term Kaizen was introduced in the western world. In the same year, he founded the Kaizen Institute Consulting Group (KICG) to help Western companies introducing the concepts, systems and tools of Kaizen.

“It does not matter how slowly you go as long as you do not stop.”

Confucius

The Japanese word Kaizen means ‘Change for better’, in the same sense as the English word ‘Improvement’. Another definition of Kaizen is ‘To disassemble and put together again in a better way’. Today Kaizen is recognized worldwide as an important pillar of Continuous Improvement, especially small incremental improvements at the shop floor, also called the ‘Gemba’.

History of Total Productive Maintenance (TPM)

Within machine intensive factories such as food, pharma, chemical and automotive, 'Total Productive Maintenance' or 'Total Productive Management' (TPM) is a commonly used Continuous Improvement approach. The method focuses on the effective and efficient use of equipment by avoiding breakdowns, delays and machine-related rejections. This is achieved to ensure that more is produced using existing machinery.

Preventive maintenance was developed by U.S. factories that supplied the military during the Second World War. After the war, preventive maintenance was introduced in Japan (1951). Nippon Denso (Toyota Group) was the first company to introduce preventive maintenance plant wide (1960). Nippon Denso was the first company to receive the prestigious prize from the 'Japanese Institute of Plant Maintenance' (JIPM) for the implementation of TPM. In 1987 the first real TPM initiative in the U.S. was developed by the Kodak's Tennessee Eastman facility.

History of Lean

Lean focuses on stability and elimination of Waste. Lean Manufacturing began with Henry Ford who was the first person to truly integrate an entire production process. He did this by lining up fabrication steps in process sequence using Standardized Work and interchangeable parts. Ford called this 'Flow' production (1913). The problem with Ford's system was its inability to provide variety. As mentioned, the Model-T was limited to one color and to one specification. As a result, all Model-T chassis were essentially identical until the end of production in 1926.

In the 1930s, and more intensely just after World War II (1950), Kiichiro Toyoda, Taiichi Ohno and others at Toyota started looking at Ford's situation. While Ford was producing 8,000 vehicles per day, Toyota had produced only 2,500 vehicles in 13 years. Toyota wanted to scale up production but lacked the financial resources required for the huge quantity of inventory and subassemblies as seen at the Ford's plant. What impressed Ohno even more than the visit to the Ford factory was the visit to the 'Piggly Wiggly' supermarket. At that time, Japan did not have a supermarket where customers could pick up their products themselves and where the stock on the shelves was frequently replenished from the warehouse. This process inspired Ohno to set up production in the Toyota factory in the same way and only produce what the next process needed. Toyota developed its famous 'Toyota Production System' (TPS) to avoid the problems and high costs of large inventories. TPS includes some of Ford's ideas, but also incorporated the philosophy of 'Just In Time' (JIT) and 'Pull', based on Piggly Wiggly's supermarket concept.

In 2008, Toyota became the world's largest auto manufacturer in terms of overall sales. Over the past two decades, Toyota's continued success has created an enormous demand for further knowledge concerning Lean Thinking. There are literally hundreds of books, papers and other resources currently available to this growing Lean Management audience.

The Lean thought process is thoroughly described in the book 'The machine that changed the World' (Womack and Jones, 1990) and in a subsequent volume, 'Lean Thinking' (1996), which specifically describes the five Lean principles. The concepts of Lean have been widely distributed around the world. Lean principles and tools are being applied in production, logistics and distribution, services, trade, health, construction, maintenance and even in government with the common goal of reducing turnaround time and operational costs while at the same time improving quality. One of the most important activities within Lean programs is the identification and elimination of Waste, also called 'Muda'. Within a value stream eight types of waste can be distinguished: over-production, waiting, transport, over-processing, inventory, movement, defects and unused expertise. We will review value and waste in more detail in Chapter [6].

History of Six Sigma

It was 1979 when Motorola was engaged in a painful process of self-discovery and began to realize the extent to which it had lost market share in many key segments, including televisions, car radios and semiconductors. That same year, during a company officers' meeting, Motorola's President and CEO Bob Galvin asked the question, ‘What is wrong with our company?’ Many officers and corporate chiefs began voicing the standard, politically correct excuses. Blame it on the Japanese, blame it on the economy in general, blame it on weak research and development. While all this was going on, a lone voice in the back of the room spoke up loudly and clearly saying, ‘I will tell you what is wrong with this company... Our quality stinks!’ That voice was Art Sundry, a sales manager for Motorola's most profitable business at the time. Everyone thought he would be fired for this ballsy assertion. How could someone make such a statement in such horrible and turbulent times? Surely Motorola had always been and still was among the world's best manufacturers, regardless of the hard times it was facing (Mikel J. Harry). Motorola was at a major turning point in its history. It could continue on a downward trend relative to competitors, or it could break that trend with an ambitious culture change and quality improvement initiative. This was the moment Motorola began its search for ways to eliminate Waste and improve its quality. Two Motorola engineers, Bill Smith and Mikel Harry, were credited for their pioneering work aimed at improving processes and for finding and resolving defects. Their work on process capability, tolerance, critical-to-quality characteristics and design margins laid much of the foundation for what today is called Six Sigma.

Six Sigma focuses on capability and reducing variation. Recognizing a link between fewer defects and lower costs, Motorola set out to incorporate this connection into their manufacturing processes, which they called ‘Six Sigma’. Motorola's Six Sigma quality program was so radical that managers were forced to think about the business differently. Applying these concepts to Motorola's electronics manufacturing delivered more than $2.2 billion in benefits within four years and $16 billion within 15 years. Motorola's CEO Bob Galvin cited the work of Bill Smith and Mikel Harry in achieving these benefits.

One of the companies that embraced the Six Sigma philosophy was General Electric (GE). GE Chairman, Jack Welch was told that Six Sigma could have a profound effect on GE’s quality. Although skeptical at first, Welch initiated a huge campaign called ‘the GE Way’. He made an official announcement and launched the quality initiative at GE's annual gathering of 500 top managers in January 1996. Welch described the program as ‘The biggest opportunity for growth, increased profitability and individual employee satisfaction in the history of the company’. His goal was to take quality to a whole new level and to become a Six Sigma quality company, producing nearly defect-free products and providing nearly defect-free services and transactions. Welch’s intention was to infuse quality into every corner of the company. He later called Six Sigma ‘the most difficult stretch goal’, but also suggested that it was ‘the most important initiative GE had ever undertaken’. General Electric saved more than $12 billion with Six Sigma in the five years after implementation.

1.1.2 Continuous Improvement values and principles

In the previous paragraph we have discussed that within the domain of Continuous Improvement, various methodologies have been introduced over the past few decades. Each of these methodologies contains a certain set of tools and techniques, but before we review these, it makes sense to first review their values and principles. In this paragraph, we will discuss the values and principles of the most important methodologies like Kaizen, Lean, Six Sigma and Agile. Although there is no common, global set of values and principles of Continuous Improvement, there are certainly similarities between them. For instance, all have a strong foundation of improving customer value by involving the entire organization in the Continuous Improvement efforts.

Kaizen principles

Kaizen is about teamwork and empowerment. Participation is voluntary, but not without commitment. It is a bottom-up approach and encourages the involvement of all employees. As such, Kaizen is an approach that is often used to create a culture of Continuous Improvement. Kaizen is carried out at the place where it happens: the shop floor or 'Gemba'. When problems occur, you should 'Go to the Gemba' rather than looking for solutions behind a desk or in a meeting room. Problems on the shop floor are experienced mostly by employees on the shop floor, rather than by managers sitting behind spreadsheets and PowerPoints. Employees on the shop floor very often have good ideas for solutions and improvements. The only issue is that managers forget to ask them and involve them.

The five foundations of Kaizen are listed in Table 1.

Kaizen principle	Description
Teamwork	Create commitment for all
Personal discipline	Follow the standards
Better moral	Ensure good work morale
Quality circle	Follow the PDCA improvement cycles
Suggestion for improvement	Be receptive to new ideas and suggestions

Table 1 – Kaizen principles

Lean principles

Womack, Jones and Roos published two successful books entitled 'The machine that changed the World' (1990) and 'Lean Thinking' (1996) [21.]. Both books address the revolution in manufacturing represented by the Toyota Production System of the Toyota Corporation of Japan. They compared this way of working with the traditional mass production system that was used by other companies in the Western world. They described in their book 'Lean Thinking' the following five principles:

Lean principle	Description
Value	Define what is of value to the customer
Value stream	Identify the value stream and eliminate Waste
Flow	Create a constant flow
Pull	Deliver based on demand
Perfection	Continuously improve the process

Table 2 – Lean principles

We will describe each of these five principles briefly. In Chapter 6 we will review them in more detail and also show how applying these principles will result in shorter Lead Times and better quality.

1 – Value

The first principle is to define who your customer is and understand what the meaning of value is for your customer. Lean takes the customer as the starting point because in the end, satisfied customers are the reason for the existence of your organization and your job. But who is your customer? Sometime it is very clear to define your customer, but sometimes it is less obvious. Once you can point out who your customer is, it is also important to be able to define customer value, also called the 'Voice of the Customer'.

2 – Value stream

The value stream is the operational process, or all concatenated activities that ultimately lead to the product or service as delivered to the customer. Not every activity can be classified as value-adding. A value adding activity must meet the following requirements: the customer is willing to pay for it; it must be performed correctly the first time and the activity must alter the product or service in a certain way. If one of these criteria is not met, the activity is classified as a non-value-adding activity or Waste. One of the main objectives of Lean is to identify and eliminate Waste.

3 – Flow

Lean is focused on getting the right things in the right place at the right time in the right amount to achieve a perfect Flow. The easiest way to observe Flow is to take a look at the shop floor. At one side you see orders entering the shop floor (e.g. parts, components, sick patients, clients, bins, trucks, requests, etc.)., while at the other side you see finished products leaving the shop floor (e.g. finished product, healthy patients, products, passports, answers, etc.). At the shop floor itself, employees and equipment are busy adding value to the products or services. The more products are idle or waiting, the less Flow is present. If no Flow is experienced, there is no Lean.

4 – Pull

Imagine what would happen if each step in the process produces the amount that it is capable of, without accounting for what is actually needed. This would result in true chaos with huge piles of stocks and work in process between process steps. To prevent this, it is necessary to work according to the 'Just In Time' principle. This means that activities only take place at the right time and in the right amount. This can be achieved by applying Pull. Pull means that the subsequent process step determines the amount to be delivered by the previous process step. This starts with the customer who Pulls first. Working according to Pull instead of Push will prevent piles of work and overproduction.

5 – Perfection

Lean focuses on continuous improvement of processes through the implementation of many small improvement projects, also known as Kaizen events. Typical for this type of project is the elimination of Waste and the reduction of Cycle Times. The continuous execution of Kaizen projects is an important element of the fifth Lean principle. Many small improvement steps will result in a major improvement in the end.

In addition to the main five principles, Dr. Jeffrey Liker, a University of Michigan professor of industrial engineering, published 'The Toyota Way' [14.] in 2004. The book describes the 'Toyota Production System' (TPS). TPS borrowed ideas from Ford but added the 'Just In Time' (JIT) philosophy and the 'Pull Concept' to address the issues of high cost associated with Ford's large inventories. The Toyota Production System is an integrated system that comprises its management philosophy and practices. In his book Liker calls this "a system designed to provide the tools for people to continually improve their work". Liker defines 14 principles, organized in four sections.

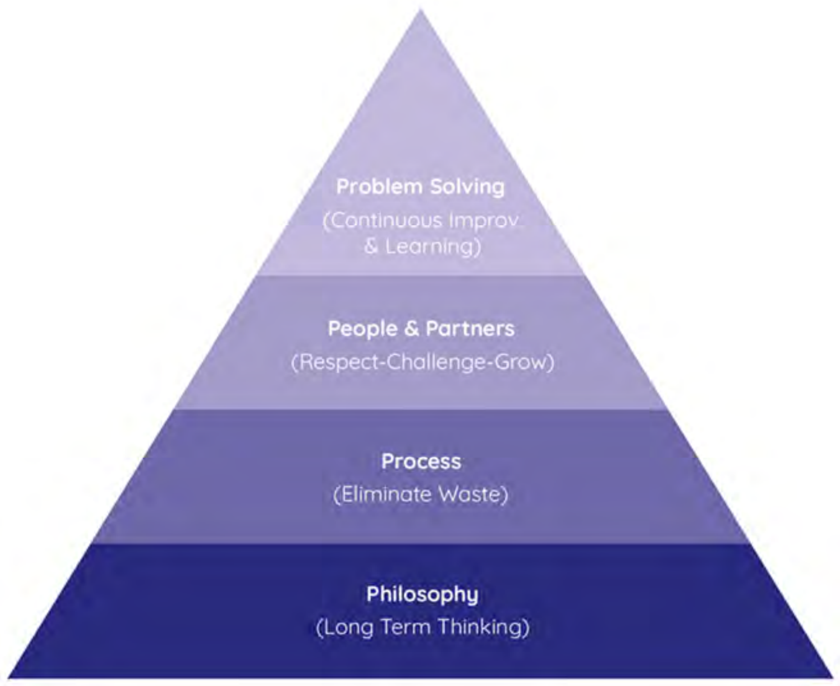


Figure 1 – Toyota Production System (Liker, 2004)

Philosophy – 'Base your strategy on a long-term philosophy':

1. Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.

Process – 'The right process will produce the right results':

2. Create a process flow to surface problems.
3. Use Pull systems to avoid overproduction.
4. Level out the workload (Heijunka).
5. Stop when there is a quality problem (Jidoka).
6. Standardize tasks for Continuous Improvement.
7. Use visual control so that no problems are hidden.
8. Use only reliable, thoroughly tested technology.

People & Partners – 'Add value to the organization by developing your people and partners':

9. Create leaders who live the philosophy.
10. Respect, develop and challenge your people and teams.
11. Respect, challenge and help your suppliers.

Problem Solving – 'Continuously solving root problems drives organizational learning':

12. Go see for yourself to thoroughly understand the situation.
13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly.
14. Become a learning organization through relentless reflection (Hansei) and Continuous Improvement (Kaizen).

Within Lean, identifying and eliminating waste is one of the most important activities. Wastes are also referred to as Muda. We distinguish eight forms of Waste, which are listed in the figure below. In Chapter 6 we will discuss in detail a number of techniques to eliminate Waste.

Figure 2 – Muda: 8 types of Waste

Six Sigma principles

The main focus of Six Sigma is to reduce variation in order to improve the quality of a product or process. Variation is everywhere. A driver has variation when parking his car; the arrival times of trains have variation; the human race shows enormous variation and products extracted out of a process are never the same. Every process demonstrates variation. The less variation a process has, the better we can predict its outcome and control the level of defects produced. Therefore, Six Sigma has a strong focus on reducing variation. If we want to base our decisions within problem-solving projects on facts, we have to know how to analyze and interpret data.

The difference between the so-called 'Old view' of variation and the 'Modern view' of variation is shown in Figure 3. The old approach is about approving the product when it meets the specification and rejecting the product when it does not meet the specification. There were only good and bad products. A much better way of looking at products meeting specification is to realize that a product that is exactly in the middle of the specifications is better than a product that is very close to one of its specification limits. Furthermore, a process that demonstrates little variation is better than a process that demonstrates a lot of variation.

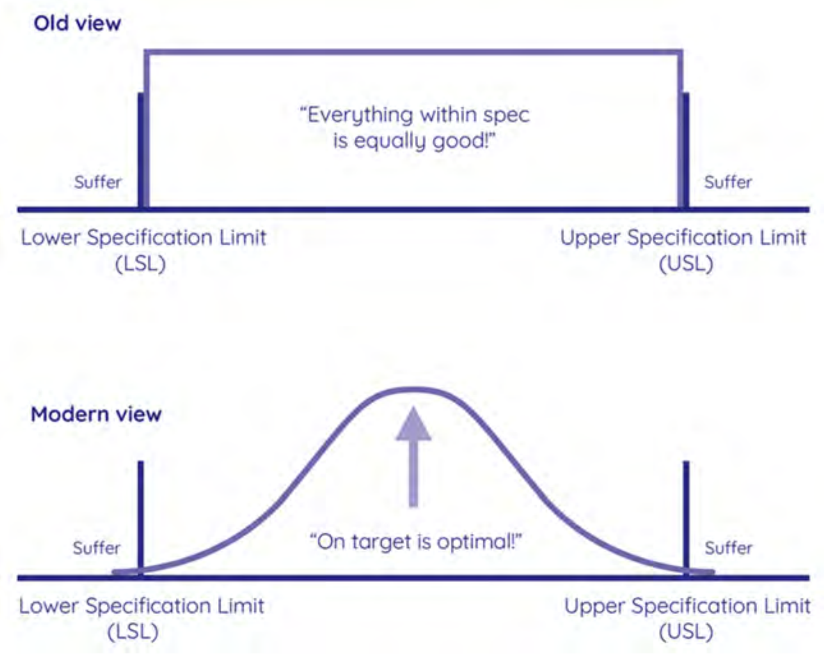


Figure 3 – Quality (Old view versus Modern view)

Genichi Taguchi (1950) claimed that customers do not necessarily define quality as Good or Bad, but that there is a certain optimum. Customers can recognize a deviation from this optimum, so one product may be slightly better (or worse) than the other. Deming was a supporter of this philosophy and striving for the optimum was one of the foundations for continuous improvement. This philosophy is also completely in line with the Six Sigma philosophy, where reducing variation is the primary focus.

Taguchi further claimed that poor quality costs increase as products deviate from the optimum. Adverse costs can occur even when a product conforms to the design but is not nominal. The 'Taguchi Quality Loss Function' (QLF) is the graphic representation and shows that when a critical quality characteristic deviates from the target value, this leads to a decrease in the quality experience for the customer, called 'Loss'. Taguchi claimed that tolerance specifications are determined by engineers and not by the customer.

Taguchi's Quality Loss Function includes the following principles:

- A deviation from the optimum leads to a loss for the customer.
- A loss for the customer leads to costs for the organization.
- Quality can be improved by reducing variation.
- Costs can be reduced by reducing variation.

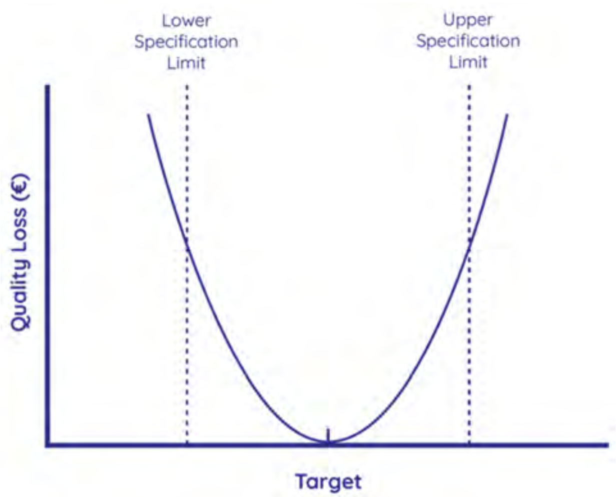


Figure 4 – Taguchi Quality Loss Function

Six Sigma is a long-term, forward-thinking initiative designed to fundamentally change the way organizations do business. It is first and foremost a 'Business improvement method' that enables companies to increase profits by streamlining activities, improving quality and eliminating defects or mistakes in everything an organization does. While traditional quality programs have focused on detecting and correcting defects, Six Sigma encompasses something broader. It provides specific methodologies to recreate the process in a way that defects are significantly reduced or even completely prevented [8.].

'Critical to Quality' measures (CTQs) are the key characteristics of a product or process which performance standards or specification limits must meet in order to satisfy the customer. CTQs can be measured and its data can be analyzed. A measurement that falls outside the CTQ specification limits is called a defect. A 'defect' does not necessarily mean that the product is damaged or broken, but that the CTQ is outside its specification. Products that perform outside their specification can still be functional, but it is not perfect. The objective of Six Sigma is to reduce the variation of the CTQ measures by identifying and removing the causes of variations. This can be done in both manufacturing and business processes.

The maturity of a process can be described by a Sigma rating, indicating the yield or percentage of defect-free products it creates. A process performing at a Six Sigma level means that 99.99966% of the products produced are within specification and 0.00034% are outside specification (defective). Processes that perform at the level of 6 Sigma are assumed to produce less than 3.4 defects per million opportunities (DPMO). Six Sigma's implicit goal is to improve a process, but not with the intention that in all cases the above-mentioned level of 6 sigma (eq. to 3.4 DPMO) should be achieved. Actually, the Six Sigma philosophy is to realize breakthroughs in quality performance. A process that originally operated at the level of 2 sigma (equal to 31% defective or 308,538 DPMO) and after a Six Sigma project now operates at the level of 3 sigma (equal to 6.7% defective or 66,807 DPMO) can still be called a Six Sigma improvement project because a significant improvement has been achieved.

Six Sigma is more sophisticated than applying simple problem-solving tools. Six Sigma applies statistical tools to identify and remove causes of variation. For applying statistical tools, you need to keep in mind the statistical fundamental rules. Most noteworthy is that you have to be very careful about how you apply statistical tools when the set of data represents an instable process. For instance, to apply a normal distribution analysis on a set of data that contains outliers from an instable process or measurement is not allowed. The first step in a breakthrough process should always be to investigate the stability of the data set and the process performance over time. The Six Sigma toolbox contains a number of tools that can be applied to visualize and analyze the stability performance of a process. When the defects are mainly caused by an instable process, the process of searching for its root causes is more likely to involve the application of basic problem-solving tools. A proper maintenance program or a Lean or Kaizen approach should be applied in order to remove causes for instability before continuing with a variation reduction initiative with sophisticated Six Sigma tools.

Agile principles

Within the field of project management and Continuous Improvement, Agile is one of the biggest revolutions in the last two decades. In 2001, a group of 17 software developers published the Agile Manifesto in which the starting points of Agile were elaborated. The Agile Manifesto sought to change the traditional software development approach, drastically reduce development time and improve quality. Nowadays, Agile is not only used in software development but has become one of the most practiced project management approaches. We will describe the four fundamental Agile values briefly:

1. 'Individuals and Interactions', over processes and tools.

   It is the people who respond to business needs and customer requirements, which should drive the development process. If the process or the tools would drive the development process, the team is less responsive to change and less likely to meet customer needs. Communication is an example of the difference between valuing individuals versus process. In the case of individuals, communication is fluid and happens when a need arises. In the case of process, communication is scheduled and requires specific content.

2. 'Working Products', over comprehensive documentation.

   Within traditional project management, an enormous amount of time is spent on specification, requirements, interface design, testing, approvals, etc., When all preparation work is finished the execution can start. This is called the Waterfall approach. In the execution phase there is little room for adapting specifications. Within Agile, requirements and documentation are still necessary, but its aim is to avoid working out all the details before the development work can actually start. Within Agile, user stories are utilized which describe the minimum requirements for the team to start the development process. The aim is to deliver a first working version of a product or service at an early stage. This is called a 'Minimum Viable Product' (MVP). In this way, feedback is quickly obtained from the customer or users. This feedback is important for determining the most important next steps.

3. 'Customer Collaboration', over contract negotiation.

   Within the Waterfall approach, it is common that customer requirements are discussed prior to the start of the development process and at the point the product is completed. During the development process, there is little room to change any requirements or add functionality. Within Agile, the customer is heavily involved throughout, giving room for changing requirements along the development process.

4. 'Responding to Change', over following a plan.

   Within the Waterfall approach, any change of requirements during the development process is a burden and costs are associated with it. So, all parties are inclined to avoid any change. The idea is to develop and to follow a very detailed and elaborate plan. Within Agile, short development loops are used, called 'Sprints'. At the start of each Sprint, requirements and functions are agreed between the customer and the development team. Priorities can be shifted from iteration to iteration and new features can be added. The belief within Agile is that changes always improve the product rather than it disturbs the process.

Within an Agile organization, the customer is the focus of the development process; employees have a positive attitude; changes are seen as a chance rather than a threat and activities should be aligned with business needs. There is a good balance between standardized work and the ability to respond to special customer wishes. Instead of a large inert organization and stuck employees, self-organizing teams will improve agility and speed within the organization. These teams have their own result area, are accountable and empowered. Techniques that contribute to an Agile organization are Short Interval Management and Scrum [section 3.2.4].

Principles behind the Agile Manifesto:
(Source: Agilemanifesto.org)

1. Satisfy the customer:
   Our highest priority is to satisfy the customer through early and continuous delivery of valuable software.
2. Welcome change:
   Welcome changing requirements, even late in development. Agile processes harness change for the customer's competitive advantage.
3. Deliver frequently:
   Deliver working software frequently, from a couple of weeks to a couple of months, with a preference to the shorter timescale.
4. Work together:
   Business people and developers must work together daily throughout the project.
5. Trust and support:
   Build projects around motivated individuals. Give them the environment and support they need, and trust them to get the job done.
6. Face-to-face conversation:
   The most efficient and effective method of conveying information to and within a development team is face-to-face conversation.
7. Working product:
   A working product is the primary measure of progress.
8. Sustainable development:
   Agile processes promote sustainable development. The sponsors, developers, and users should be able to maintain a constant pace indefinitely.
9. Continuous attention:
   Continuous attention to technical excellence and good design enhances Agility.
10. Maintain simplicity:
    Simplicity--the art of maximizing the amount of work not done--is essential.
11. Self-organizing teams:
    The best architectures, requirements, and designs emerge from self-organizing teams.
12. Reflect and adjust:
    At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly.

Lean versus Agile

Because nowadays Lean and Agile are the most common applied improvement methodologies, we will discuss their similarities and differences. Both methodologies have a clear customer focus *('Customer Value' and 'Satisfy the customer')*. Nothing is more important than meeting customer requirements and expectations. Products delivered must create value for the customer which is the most important goal of development and production processes. Both methodologies instruct that regular checks of the results and working method should be carried out in order to evaluate possible improvements and simplification of the process *('Continuous Improvement'; 'Continuous attention'; 'Reflect and adjust'; 'Maintain simplicity')*. Both methodologies incorporate stand-up meetings with the team around visual management boards and they work according short interval management *('Kaizen'; 'Face-to-face conversation'; 'Self-organizing teams')*. Within Lean these efforts are called Kaizen events and within Agile these are called Sprints. Also, both methodologies expect the delivery of objects in the least possible number of lots because it is the most efficient way and because it will reveal quality issues at an early stage *('Deliver frequently')*. Within Lean this is called 'One Piece Flow', while within Agile this is called a 'Product Increment'. Another similarity between Lean and Agile is the strong focus on employee development and working in teams. Both emphasize that development of people is more important than applying tools *('Team-work'; 'Work together'; 'Trust and support')*.

But Lean and Agile are also very different. The main difference is that Agile concerns the optimization of the development process, while Lean concerns the optimization of the operational process. In most cases the development process concerns one unique product, while the operational process concerns a series of products. Within a Lean environment the end-goal is clearly defined while within an Agile environment the end-goal is not. The focus within a Lean environment is to deliver as many high-quality products or services as possible in the most economical way possible. Within a Lean environment the product or service and the operational process are predefined, and employees working in the delivering process are well trained and follow standard work instructions. Even if we consider different variants of the product, they are all predefined. Within a Lean environment it is the objective to avoid variation and iterations, while in an Agile environment there is a lot of room to discover and investigate to come up with the best solution. During the Agile development process, factors are continuously reviewed and changed according to new information or feedback. Lean principles and tools are being applied in environments like production, logistics, services, healthcare and in government, with the common goal of reducing Lead Time and operational costs while at the same time improving quality. The Agile methodology finds its origin in the creative and development environment, like software and new product development.

We can therefore not say that one methodology is better than the other. The question that needs to be asked is where we should apply Agile and where we should apply Lean? Agile is the most appropriate methodology to apply to the development processes, while Lean is the most appropriate methodology to apply to operational processes. Since, most organizations have both types of processes: development processes and delivery processes, it can benefit from both methodologies. A car manufacturer also needs to develop new cars and an IT-organization benefits from standardized processes for providing services and administration. Take a look within your organization and review where you should apply Lean and where you should apply Agile.

Flipped pyramid

Traditional organizations are hierarchies. Authority and decision-making power are concentrated at the top. Within traditional organizations, directions flow primarily from top to bottom; the top management establishes the objectives, guidelines, information, timing and budgets. This top-down approach may be convenient in some ways, but it also obstructs organizational agility, communication, creativity and the capacity for solving problems.

It appears that traditional organizations lack the bottom-up approach, which is a roadblock for creating a powerful Continuous Improvement organization. Change cannot be sustained for a longer period of time if managers are the only ones to ever lead improvement initiatives. Even a top-down approach should encourage and involve all people of the organization in the improvement process (Kotter, 1996). By encouraging the bottom-up in the organization, collaboration will become much more efficient and the workforce will work together more productively. The bottom-up approach will also increase the motivation of employees as they are empowered, involved, responsible and appreciated.

Organizations that truly embrace Lean have long abandoned the traditional top-down approach and have adopted the Lean leadership model of the ‘Flipped pyramid’. They have implemented a bottom-up approach in a successful attempt to mobilize the full capacity of the workforce. The inverted pyramid is a metaphor for a reversal of traditional management practices. Employees who are the closest to clients or operational processes are placed at the top and managers at the bottom. The workforce is empowered with greater decision-making authority and freedom of action. The manager’s role becomes the one of a facilitator and coach.

This bottom-up approach will improve the agility and productivity of problem solving, especially for so-called ‘Low-hanging fruit’ projects where there is no need for management involvement to identify and implement solutions. Problems are solved by the employees who are experiencing the problems every day. It is in their benefit that these problems are solved because it makes their lives easier. Very often it appears that employees think creatively and already have ideas on how to solve problems, but in traditional organizations the issue is that they are not encouraged and empowered to do so. Another advantage of the bottom-up approach is that it involves the entire organization rather than having projects done by a small group of senior staff.

Figure 5 – Dual Pyramid model

Flipping the organizational pyramid is difficult for both sides of the pyramid. It requires a behavioral change from everybody. The manager is expected to communicate objectives and values rather than activities and detailed planning. An effective manager learns to trust subordinates and rely on their ability to achieve organizational goals. A proactive input and execution, as well as decisions about the course of action, are taken by the workforce rather than by the manager. The workforce is encouraged and empowered to develop the necessary steps and to make their own choices of techniques to achieve the expected results.

Also, the role of middle management and senior staff is to provide coaching and support. This involves informing the workforce about other initiatives and best practices, implementing the changes in the IT-system and providing the supplies and resources that the workforce needs. Shifting decisions to the workforce requires that they develop additional skills. Rather than simply following instructions, they must become more pro-active and develop communication skills and problem-solving skills. In order to be successful, they will need to acquire and analyze information. To make effective decisions, each employee must know organizational goals and understand his or her role. Imagine that a team of nurses is working together in a Kaizen event to improve logistics processes in their unit. It is not the role of the department manager to tell them how to do this. Neither is it his role to sit and wait while the nurses are struggling to find a solution. The role of the manager is to empower the nurses but also to coach them, show interest, give advice and – most important – ask them what support they need. The role of senior staff is to support the team by implementing the changed work procedure in the system.

'Flipping the Pyramid' is a metaphor that is described in many Lean books. It is however not the complete story. Even within the most successful Lean organizations, top management still owns the responsibility for vision, mission, strategy and major projects. For example, acquiring a company, outsourcing a division, managing a crisis, building a new factory and even managing key accounts should not be delegated to the workforce. These topics are initiated and guided by (top)management. The bottom-up approach is particularly suitable for sustaining improvement initiatives at the workplace. Later in this book we will refer to these projects as CIMM level-I and level-II projects. Nevertheless, new initiatives at these level are also initially initiated from the top. For example, initiating the first 5S project or Lean initiative is probably started from the top. It is important, however, that after a successful first and second initiative, the responsibility for extending the program is done bottom-up instead of top-down. Empowering the workforce at these levels frees up time for Green Belts, Black Belts and senior staff to manage higher level projects.

Organizations that have been working on the inverse pyramid principle for several years have also implemented a system in which problems are escalated. An example is Scania, where every improvement project on the work floor is carried out according to a fixed schedule. A new improvement project starts on Monday morning and the goal is to report the solution to management on Friday. If, midway through the process, it appears that the team is stuck or the solution is not ready in time, this is escalated to a higher level. The team then receives support or the project is transferred to specialists. The same process is also followed at this level. In this way, it may be that a problem ends up at the highest level, but this only happens if all underlying levels were not able to solve the problem independently.

Monozukuri

In this paragraph we will review a very old Japanese concept of creating a Continuous Improvement culture, called Monozukuri. The Japanese word Monozukuri is a combination of 'Mono', meaning thing and 'Zukuri', meaning the act of making, sometimes translated as manufacturing or craftsmanship. Monozukuri describes the gap between the end result and the process that leads to that end result. Yet, there is so much meaning lost in just translating the word, because it literally does not cover the meaning of the philosophy at all. It is a mindset, a spirit, a philosophy. If Japanese want to talk only about manufacturing, they would use Seizo (manufacturing) or Seizan (production). Monozukuri is a typical Japanese concept and therefore is difficult to place in our Western culture. Before we can apply the concept, we first have to understand the essence of it.

So, what is the meaning of Monozukuri? Monozukuri combines the technical part of Continuous Improvement with the social part of Continuous Improvement. It is not only about achieving the goal (the end product), but also the journey (the production process) is important. As such the resemblance to Zen thinking can be recognized, because Monozukuri connects head and heart in a way that Continuous Improvement penetrates into the DNA of the organization.

The word itself is quite old. Historically, it was used in connection with an individual artisan and craftsman who took pride in his or her products. You certainly know famous poets or painters like Shakespeare, Rembrandt or Michelangelo. But do you know famous weavers, carpenters or electricians? Probably not. In Japan, however, it is possible to become a recognized skilled artist in pottery, textiles, dying, lacquerware, metalworking, woodworking etcetera. Japan values such craftsmen on a similar level to traditional artists. Shoji Hamada for example, received in 1955 the honorable title of 'Living National Treasure', which is the highest award achievable in the Japanese arts and awarded to a very select few who have demonstrated mastery of their craft.

Figure 6 – Shoji Hamada (1894 – 1978), The best-known potter of the 20th century

From the 1970s on, given the appreciation of technical skills, Monozukuri was used in industrial production to boost its image. Working in manufacturing had the image of being dirty, demanding and even dangerous. The meaning of the Monozukuri concept was used to improve the image and self-value of industrial production. Suzuki, for example, used Monozukuri to make working in production more attractive. In 1999 the Japanese government even created a law for the promotion of Monozukuri, called the 'Basic Technology Promotion', with the purpose to improve the image of factory work by connecting the historically significant value of craftsmanship and artisans with modern manufacturing technology.

Nowadays, Monozukuri is associated with Japanese work ethic and the drive toward perfection. It is not only about the attitude to want to make perfect products, but to do this in a way that leaves room to constantly improve the process and its underlying processes. On the one hand it means that a service or product does not have to be perfect from the beginning and on the other hand that even a good service or product can always be improved. This may sound like a contradiction. How can you deliver a perfect product or service that at the same time offers room for improvement? This apparent contradiction is less self-evident within the Japanese culture. It is accepted here that many things are not (yet) perfect and that it is therefore your duty to realize the highest attainable quality within these limitations. By simultaneously striving for perfection and paying attention to improve the operational processes even further, you will reach a higher level every day. From the Western way of thinking, you could compare this with the pursuit of Utopia, an ideal world that cannot be reached. This is the essence of Continuous Improvement concepts like Kaizen, Lean, Kata etcetera.

Within the Monozukuri philosophy, it is not just about working optimally, striving for 'Zero Waste', but also about people feeling good about it and that the work gives satisfaction. For this it is important that people have the sense to be meaningful, that they belong to a group and that they get appreciated for their commitment and achievements. In Japan, it is important that you take more pride in your work and that you get respected for this. In our Western society, where most people have everything they desire, it is important to realize that appreciation is not only about the monthly pay check, but it is about respect and appreciation.

So, does this mean the Japanese work environment is superior to the Western work environment? Certainly not. Japan has the longest working hours in the world, and some young Japanese workers are literally working themselves to death (BBC, 2017). As we already explain many Japanese terms in this book, let me explain one more: 'Karoshi', which is the Japanese term to describe death attributed to overwork. Furthermore, Japanese employees look to their superiors for approval before making big decisions. When you start telling your Japanese colleagues that they are wrong about something, you aren't helping yourself and just making it more likely that you will lose respect. Working in Japan is not easy.

Yet, it is very good possible to embrace the positive elements and the deeper meaning of Monozukuri into your organizational culture. An example of how to apply the Monozukuri concept in a Western organization can be found at BMW. Here the management no longer speaks about the concept of Quality, but the word Pride is used instead. This may seem like a small difference, exchanging one word for another, but it goes much further in practice. By replacing this word cold computable and often accountable terms are replaced for warm, personal and attractive emotions. If every person in the organization can honestly say that they are proud of what they have contributed to the product, the quality of the final product will certainly be guaranteed as well. A similar example can be found for some handmade cars, where employees put their personal signature on the engine block after assembling. Monozukuri is about common principles and by communicating them loudly and clearly, for example through visualization or banners. This can also be done by sharing emotions, working together in teams, by appreciating commitment and by celebrating achievements.

1.1.3 Continuous Improvement Maturity Model (CIMM)

The Continuous Improvement methodology that best suits for a certain organization heavily depends on the level of maturity of that organization. This also applies to the corresponding values and techniques. To support organizations to apply the best suitable methodology, the LSSA has developed the 'Continuous Improvement Maturity Model' (CIMM™). CIMM summarizes best practices and techniques of different methodologies in one framework, for different stages of maturity. The CIMM framework should be run sequentially as much as possible. It is not recommended to move on to the higher CIMM levels too quickly if the lower levels are insufficiently developed and secured. For example, it makes no sense to use statistical techniques to reduce the variation if the processes are not yet stable and predictable.

Figure 7 – CIMM 1st axis – Process (HOW)

In this paragraph, we will briefly introduce the five levels of the CIMM framework. Each of these levels is discussed in detail in a separate chapter.

CIMM level I – Creating a solid foundation (Structured) – [see Chapter 4]:

Before organizations can work on process improvement programs like Lean and Six Sigma, it is necessary to establish a proper foundation. The basic principle of the first level includes a safe and professional work environment, reliable equipment, standardized work (i.e., clear procedures, work instructions and protocols) and a quality management system. This provides a solid foundation for all future initiatives and improvement programs.

CIMM level II – Creating a Continuous Improvement environment (Managed) – [see Chapter 5]:

The second level focuses on creating a culture in which all employees are involved in the improvement process. This level follows the Kaizen philosophy of Masaaki Imai. Kaizen focuses on improvements in the workplace, in Japanese called the 'Gemba'. The Kaizen philosophy is based on a process of Continuous Improvement in small steps. The idea behind this is that by realizing a large number of minor improvements, eventually a big improvement has been achieved. Also, it is much easier for employees to adapt to small changes instead of dealing with a major change. The roadmap used at this level is the PDCA cycle, which stands for Plan – Do – Check – Act. A Kaizen project lasts about a few days and is often executed by employees at the shop floor. In order to support the realization of a Continuous Improvement culture, it is important to involve as many employees as possible so that the entire team becomes part of the improvement culture. Communication about daily performance is important to keep everyone involved and to keep track of daily performance. This is achieved through the introduction of communication boards. Short stand-up meetings may be organized daily to review daily performance, address issues and to assign actions to be taken.

CIMM level III – Create stable and predictable processes (Predictable) – [see Chapter 6]:

The third level focuses on creating stable and reliable processes with a predictable outcome. The main goal of creating predictable processes is the prevention of long delivery times, firefighting and poor quality. In other words, creating an environment where one knows what will happen and where clear promises can be made to customers. Realize that a reliable delivery time is usually better than a fast but unreliable delivery time. This level focuses primarily on optimizing operational logistics by focusing on adding value and eliminating waste. A side effect of this is that quality also automatically increases. The five Lean principles are the base for this level. One of the most powerful techniques used here is Value Stream Mapping. In production environments that are very machine-intensive, such as the automotive and food industries, 'Total Productive Maintenance' (TPM) is also often used. The 'Theory of Constraints' (TOC) or Bottle Neck theory, developed by Eliyahu Goldratt, is another powerful method.

CIMM level IV – Create capable processes (Capable) – [see Chapter 7]:

The fourth level focuses on reducing the variation of the stable processes created in the first three levels. The goal is to increase predictability and quality. The improvement method used in this level is Six Sigma. Six Sigma's starting principle is reducing variation and increase capability. The roadmap followed at this level is the DMAIC approach, which stands for Define – Measure – Analyze – Improve – Control. At this stage, statistical techniques are used to analyze and improve the performance of processes and products. To be able to use statistics, data is required. Therefore, it is important to use a good measurement system that is capable of generating reliable data. Six Sigma projects are often called breakthrough projects, as these are usually larger projects with a huge impact. This approach is suitable for problems that cannot be solved by applying simple techniques. A Six Sigma project usually takes 3 to 6 months and is led by a Green or Black Belt.

CIMM level V – Create future-proof processes (Sustained) – [see Chapter 8]:

At the fifth level, Design for Six Sigma (DfSS) is used in the development process of new products or systems. This is a systematic approach, with the aim to ensure that new products perform at a high-quality level from the first product. DfSS puts the process in a controlled state much earlier by focusing on risks and critical requirements of the customer from the first phase of the development process. Suppliers and partners are also much more actively involved. The application of Design for Six Sigma is done by Black Belts, Reliability engineers and in some cases by Green Belts. At this level, we also look at Industry 4.0 and the use of modern techniques in the operational process and in problem solving, such as Data Science, Internet of Things, Process Mining, Robotics Process Automation (RPA) and Cyber Physical Systems.

During the improvement of the processes, attention must also be paid to the development of employees and the organization. For each instrumental technique in the CIMM framework, it is possible to indicate the associated desired responsibility and behavior. The CIMM framework identifies a number of responsibilities and behaviors for each improvement technique, which helps determine whether or not the implementation of the technology in question will be a success and results in a lasting impact. A distinction is made here between those of the top management, middle management and employees on the shop floor.

A clear direction and focus are required, because employees are more involved and motivated by why they do things than by what they do. Without a clear strategy, the organization will not effectively achieve its objectives. In Lean terms, we call this the 'True North'. The strategy must ensure cooperation and coordination between the different parts of the organization and connect the strategic and operational objectives, initiatives and implementation. To ensure that set objectives are achieved, it is necessary to focus. The management of the organization has a crucial role in ensuring that the strategy is implemented successfully. Their responsibility is to facilitate improvement initiatives to achieve better results. This can be done, for example, by inspiring, motivating and coaching employees. Managers must also be visible on the Gemba. The development of the employees and the organization are called the non-visible aspects.

Figure 8 – CIMM 2nd axis – People (WHO)

1.1.4 Continuous Improvement roles and responsibilities

Within the field of continuous improvement, different roles and responsibilities have been defined. In this book we will mainly focus on the so-called 'Belt-structure'. The structure was originally defined by Motorola for those applying Six Sigma projects. This structure has become the common identification of different levels for applying continuous improvement. Around 2008, the Lean principles and techniques were added to the Six Sigma body of knowledges. However, some organizations use the Belt-structure for people that are trained and experienced in Lean only. This may lead to confusion as these people do not have any background or knowledge in Six Sigma. Since this is the practice today, it is important to clarify that we will specify each discipline by talking about a 'Lean Black Belt', a 'Six Sigma Black Belt' or a 'Lean Six Sigma Black Belt'.

Figure 9 – Lean Six Sigma Belt levels

Depending on the size of the organization, one or more (Master) Black Belts or Senseis are responsible for demonstrating and teaching the Lean Six Sigma principles within the entire organization. They are supported by Green Belts, who execute improvement projects. The Yellow Belts support the projects as team members. The management, in their role of 'Champions', should consider Continuous Improvement as being an integral part of the organization's approach to achieve World Class Performance. They facilitate and supply the resources needed to support the projects i.e. availability of resources, budgets etc.

Champion:
The Champion is the problem owner or the person who has identified the project. The Champion is involved in project selection and in assigning the project manager. For a Green Belt project, this can be a supervisor or department leader. For a Black Belt project, this can be a manager at a higher level. The Champion is also the person who approves the project charter. Champions play an important role in the Continuous Improvement deployment process as they are the initiators and sponsors of the projects. They are also responsible for monitoring the project's progress. The role of the Champion during the different project phases and Tollgate reviews is therefore essential. They ensure that the projects get the proper priority and that any barriers for executing will be removed. This also includes gaining commitment for resources, whether human or financial.

Project Board:
To support larger projects, a project board may be appointed. The project board consists of the Champion and one or more others managers. The Champion is the chairman of the board. For large projects or projects with a huge impact, a Supplier and a User can be specific roles within the project board. However, this is not strictly necessary. The Supplier is an internal manager who is assigning resources to the project. The User represents the department that will reap the benefits from the project. These roles are derived from PRINCE2 project management. For Green Belt projects these roles are not common and only the Champion is monitoring the project. Black Belt projects however can be more comprehensive and are often cross-departmental. In this case a project board might be established.

Figure 10 – Team structure

Yellow Belt:
When an organization decides to implement Lean Six Sigma company-wide, very often large groups of employees will be trained at the level of Yellow Belt to create a strong foundation. The organization's vision and strategy related to continuous improvement will form the basis for this training. Teaching the Lean Six Sigma methodology and some of the more practical tools are part of the training process. The specific tools that are part of the training may depend on the improvement program objectives, which makes this level of training 'Fit For Purpose'. Yellow Belts have experience about the processes in daily practice and are therefore the ideal team members of Kaizen projects, or Green and Black Belt projects. Yellow Belts are also responsible for enhancing operational performance within a certain department or factory line. This may refer to shortening lead times, problem solving or improving quality. Activities can be related to 5S, implementing visual management techniques, contributing to the development of standards or participating in brainstorm sessions.

Orange Belt:
Orange Belts are familiar with the Lean Six Sigma methodology and are able to apply problem solving and Lean techniques. For applying the more analytical and statistical tools, they will probably need the support of a Green or Black Belt. Orange Belts are leading Kaizen and Lean projects within their immediate environment. Orange Belts are often team leaders or supervisors with an in-depth knowledge of a process, product or equipment. Therefore, they will also be valuable team members in Green or Black Belt projects.

Green Belt:
Green Belts are specialists in executing Lean Six Sigma projects. With the right combination of specialist expertise and structured methodology, the Green Belt is able to achieve significant improvements in operational performance and quality. The impact on the organization and savings can be as large as a Black Belt project, but in general Green Belt projects have a smaller scope and are less complex than Black Belt projects. The scope of the project is often within one department, process or expertise rather than across departments. Green Belts might work alone or as a project manager in a team. Team members can be other Belts or employees without specific Lean Six Sigma competencies. Green Belts can also be team members in larger Black Belt projects. We can distinguish Lean Green Belts, that are working on improvement projects and Lean Six Sigma Green Belts that are working on more data driven projects. Lean Six Sigma Green Belts master all Lean techniques as well as additional statistical and analytical techniques.

Black Belt:
Black Belts are experts in executing improvement projects. As a program manager they are responsible for managing complex breakthrough projects and supporting improvement teams with tools and techniques. Very often Black Belts are assigned full time to work on improvement programs. Black Belts have both skills for applying analytical tools and skills for leading change. The scope of the project is often across departments and organizations. We can distinguish Lean Black Belts that are working on process improvement projects and Lean Six Sigma Black Belts that are working on complex data driven projects. Lean Six Sigma Black Belts master all Lean techniques as well as additional statistical and sophisticated analytical techniques. In the case that an organization does not employ a Master Black Belt, the Black Belt may fulfil the role of supporting management in Lean Six Sigma deployment and coaching Green Belts in executing their projects.

Master Black Belt / Sensei:
The Master Black Belt (MBB) is an expert in applying Lean Six Sigma. In many cases, they are responsible for deploying the overall Lean Six Sigma program within the organization and also performs training programs. The Master Black Belt has at least 5 years of experience in executing Lean Six Sigma projects himself. They support management in selecting the proper breakthrough projects and they coach Green and Black Belts in executing their projects. Within the field of Lean, the master of knowledge and expertise is called the ‘Sensei’, meaning teacher or literally "person born before another".

1.2 Customer value

Many projects start with a customer complaint or quality problem. It can also be an internal problem, like a high fall-out rate at a machine or a logistical bottleneck in the process. Hence, we need to understand why the problem is actually a problem to the customer. Even if you think a good product was delivered, it might not meet the customer's expectation or specification. You can try to convince the customer that the product meets the quality standards, but you can also try to understand the customer and be grateful for the opportunity that is giving to you to improve your process. Each improvement project must ensure it is customer focused.

1.2.1 Voice of the Customer (VOC)

Any Lean or Six Sigma project takes the Voice of the Customer as a starting point. Even in smaller projects the customer should always be the starting point. Defining what will be the benefit for the customer is a critical initial step of every improvement project as it nails down the commitment of what should be delivered at the end of the project.

External clients, customers, shareholders and other stakeholders all expect us to continuously become better, cheaper and faster. They all drive the Continuous Improvement efforts we work on. In general, we distinguish two groups of customers. The first group includes the external clients and customers to whom we deliver our products and services. They desire products and services according to specifications, at competitive pricings and at agreed timings. This determination is called the 'Voice of the Customer' (VOC). The drive from the second group is the internal drive from shareholders, executive management, employees or internal departments. Their desire is mostly about a safe and good work environment, internal delivery times, no mistakes, employee satisfaction, new business opportunities and cost reductions. Furthermore, we have to consider regulatory requirements, durability and environment. The determination of the needs for this second group is called the 'Voice of the Business' (VOB). Some drivers may be important for both groups while other drivers may be important for one of the two groups. In all cases, improvement projects have to consider the 'Voice' of both groups. In the case that they are contradictory, the Voice of the Customer is generally given a higher priority than the Voice of the Business.

In order to understand what is necessary to satisfy our customer, we can ask the following questions:

- Who is the customer?
- What do we provide to our customer?
- What is important to our customers' needs, wishes and requirements?
- Is the process focused on the needs of the customer?

To understand your customer requirements, you need to become a customer. Call your own call center, buy your own product and be critical to yourself. Go out to meet your customer or perform a survey. Do not be afraid of the outcome, because it might lead to improvement opportunities. You can also do this internally in your own organization. In the TV series 'Undercover Boss', a director of a huge company goes undercover to the work-floor, talking to employees to really understand what is going on.

KANO model

A helpful tool to understand the VOC is the 'KANO model' (by prof. Noriaki Kano, 1980). This model is a framework for categorizing and prioritizing the different experience characteristics of a product or service. There are three categories:

- 'Must be' or 'Must have':
  Basic needs that are taken for granted. Fulfilment of this attribute alone will not result in satisfaction, but when not fulfilled it will result in dissatisfaction. Examples: 'A modern car should have a radio' or 'a call center should answer the phone'.
- 'More is better':
  This is called a one-dimensional quality attribute. The more that is provided of this feature (at a certain price), the more the customer is satisfied. It can also mean 'the faster the better'. Examples: 'Speed of computer' (more is better) or 'Waiting time at restaurant' (less is better).
- 'Delighters':
  These attributes provide satisfaction when achieved but do not cause dissatisfaction when not. These attributes are extra benefits and beyond the customers' expectations. Examples: 'Thermometer on a package of milk showing the temperature of the milk' or 'Helpdesk operator wishing you a good day'.

Looking at the examples mentioned above, you will understand that the customers' expectations might change-over time. A decade ago, each modern car was expected to have a radio. An air conditioner would have been a delighter, but nowadays each modern car is expected to have an air conditioner.

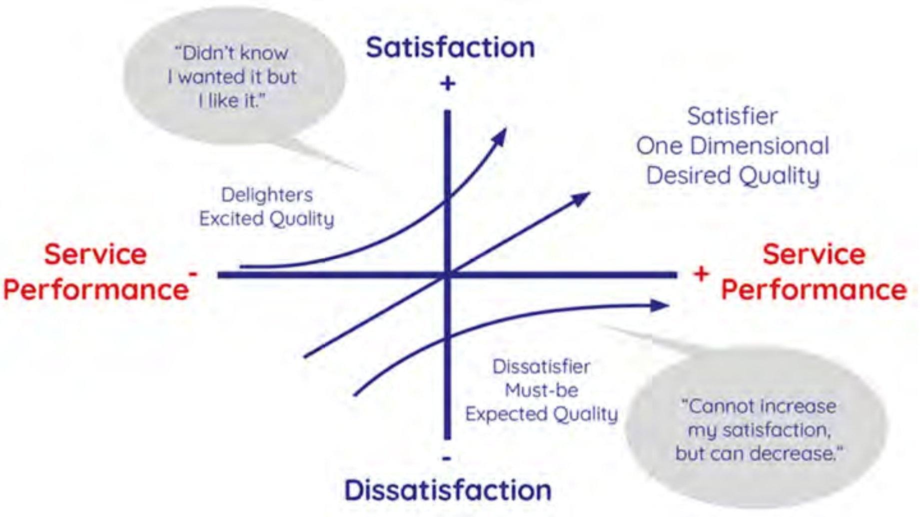


Figure 11 – KANO model (Noriaki Kano, 1980s)

Net Promoter Score (NPS)

A service center may perform at consistent service levels, but the customer retention and satisfaction index may be low. To better understand the actual voice of the customer, direct measurement of customer perceptions can be performed using questionnaires, surveys or focus groups. This will inform us better than internal service level metrics.

A special type of customer survey is the 'Net Promoter Score' (NPS). This management tool is used to measure the loyalty of customer relationships. It serves as an alternative to traditional customer satisfaction research. The Net Promoter Score has been developed by Fred Reichheld, Bain & Company and Satmetrix. It was introduced by Reichheld in his 2003 Harvard Business Review article as the 'One Number You Need to Grow.'

Instead of asking a dozen questions with a survey, NPS basically asks only one question: 'How likely is it that you would recommend our product/service to a friend or colleague?' The scoring for this answer is based on a scale from 0 to 10. Often a second question is asked to explain the answer that was given:

Based on the scores the respondents can be divided into three groups:

- Detractors: those who respond with a score of 0 to 6; the unhappy customers.
- Passives: those who respond with a score of 7 or 8; the content customers.
- Promoters: those who respond with a score of 9 or 10; the loyal enthusiasts.

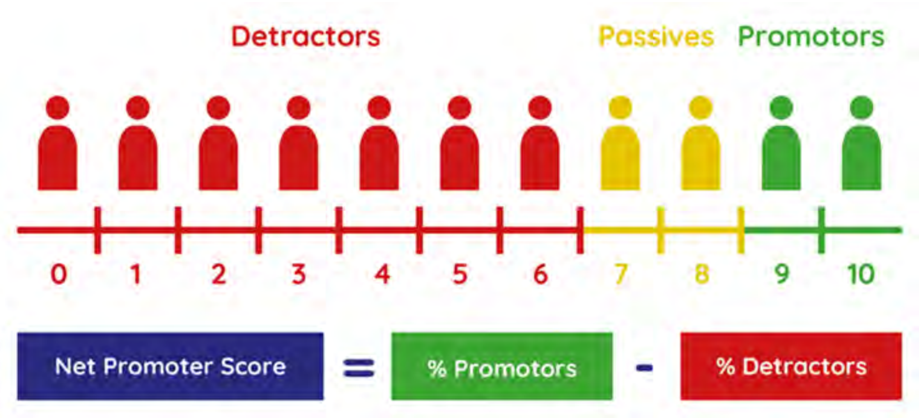


Figure 12 – Net Promoter Score (Reichheld, 2003)

The NPS-score is calculated by subtracting the percentage of the 'Detractors' from the percentage of the 'Promoters', while the 'Passives' are being ignored in this calculation. The NPS score can be as low as −100 (everybody is a detractor) or as high as +100 (everybody is a promoter). An NPS that is positive (i.e., higher than zero) is interpreted as 'good', while an NPS of +50 is rated 'excellent'.

$$Net\ Promoter\ Score = \frac{Number\ of\ Promoters}{Total\ respondents} \times 100 - \frac{Number\ of\ Detractors}{Total\ respondents} \times 100$$

1.2.2 Critical to Quality (CTQ)

One of the first tools in the Define phase of a DMAIC project is that we have to compose a CTQ Flowdown based on the Voice of the Customer. The CTQ will be our thread throughout the entire improvement project. Therefore, it is an important element that we should work on very seriously.

The Voice of Customer requirements are often expressed in an unclear manner. It is our task to interpret this into an unambiguous and measurable specification of the requirement. This metric is called the external Critical to Quality (CTQ_{ext}).

In addition, a distinction can be made between 'normal' specifications which are also very feasible, and specifications that are very important to the customer and that are also difficult to fulfill. These are called critical requirements or critical characteristics. These specifications require extra attention and are often the CTQ in a Six Sigma improvement project.

Figure 13 – Voice of Customer & External CTQ

Projects are often linked to a particular area. Therefore, the CTQ is sometimes called Critical to Safety (CTS), Critical to Process (CTP), Critical to Delivery (CTD) or Critical to Cost (CTC). In most cases, however, the measure is simply called 'Critical to Quality' (CTQ).

CTQ Flowdown

After defining the critical requirements from the customer, it is necessary to translate the external CTQ to an internal CTQ. The external CTQ is the metric that is related to the customers' requirement or complaint. The internal CTQ is the metric that is related to what we measure in our product or process to verify the quality of the product or service. Defining the proper CTQs is crucial for the project because the CTQ_{int} becomes the thread throughout the entire project. Focusing on an incorrect CTQ_{int} will result in a lot of effort but not in improved customer satisfaction.

- Define:
  The CTQ_{int} is the measurable characteristic that is representing the customer's need.
- Measure:
  The CTQ_{int} should be measured properly and CTQ_{int} data should be available and reliable.
- Analyze:
  Potential factors of influence on the CTQ_{int} should be identified and investigated. The capability of the CTQ_{int} performance against the customer specifications should be analyzed.
- Improve:
  The negative effect of factors that have a significant influence on poor CTQ_{int} performance should be eliminated or decreased.
- Control:
  The improved performance of the CTQ_{int} should be verified and controlled.

A helpful tool for this is the CTQ Flowdown. A CTQ Flowdown represents the key measurable characteristics of a product or process whose performance standards or specification limits must be met in order to satisfy the customer requirements. The effort of decomposing the VOC to a lower level should focus on responses and not on defining the factors of influence. This will be done later in the DMAIC project. In problem solving, the response is called '*Y*' and the factors of influence '*X*'. Finally, we need to define how we are going to measure the CTQ_{int}. We call this the Operational Definition of the CTQ_{int}. This definition consists of all of the following:

1. The characteristic of the product / service to be measured.
   The 'hard' (measurable) metric of the 'soft' CTQ description.
2. The measurement procedure.
   Includes the instrument that is used and data collection procedure to follow.
3. The requirements on the CTQ_{int}.
   The specification for the measure that determines (without discussion) if the VOC is met or not.

A project ideally focuses on one problem and one CTQ_{int}. The reason for this is that each CTQ_{int} often has its own factors of influence. If there are multiple problems, there are usually also multiple CTQs and multiple factors of influence. After the Define phase, it is then advisable to split the project into multiple DMAIC projects, each focusing on one CTQ_{int}. In the Control phase, these projects can then be merged again if desired.

Example: the following figure shows an example of a CTQ Flowdown of a coffee bar. The Voice of Customer is first translated into four external CTQs and then translated into five internal CTQs with the process specifications.

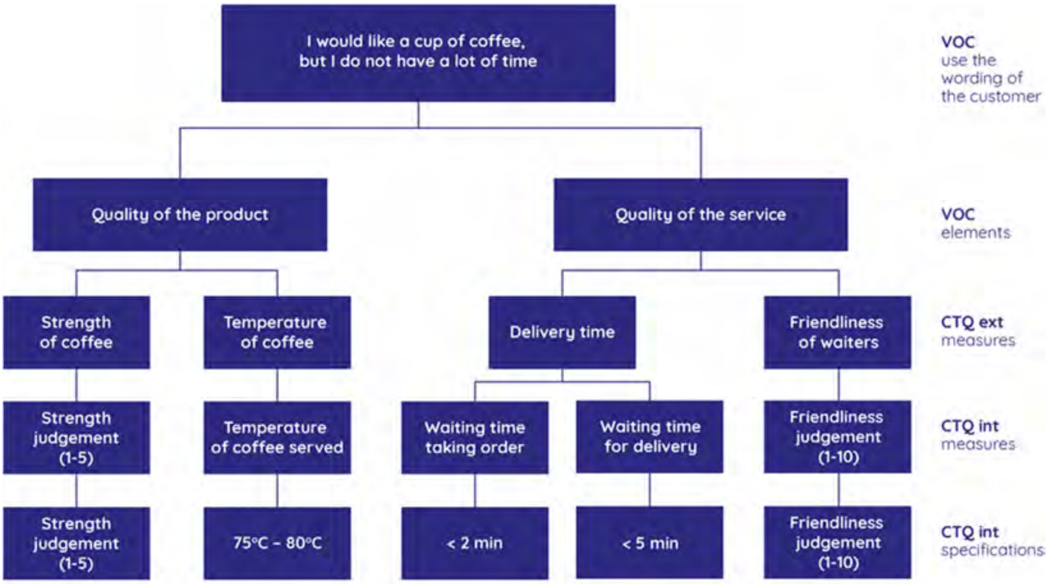


Figure 14 – Example CTQ Flowdown coffee bar

“If you pick the right people and give them the opportunity to spread their wings and put compensation as a carrier behind it you almost do not have to manage them.”

— Jack Welch —

2 Policy development and deployment

Applying policy development and deployment helps organizations to define a continuous improvement strategy and to run efficiently in achieving the organization's objectives. Policy development is focusing on the planning process, while policy deployment is focusing on the execution process. The third element is competence development, which is about the development of employees.

Policy deployment should not be confused with strategy deployment. Strategy deployment is applied for defining new strategic directions and implementing key strategic business imperatives. Typically, top management and middle management are involved in this process. Policy deployment is a way to monitor, manage and improve the daily performance of each function in the organization. We can say that strategy deployment is working "ON" the business, while policy deployment is working "IN" the business. Continuous improvement and Lean Six Sigma are about developing and improving the existing organization and not about new strategies. For this reason, within the field of continuous improvement policy development is discussed more often rather than strategy development.

2.1 Policy development

Policy development is fundamental for running and developing an organization. This is also the case for developing operational excellence within the organization or for implementing Lean or Six Sigma. Employees are more involved and motivated by why they do things than the actual things they do. Without a clear strategy, the organization is not effective at its goal. The process of Continuous Improvement and renewal begins, therefore, by defining a clear strategy that will distinguish the organization from its competitors. The strategy must ensure cooperation and coordination between the different parts of the organization and connects strategic and operational objectives, initiatives and implementation. In order to ensure that set goals are indeed met, it is necessary to maintain focus. The required time and resources must be allocated and management must adhere to the defined priorities. Simply put, it's a game plan that sets specific goals and objectives while heading for the so called 'True North' [2.1.1].

Anyone who works with annual plans and program development knows that these are often bulky documents that do not really invite you to read. And this is a pity. The management team has spent a lot of time working out the vision and then chooses a form of communication that is difficult to access. This creates a huge barrier to actually including the information. Sometimes a management summary is drawn up so that the core is read in any case, but it remains strange to spend a lot of time and money on a document that is unsuitable for proper communication. Within Lean organizations, this issue is addressed by the use of Hoshin Kanri's X-matrix for strategy development and deployment [2.2.3].

2.1.1 Vision & True North

Mission, Vision and Core values

The mission statement describes the reason for existence of an organization, based on the organization's values and identity. The mission is the purpose of an organization. The question that lies under the mission is: 'What do we stand for?' or 'Why do we exist?' A mission statement will grow over the years and is the foundation of an organization.

The vision statement is a declaration of an organization's objectives. It is a clear picture of the future or the measurable long-term goal for the organization. The vision is a guidance for product development, renewal of services, hiring and competence development, operational management and so on. As such the organization's vision is the central starting point and ensures coherence and direction of other management instruments.

Core values, also called 'Code of ethics', support the vision, shape the culture and reflect the organization's values. The core values define what the organization believes in and how people in the organization are expected to behave, with each other, with customers and suppliers and with other stakeholders. It provides a moral direction for the organization that guides decision making and establishes a standard for assessing actions.

Golden Circle (Simon Sinek)
Many companies nowadays follow the approach of Simon Sinek, as described in his book 'Start with Why'. Sinek mentions that people are inspired to do business with an organization or to work for an organization because of the so-called 'Sense of purpose', rather than the products or service the organization delivers. He calls this the "Why". The Why inspires people more than the "How" and "What". Sinek calls this triad the Golden Circle, a diagram of a bullseye, putting the purpose of the organization in the center. The center is surrounded by a ring labeled "How", representing the organization's processes or methods. The next ring is labeled "What", representing the organization's results or products. While traditional organization think from the outside-in (What-How-Why), Sinek emphasizes that organizations should think from the inside-out (Why-How-What). In his presentation, he takes 'Apple' as an example. The TED-talk video on YouTube is worth watching.

Figure 15 – Simon Sinek's Golden Circle (Why – How – What)

"People work better when they know what the goal is and why"

Elon Musk

Competitive strategies

Policy development is strongly linked to Operational Excellence, which is one of the three competitive strategies. Michael Treacy and Fred Wiersema described in their book 'The Discipline of Market Leaders' (1997), three generic competitive strategies: Operational Excellence, Customer Intimacy and Product Leadership. We will review each of these three competitive strategies briefly, but because continuous improvement is the main scope of this book, we will focus on 'Operational Excellence' as the main part of policy development.

- Customer Intimacy:
  Customer Intimacy strategy focuses on offering a unique service or product to the market. This requires the personalization of services and the customization of products to meet the needs of an individual customer. This strategy bundles services or products into a 'solution', designed specifically for one individual customer. These kind of companies tend to have a decentralized organization. This allows them to change quickly according to customers' needs. The development processes, delivery processes and support processes are designed to meet the need for high flexibility. Examples of companies who pursue this type of strategy include construction, IT development, retail and hospitality.

- Operational Excellence:
  Operational Excellence strategy focuses on delivering to customer expectation, without failures, on time and in a cost-efficient manner. It is a philosophy where problem solving, teamwork and leadership result in the on-going improvement of the organization. Leaders in this area are often centralized, combined with a strong organizational discipline and a standardized, rule-based operation. The process involves focusing on the customers' needs, keeping the employees concerned and empowered and continually focusing on elimination waste and variation in the process. Examples of companies who pursue this type of strategy include high-volume and transaction-oriented companies that operate in a mature and commoditized market such as automotive, food, logistics but also some service providers like finance, government and healthcare.

- Product Leadership:
  Product Leadership strategy focuses on continuously offering superior products to the market. Product leaders achieve premium market prices thanks to the experience they create for their customers. Examples of companies who pursue this type of strategy include automotive companies, consumer electronic companies, pharmaceutical industries and fund management.

According to Treacy and Wiersema, an organization should embrace and become successful in one of these three strategies and perform to an acceptable level in the other two. While market leaders typically excel at one discipline, a few maverick companies have gone further by mastering two. In doing so, they have resolved the inherent tensions between the operating model that each value discipline demands (Treacy and Wiersema, 1997).

Although this model has been valid for decades to guide companies with their long-term strategy and although this model may still work for most traditional companies, it is not sufficient anymore for modern companies in today's digital world. The new stars at the horizon are companies like Booking.com, Amazon.com, WhatsApp and Über. Facebook is now worth more than IBM and Instagram managed to gain a value of 1 billion dollars with only 8 employees. These companies have proven that Customer Intimacy can be combined very well with Operational Excellence and Product Leadership. They accomplished to meet individual needs (Customer Intimacy), they operate incredibly efficiently (Operational excellence) and their product is way beyond traditional competitive products (Product Leadership). The new Competitive Strategy to aim for in the coming decades therefore is the combination of all three competitive strategies, in Figure 16 illustrated as 'C.O.P.', which is the combined strategy of Customer Intimacy, Operational Excellence and Product Leadership.

Figure 16 – C.O.P. the new Competitive Strategy

True North

Within Lean thinking the vision is often called 'True North', like Jeffrey Liker explains in his book 'the Toyota Way'. The True North works as a compass proving a guide to take an organization from the current condition to where it wants to be. True North refers to what we should do, not what we can do. It is a term used in the Lean lexicon to describe the ideal or state of perfection that your organization should be continually striving towards. Lean is a journey without an absolute destination point, we will never achieve perfection. Opportunities for improvement never end, and it is only when we take the next step that we see possible future steps. However, like a sailor we must be guided towards our shoreline. We look to 'True North' to guide us while knowing that we can never arrive at the True North. True North is a concept, not a goal. It is the persistent practice of continuous improvement on a daily basis, involving the entire organization.

Figure 17 – True North

Heading for the True North can be compared with a sailing ship. A sailing ship can never head in a straight line to its final destination. The crew is constantly busy to verify its direction and to bring the ship in the right position, against the wind. It needs to make small iterations in direction constantly to reach the fantasy island. This is the same in a Continuous Improvement organization. Both management and employees have to look for their current situation compared to the desired situation. A combination of small improvement projects and large breakthrough projects will maneuver the organization in the right direction.

House of Quality

Organizations that deploy continuous improvement often build a so-called House of Quality. Although many examples of these houses of quality can be found on the internet, each organization need to develop their own house. The structure of such a house is pretty much the same.

The roof of the house visualizes the goals of the organization. The foundation of the house describes the values and principles as well as conditions for continuous improvement. The house has two pillars. One pillar is about optimizing the processes and the other pillar focuses on the culture within the organization. To become a continuous improvement organization, attention must be paid to both pillars, so both to Process as well as People.

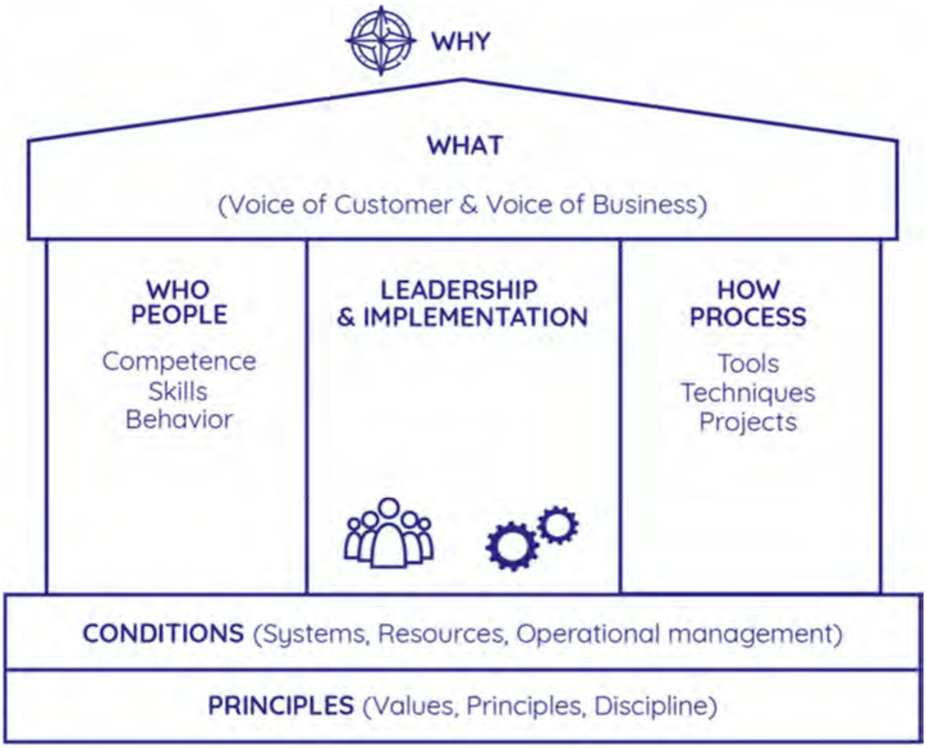


Figure 18 – House of Quality

2.1.2 Transformation roadmap

In this paragraph we will review how to create a transformation roadmap to develop organization in the direction of the True North. The transformation roadmap starts with performing a CIMM assessment, to determine at what level the organization is currently acting. The level of process improvement is assessed as well as the associated behavior of the top management, middle management and employees. The assessment results are discussed in the management team. Is everyone on the same page? What is the current maturity level of the organization and what is the desired level? Are Process and People in balance? The assessment and organizational objectives form the input for the policy development plan. The execution of the transformation process will take a certain period of time (several months or years). The transformation is concluded with a second CIMM-assessment to verify if the program objectives have been achieved.

The parts of the transformation process are visualized in Figure 19. The three elements cannot be seen separately. It is therefore that they are displayed as puzzle pieces. If there is no clear strategy, everyone will go in a different direction. If only investments are made in training, no impact will be realized and if employees are assigned to projects without the necessary knowledge and expertise, the projects will not be successful. It is therefore important to give proper attention to each of these three elements.

Figure 19 – Transformation elements

The transformation roadmap should address each of the following three elements:

- Policy development:
  First of all, it is determined what the current situation of the organization is. The CIMM assessment can be used for this, looking at the five levels of process improvement (75 statements) and the associated behavior of management, management and employees (75 statements). The assessment is described at the end of chapters 4 to 8. The vision and objectives are determined from the organizational strategy. This is the intended situation. In Lean terms we call this the 'True North'. We then draw up the transformation plan that describes how the organization should develop from the current situation to the intended situation..

- Policy deployment:
  Objectives are only achieved once improvements have been made. Breakthrough projects are selected based on the strategic and operational objectives. Depending on the intended CIMM-level, it follows which building blocks should be developed or implemented. Green and Black Belts are then assigned to lead improvement projects and employees are assigned as team members.

- Competence development:
  A competence development plan and training agenda are set up to get managers and employees at the right level and to learn new techniques. The first part is gaining the right knowledge and skills, by following training. The second part is gaining experience by carrying out improvement projects. In addition to training, coaching and intervision will be needed to successfully complete projects.

If we plot the elements described above in time, we will obtain the approach as visualized in Figure 20. The content of the action plan and the building blocks that are part of the plan depend on the current CIMM-level of the organization and on the intended objectives.

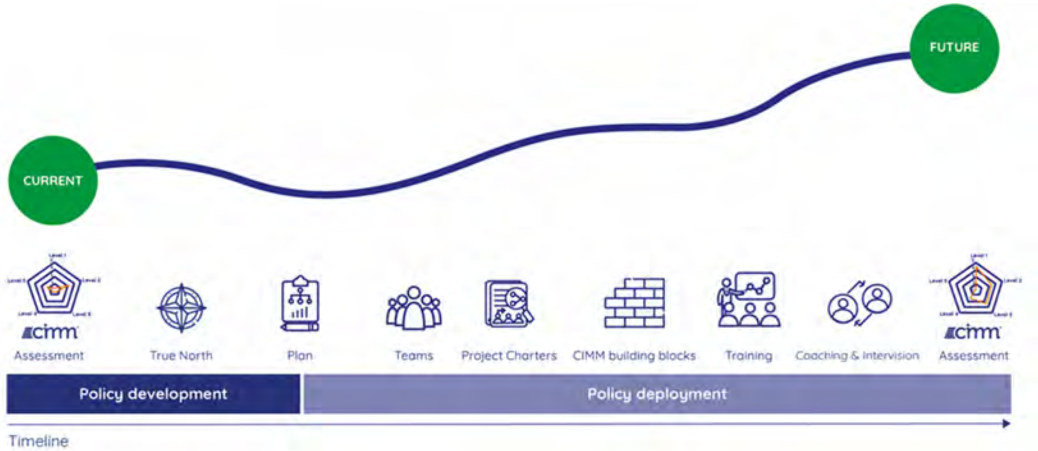


Figure 20 – Transformation roadmap

2.1.3 Performance and financial metrics

Critical Success Factors and Key Performance Indicators

Most organizations periodically monitor whether they are still on target and have achieved their objectives. This applies for operational performance (did we achieve the numbers today?; did we deliver on time?; etc.), for project management (are we still on schedule?; are risks under control?; etc.) and at organizational level (did we achieve our revenue target?; do we have sufficient resources?; etc.). The process of collecting, analyzing, reporting and adjusting is called Business Performance Management. The goal is to ensure that the organization is still on target to achieve the strategic objectives. In this paragraph we will discuss the importance of the 'Critical Success Factors' (CSFs) and the 'Key Performance Indicators' (KPIs).

"What gets measured gets managed."

Peter Drucker

CSFs and KPIs are two different concepts though, that may cause confusion. We will explain the difference and how they work together. CSFs help us to define the areas which are to be improved so that success is ensured, whereas KPIs are used to measure success. CSFs are defined as 'what should be done in order to get successful?', whereas KPIs are defined as 'how successful are we?' CSFs are more of qualitative nature like 'what makes customers satisfied?' while KPIs are usually quantitative, i.e. in the form of a ratio or percentage value. CSFs can't be measured, but it can be discussed or analyzed. Summarized: CSFs are the cause of success, whereas KPIs are the quantified effects of the actions.

We will now zoom in a bit on the Key Performance Indicator. A KPI is a business metric used to quantify and evaluate factors that are crucial to the success of an organization. KPIs make it possible to determine the gap between actual and targeted performance and are used to rationalize organization effectiveness and operational efficiency. If you don't measure results, you can't tell success from failure and thus you can't claim or reward success. It will also be difficult to redirect or adjust a process that is not performing, because if you can't recognize failure, you can't correct it or learn from it.

Leading versus Lagging indicators

KPI's used for assessing performance in an organization can be leading or lagging indicators. Lagging indicators are output measurements, or results. For example quality performance and lead time are the resulting measurements of the operational process. Leading indicators on the other hand, are predictive measurements. For example measurements about safety, supplier audits or time spend on employee training are predictive measurement for the operational process. All too often we concentrate on measuring results, outputs and outcomes. Why? Because they are easy to measure and everybody wants to know them. If we want to know how many products or sales have been made this month, we simply count them. But looking at lagging indicators only, is as constantly looking into the rearview mirror. Organizations that want to stand out will look more into the leading measures.

Balanced scorecard
Each organization has its own set of KPIs. Some KPIs are common for commercial organizations, like revenue, costs and profit. Other common KPIs are output, headcount, customer loyalty and Cost of Poor-Quality. Government might consider unemployment rates, inflation percentage and average income. Performance management systems like the 'Balanced Scorecard' and the 'EFQM Excellence Model' are based on a set of CSFs and KPIs which are connected to the organizations' strategy. Further, these performance management systems involve a communication structure around these CSFs and KPIs.

The 'Balanced Scorecard' (BSC) is a strategic planning and management system that is used extensively in business and industry, government and nonprofit organizations worldwide to align business activities to the vision and strategy of the organization, improve internal and external communications and monitor organization performance against strategic goals.

Balanced scorecard was originally designed by Drs. Robert Kaplan (Harvard Business School) and David Norton as a performance measurement framework that added strategic non-financial performance measures to traditional financial metrics to give managers and executives a more 'balanced' view of organizational performance.

"The Balanced Scorecard retains traditional financial measures.
But financial measures tell the story of past events, an adequate story
for industrial age companies for which investments in long-term capabilities
and customer relationships were not critical for success.
These financial measures are inadequate, however, for guiding and evaluating the journey
that information age companies must make to create future value through
investment in customers, suppliers, employees, processes, technology and innovation."

Robert S. Kaplan and David P. Norton (1996)

The Balanced Scorecard describes four perspectives. For each perspective the organization will continuously monitor and report on the goals and achievements. Department managers and process owners are given the responsibility to gather process data and to report the process performance using the defined metrics. If a metric is not on target, appropriate corrective actions should be defined or improvement proposals should be developed.

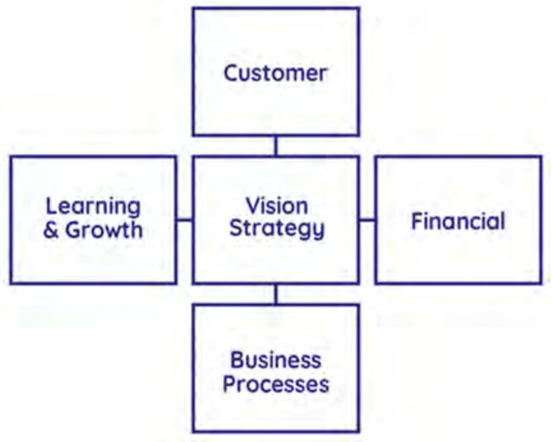


Figure 21 – Balanced Scorecard perspectives

Balanced scorecard describes the following four perspectives:

1. Learning & Growth Perspective:
   Metrics referring to employee training and corporate cultural attitudes related to both individual and corporate self-improvement.

2. Business Process Perspective:
   Metrics referring to how well the business is running and whether its products and services conform to customer requirements.

3. Customer Perspective:
   Metrics referring to customer satisfaction, both external and internal.

4. Financial Perspective:
   Metrics referring to financial performance, but also to non-financial performance like risk assessment and cost-benefit data.

There are different possibilities to present business performance KPIS in a visual and attractive way. ERP systems already offer many possibilities, but more and more organizations are now using special applications for reporting and visualization of KPIs. These applications can be linked to the ERP system and other data sources. By using such applications, employees have always and everywhere insight into the actual process and business performance. Figure 22 shows an example of Microsoft Power-BI, a widely used application for dashboards.

Figure 22 - Microsoft Power-BI

Cost of Poor Quality (COPQ)

Despite the type of customer complaint or request, in the end it is all about 'Costs'. Even if the issue is about quality or delivery, it can often be converted to costs. For the management to make decisions about prioritizing projects, the problem statement may be converted to 'Costs', as Philip Crosby stated in his book 'Quality is Free' (1979): *"Money is the language of management; you need to show them the numbers"*. By presenting the overall size of poor quality in monetary terms, issues are more likely to be brought to the attention of management and fast actions are more likely to occur (Krishnan, 2006; Harrington, 1987). Different studies reveal that costs of poor-quality stands for 10-40 percent of a company´s turnover, as Juran stated in several publications: *"About a third of what we do consists of redoing work previously done"* (Juran, 1999).

Although most improvement projects start from a cost-perspective, many companies have little knowledge regarding cost of poor-quality and are not able to measure it. This is a problem, because without measuring cost of poor-quality, information relevant for decision-making will remain vague.

Feigenbaum was an American quality control expert and businessman. He devised the concept of 'Total Quality Control' and separated quality costs into visible and invisible costs. Feigenbaum stated that visible quality costs are easy to identify and are easily measured, while invisible quality costs are difficult to identify and not easy to measure. The combination of visible and invisible quality costs are represented by an iceberg. Only a small amount of the costs are visible, represented by the upper portion of the iceberg, while the majority of the costs are invisible and hidden under the water surface (Krishnan, 2006). Feigenbaum classified quality costs into the categories Prevention, Appraisal and Failure costs. This was called the PAF-model (Feigenbaum, 1991). Failure costs can be divided into internal failure costs and external failure costs (Campanella, 1990). Philip Crosby classified prevention and appraisal costs as 'Price of Conformance' and classified internal and external failure costs as 'Price of Non-conformance', (Philip B. Crosby, 1979).

Figure 23 – Costs iceberg (Krishnan, 2006)

In 1987, Harrington introduced the term 'Cost of Poor-Quality (COPQ) in his book Poor Quality Costs, as a refinement of the concept of quality costs. Harrington stated that the cost elements as described above, are only the 'Direct Cost of Poor-Quality'. He appointed an additional group of COPQ elements, which he called 'Indirect COPQ'. These costs are related to customer-incurred cost, customer-dissatisfaction cost and loss-of-reputation cost. The indirect COPQ is even more difficult to measure than the direct COPQ, because it is a delayed result of time, effort and financial costs incurred by the customer (Harrington, 1987). In this book we will only focus on the direct COPQ. These costs can be distinguished into 'Conformance costs' and 'Non-conformance costs'.

Conformance Costs:

- Prevention Costs
  Costs related to quality planning. This includes systems and procedures to prevent things going wrong like design reviews, in-process controls, employee training etc. Whilst beneficial, they are still actually costs related to quality and as such classified under COPQ.

- Appraisal Costs
  Costs related to quality control. This includes systems and procedures that exist only to check for problems like inspections and special systems or procedures to verify the quality.

Non-Conformance Costs:

- External Failure Costs:
  Costs related to defects that have reached the customer. They include all costs related to handling the customer complaint like repair or replacement of the bad good or service delivered to the customer.

- Internal Failure Costs:
  Costs related to quality problems within the organization, like Yield loss (scrap), rework and the use of excessive resources.

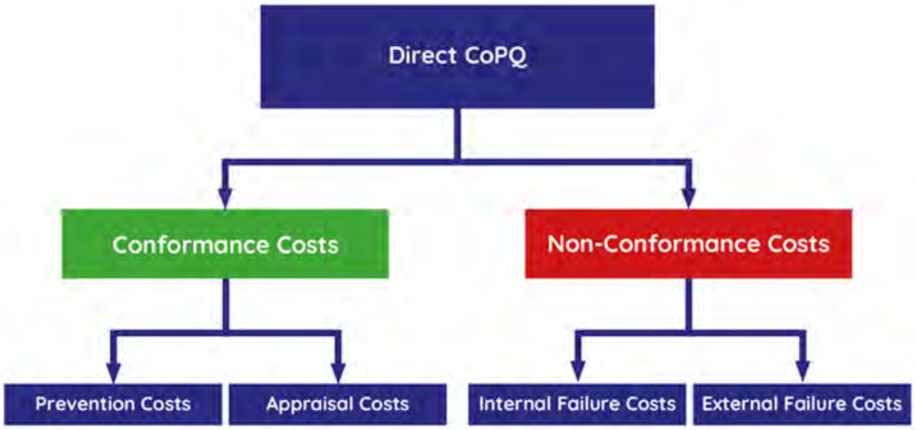


Figure 24 – Direct Cost of Poor-Quality

Total Cost of Quality

Each organization tries to prevent costs of external and internal failure (Non-conformance costs). For this they invest money on appraisal and prevention (Conformance costs). However, this cannot be done to an extreme as the costs of good quality will become larger than the cost of poor-quality. The depiction of the quality cost curve in Figure 25 reveals that the optimum total cost of quality does not occur at 100% conformance. The location of the lowest total costs point can be shifted, based on competitive market conditions and type of product.

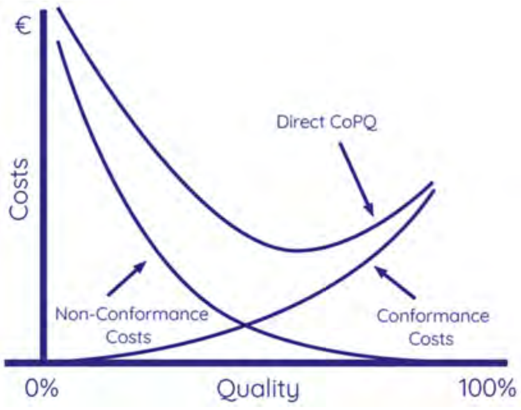


Figure 25 – Total costs of quality

Project Hard and Soft benefits

It is common that a project will be initiated due to some overt failures to meet one of the project performance measures. This leads us to understand where the benefits are likely to be realized. For example, if our customers are switching to a competitor because our delivery times are too long, then a project to reduce delivery time might be launched. The gap between current delivery performance and the target delivery performance is then used to project the target benefits. These benefits can be classified in the following three categories:

1. Hard Benefits (direct & indirect):
   Eliminating Waste and reducing the amount of Non-Value Adding activities can be quantified in terms of hard benefits to the organization in the form of reduced labor costs, resource savings and reduced Work in Process. These are called direct hard benefits. As a consequence of a more efficient process and less WIP, it is likely that fewer mistakes will be made. A shorter Lead Time will produce a more responsive service which will lead to an improved reputation. These are called indirect hard benefits.

2. Soft Benefits:
   Happier employees and an improved brand reputation are both examples of soft benefits. Soft benefits can be measured best through employee and survey responses. It is difficult to assign a monetary value to soft benefits, so they may not appear in the benefit calculation.

3. Risk or Loss Avoidance Benefits:
   Improving the Lead Time and preventing bad quality may prevent the loss of customers to the competitor. In this case, a loss avoidance benefit may be included in the calculation so long as the records or measures to support the assertion is plausible. These benefits are likely to take the form of an estimate of the number of customers that would have been lost if the improvements had NOT taken place, multiplied by the average profit earned from a customer.

OPEX and CAPEX
Savings within projects can relate to operational costs or investments. Operational costs are the costs that an organization incurs for carrying out its daily activities. Examples of operational costs are salaries, rent, lease, travel, service, advice, maintenance, etc. These costs are also referred to as OPEX and are directly and fully charged to the result of the organization.

Costs can also relate to the use of capital-intensive goods. Examples are investments in fixed assets such as real estate, equipment, IT, infrastructure, systems, etc. The expenditure for these goods is not charged to the result at once, but is spread over several years. These are called depreciation costs or CAPEX. These depreciation costs for the current year are charged to the result.

As a Green or Black Belt you have to indicate what the annual savings or annual direct hard benefits for a Lean Six Sigma project are. It must also be indicated whether the savings are one-off (current year) or structural (multi-year). Take into account the OPEX savings and the CAPEX savings. Sometimes an investment (CAPEX) may be required, the costs of which are spread over several years, to yield annual OPEX savings.

EBIT and EBITDA
EBIT and EBITDA are the two most common metrics to analyze the profitability of a company. Both metrics share similarities, but there are also some differences in their calculations.

'Earnings Before Interest and Taxes' (EBIT), also called operating income, is the company's net income, before tax expense and interest expense have been deducted. EBIT is used to analyze the performance of a company's core operations without tax expenses and the costs of the capital structure influencing profit.

'Earnings Before Interest, Taxes, Depreciation and Amortization' (EBITDA) strips out debt financing as well as depreciation of capex and amortization expenses when calculating profitability.

Working Capital (WC)
In some cases, Lean projects are selected on the increase of Working Capital. 'Working Capital' represents operating liquidity available to the organization. Liquidity and Working Capital are closely related as most goods can be sold quickly.

Working Capital consists of stock value (in services: percentage of completion not charged yet), accounts receivable and cash/bank account.

$$Working\ Capital\ = Current\ Assets\ -\ Current\ Liabilities$$

where:

Current Assets = Cash and other Assets expected to be converted into cash within one year
Current Liabilities = Debts and other obligations due within one year

Lean projects have a positive effect on stock, Work in Process and Lead Time reduction. Such projects will shift the stock value initially towards cash, which can be used to reduce current liabilities. As such, they have a positive impact on Liquidity and Working Capital.

Net Present Value (NPV)

Some Lean Six Sigma projects result in lower inventory positions. A reduction in stock of, for example, €10,000 cannot be entered in its entirety as cost savings. While keeping stock costs money, it is not equal to the value of the stock itself. Calculating the cost savings when the stock is reduced is very difficult and cannot be clearly stated. It is not the responsibility of a Green of Black Belt to define savings as a result of reduced stock. The advice is to consult the financial department of the organization for this. Nevertheless, we will clarify a few things that are important for this.

The accounting approach is twofold. On the one hand, capital invested in inventories is not available for other investments. A Euro today is worth more than a Euro tomorrow, because we have this Euro available today to invest and so we can make a return. Capital that is stuck in stock and that is not available is therefore worth less than capital that you can dispose of. The 'Net Present Value' (NPV) is a way to calculate this. The NPV compares the present value of capital today with the present value of capital in the future.

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

- *t*: Time period of the Cash flow
- *i*: Discount rate
  (rate of return that could be earned in the financial market, with similar risk)
- R_t: Net Cash flow (i.e. Cash inflow – Cash outflow), during time period *t*

On the other hand, there are also costs that are directly related to keeping items in stock (longer or shorter), for example renting warehouses, costs of running warehouses, insurance costs, spoilage and obsolescence.

Inventory Turnover Ratio (ITR)

The 'Inventory Turnover Ratio' (ITR) is a measure of the number of times the inventory is sold or used in a given period. This metric indicates how effectively a company's inventory is managed, by dividing the Costs of Goods Sold by the Average Inventory for a specified period. The ITR-ratio shows how often the average inventory is sold over the given period. The higher the ITR, the faster the stock turnover rate. For example, the Inventory Turnover for a major U.S. warehouse in 2019 was as follows:

$$ITR = \frac{Costs\ of\ Goods\ sold}{Average\ Inventory} = \frac{\$\,385.3\ billion}{\$\,44.3\ billion} = 8.7$$

Its days inventory equal:

$$\frac{1}{8.7} \times 365 = 42\ days$$

If a company buys larger amounts of inventory during the year, the company will also need to sell more. If the company is unable to sell these larger amounts of inventory, the inventory position will increase and storage and other inventory-related costs will be incurred. A turnover rate can also be calculated for transactional processes, such as the turnover rate for debtors, creditors and total assets.

Lean companies strive to keep the turnover rate high. As a result, less capital is needed to keep stocks. This capital is therefore available for investment in other projects. Increasing the ITR can therefore very well be an objective of an improvement project.

In the following Table the ITR for a number of major companies is displayed. It is difficult to compare them though, because the companies operate in different industries.
(Source: https://www.macrotrends.net)

Company	Period	ITR
Amazon	three months ending March 31, 2020	2.35
Apple	three months ending March 31, 2020	10.78
ASML	three months ending June 30, 2020	0.37
Cisco	three months ending April 30, 2020	3.48
Coca-Cola	three months ending June 30, 2020	0.95
Intel	three months ending March 31, 2020	0.85
McDonald's	three months ending March 31, 2020	60.68
Tesla	three months ending March 31, 2020	1.06
Toyota	three months ending March 31, 2020	2.41

Table 3 – Inventory Turnover Ratio (ITR)

2.2 Policy deployment

The implementation process of the previously developed implementation plan is called Policy deployment. This includes the process-based approach from project selection to realization. Breakthrough projects are initiated from the strategic objectives of the organization and Kaizen projects are carried out from the shop floor. Methods and instruments are applied in the execution of these projects. This is called the 'hard' concrete part of continuous improvement.

The other aspect of the deployment process involves creating a culture of continuous improvement. Matters such as organizational culture, change management, leadership and team development are discussed. This is also referred to as the 'soft' part of continuous improvement. Generally, the cultural aspect is much more challenging than the process aspect. It is necessary to let employees work in a different way. However, realizing such a change is not easy. People cannot be changed, they can only change themselves. To achieve this, employees must first see the benefit of this change. This requires vision, leadership, insight into resistance, communication and many other aspects. In this section we will cover a number of techniques that help to remove barriers to change. Champions, Green and Black Belts must recognize the importance of both the hard and the soft aspects of continuous improvement and give both aspects the right attention to make the policy deployment process successful.

"If you always do what you always did,
you will always get what you always got."

Many people attribute this quote to Anthony Robbins and before him Albert Einstein, Henry Ford and even Mark Twain. More important than the origin, however, is the point it makes. If you want to change the result, you need to change the way things are done.

2.2.1 Management of change

Management of change is a much discussed, yet controversial term. Most people do not like change. However, we simply cannot do without it. Our lifestyle, our economy, even our culture is based on change. Without change, we would still be chasing bears and living in caves. Within our organizations, we simply have to deal with changes. Working in an organization, we face an everlasting flow of changing requests from customers and managers on price pressure, costs cutting and innovations. As a consumer, we all want our TVs to get larger, thinner and cheaper at the same time. We all want our computers to become smaller, faster and (again) cheaper. A request for a passport and financial transactions needs to go faster and we all want a higher level of cure and care without paying more for health insurance. This is called economic growth and development.

Successful changes will result in growth. However, this will only be for a limited amount of time. Even the result of a successful change will stabilize at a certain point. If nothing is done, the growth will fade away. Organizations cannot wait too long to start the new 'Innovation curve' or 'Change curve'. This again can be illustrated with the introduction of a new TV model. No matter how innovative, after a certain period of time the market will request a new model. Also, competition is on-going. Doing nothing is not an option. If you do, you will become a sitting duck. The duration of a growth curve depends mostly on the type of product or service. High-tech products will have shorter curves than transactional processes. The only way to survive a declining curve is to start a new one. The switch from one curve to a new one is a period of 'Change'.

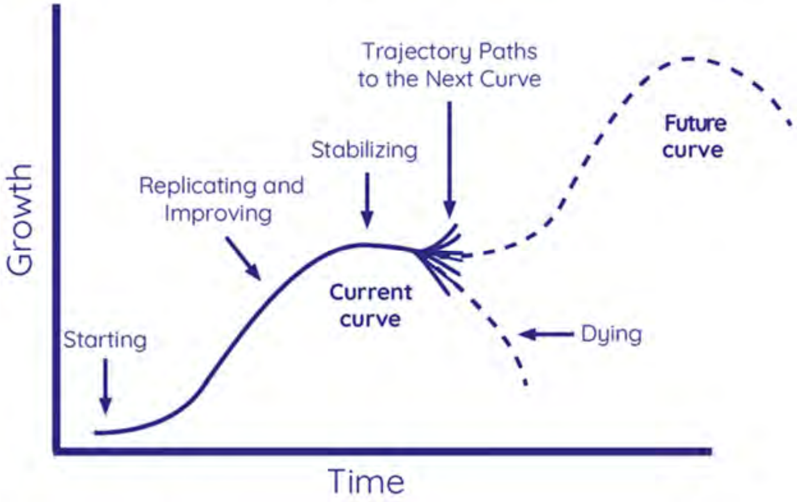


Figure 26 – Change curves over time

Process improvement and innovation have to deal with changing environments. As mentioned in the first chapter of this book, we constantly have to innovate our products and services and we constantly have to improve our processes. Changes might be small, as in 'Continuous improvement', or major, as in 'Breakthrough improvement' and 'Innovation'. Implementing each of the five levels of the maturity model for the first time within an organization should be considered as a major change and should be managed accordingly.

Reasons to resist change

The process of change is not easy because the organizational culture and the structures in which it is embedded often reflect the imprint of earlier periods in a persistent way. This may cause a remarkable level of inertia. Although the management of an organization acknowledges the importance of organizational culture in a process of change, there is clear diversity in the way they treat organizational culture. Accounting for the cultural aspects of the organization will be helpful in the acceptance of new improvement initiatives.

"Intelligence is the ability to adapt to change."

Stephen Hawking

Only 10-20% of the people in the organization can be identified as 'Movers'. They are happy with the anticipated change and help to make it work. These are the people that should be assigned to Green and Black Belt projects. About 10-20% of the people in the organization can be identified as 'Blockers'. They demonstrate resistant behavior and can barely be convinced of the need of change. The majority of the people, however, can be identified as 'Floaters'. They do not know yet what to think of the change. They wait and see what Blockers and Movers will do. This is an important group to involve after the first projects have been successful.

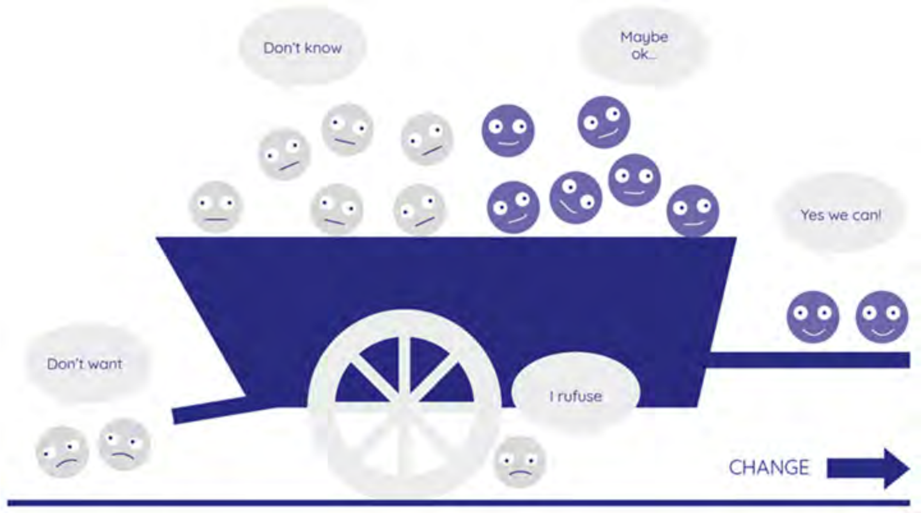


Figure 27 – Management of change within the organization

Several studies have shown that there is a strong correlation between the success of a change or transformation program and whether culture was affected during this process. It appears that a more culture-oriented approach to change is of great importance for the success of such program. Despite the fact that the management of an organization recognizes the importance of organizational culture during a change or transformation process, there is a wide variety in the way they handle it. Green and Black Belts do well to be open to the signals from employees who are part of the process. Taking into account the cultural aspects of the organization is important for the acceptance of change.

Since Green and Black Belts often deal with change of processes and the way of working, it is good to understand why people resist change and to know how to address some of these reasons. You do]not have to answer all the questions or take all uncertainty away (because you simply cannot). However, you should be able to recognize the reasons for resistance and take these seriously.

We will list the 10 most common reasons for resistance to change:

1. Surprise:
   People may resist change when they are shocked. This happens when they are not informed. People should be prepared for change early-on.
2. Self-doubt:
   People question if they are able to meet the requirements in the new environment. Show your faith in those who are involved in the change process. Explain what support can be expected.
3. Loss of control:
   People may be confused and lose control over their work. Make sure you structure the steps that it takes to regain control.
4. Growing uncertainty:
   In some situations, not everything is clearly defined from the beginning. Uncertainty may cause resistance. Make sure you are clear about what is defined and what is not yet defined.
5. Disruption of routine:
   Realize how a new way of working can disrupt routine. Prepare people in the new way of working. This takes time, training, managing expectations and support.
6. Loss of face:
   Changes may bring about loss of face because the change may evoke the feeling that people did not do their job well in the past. Engage these people, acknowledge their position and show respect.
7. Workload:
   For a certain period of time, the activities related to the change project often come on top of daily work. Managers should free up time and resources to work on the change project.
8. Loss of jobs:
   The greatest danger is uncertainty about loss of jobs. When loss of jobs cannot be avoided, it should be managed as well as possible. The advice is to separate the role of the project manager and the manager that has to deal with the reorganization.
9. History:
   People may be cynical about the proposed change when a similar program failed in the past. Make sure the lessons learned from failed projects are considered and address risks properly. Focus on achieving first results.
10. Personal disruption:
    The targeted change may spoil personal plans (e.g. vacation, being home for dinner) or interfere with ambitions (e.g. study and career). Minimize disruptions as much as possible and investigate what can be done to compensate disruptions with an alternative.

Emotional stages of change (Kübler-Ross)

As mentioned, Green and Black Belts have to deal with change. It is necessary to manage the process of change and to try to make the change transition as smooth as possible. The Kübler-Ross change model can be helpful to predict how people will react to change. The Kübler-Ross change model is named after Elisabeth Kübler-Ross, a Swiss doctor who devoted her life to studying people with terminal illnesses. In her book, 'On death and dying' (1969), she first discussed her theory of the emotional stages of grief that people go through when they learn that they are dying. Her model has also become the foundation to management of change. People will experience similar stages when they are given the news that things will 'change'. Different variants of this model can be found with different explanations, but the basic idea will remain the same. You might recognize the following phases that occur when the organization is given the news of a change program:

1.	Denial	Trying to avoid the inevitable	'This cannot be true'
2.	Anger	Strong expression of emotions	'This is not going to work'
3.	Bargaining	Resisting or avoiding the change	'I will not cooperate'
4.	Depression	Final realization of the inevitable	'There is nothing I can do about it'
5.	Acceptance	Seeking realistic solutions	'Let's give it a try'
6.	Moving-on	Finally finding the way forward	'This is good for me'

Figure 28 depicts these phases. The vertical axis represents the amount of energy and performance. Denial and anger can cause a lot of commotion in the organization. There will be a lot of negative energy, which can be expressed in a lot of different ways such as aggression, discussion, even physical and organized demonstrations. Then, at a certain moment, the energy will fade away and people will start negotiating and looking for a way out. The level of energy and productivity will drop. If people realize that there is no real way out, they might get disappointed and depressed. The level of energy will drop further as well as productivity.

In the meantime, the change has started and the first results will be visible. The organization has been shaken up and slowly it will become clear what the new situation will be like. Some people will start to realize that some of the changed elements are not that bad and might even have benefits. Some of these people will realize that the new situation will also mean new opportunities. They will start to pick up the pieces and they will investigate what these new opportunities will mean for them.

Figure 28 – Emotional stages of change (Kübler-Ross)

The question is how to make the impact in the first phases as small and short as possible. The second question is how to reach the critical mass of people in the acceptance phase. We will take a look at what we can learn from Kübler-Ross in implementing process improvement methodologies such as 5S, Kaizen, Lean and Six Sigma. We will also review a number of actions and measures that can be taken by the management.

Preparation phase:
Be prepared. Make sure you have a good plan before the message is given. Make sure the right people have been involved in preparing the plan. Make sure you have a good business case to explain the sense of urgency and your vision of the new way of working.

No one person, no matter how competent, is capable of managing a change on his own. Management will need a small group of people who support the change from the beginning. Green and Black Belts can be very helpful to support management through the execution of projects within the transition or change program. Implementing a new process improvement level requires both knowledge and competencies. Management should consider if the 'Leading coalition' has the proper knowledge and competencies to lead the first projects to success. It is recommended to involve an internal or external Master Black Belt to coach the Green and Black Belts in the first projects.

Establishing the sense of urgency will help everybody involved to understand the reason for change. When there is no burning platform, there is no sense of urgency to change and nobody will move. People will not understand the need to change if everything is running well. This, however, is a big risk of starting a change too late and unprepared. Close to 50% of the companies that fail to make intended changes make their mistakes at the very beginning (Kotter, 1996). Leaders underestimate how hard it is to drive people out of their comfort zones, overestimate how successfully they have already done so, or simply lack the patience necessary to develop appropriate urgency.

1. Denial & 2. Anger phase:
Some changes have to do with bad news like reorganizations. Other changes have to do with growth and new opportunities. Some changes only have an impact on a small part of the organization, while other changes have an impact on the entire organization. You can imagine that large changes (e.g. organizational change or a new way of working) and negative changes (e.g. reorganizations and layoffs) have a bigger impact and will result in a huge amount of emotional energy (vertical axis). The peaks will be higher and the valleys will be deeper. Also, the duration of the change (horizontal axis) will be longer.

No matter the type of change, management should realize that people rarely 'Accept' the change directly and cooperate to make it happen. In general, most people will initially 'Deny' the message and indeed actively oppose to it. This is a normal reaction and this phase should be given time. The time it takes people to go from the first phase to the acceptance phase differs. Some people will only need a few days or weeks to settle and accept the inevitable, while others will get stuck in the denial and anger phases and will never reach the acceptance phase. This is the biggest risk to a successful change because these others might pull people – who have already reached the acceptance phase – back into the depression phase. Communication is very important, especially in these phases. Management should realize that listening is more important than talking.

3. Bargaining & 4. Depression phase:
Understand that this phase is something you have to go through. Give it time, but make sure it will be as short as possible. You will need a critical mass of people in the acceptance phase to bring the change to a successful end. As long as the majority of the people are still in the first phases it will be difficult to make progress.

Again, prepare how you will act in the 'bargaining' phase. Verify upfront what would be the positive elements of the transition and the new way of working, and how to this explain to people who show resistance. For example, many people do not realize that 5S will also result in a safer workplace and that process improvement will result in fewer disturbances. Many people also need to be told that Lean does not mean working faster, but working smarter. Assure and explain that people will be trained and that people will get time to adapt to the change. Make sure that people do get time to work on the change or improvement projects. Ensure there is some budget available for relatively small requests like communication boards, changing lights, replacement of broken chairs and tooling. Finally, make sure that small requests do not have to get approval from several management layers. Remember that you can receive a lot of commitment in return of small favors.

5. Acceptance & 6. Moving-on phase:
The best way to get out of the negative spiral is to show the first results. Failing these first projects is not an option, as these are very important to bring people into the acceptance phase. This is in line with step six of the Kotter-model that focuses on 'Short-term wins'. Green and Black Belts can make the difference by showing the first positive results of projects that are part of the transition. Make sure the first successes can be shown as soon as possible. The sooner you are able to demonstrate success, the sooner those who are affected by the change will be convinced to adopt it. Black Belts and Champions should realize that the first projects chosen should have a big probability of success in a short period. This is more important than choosing the big projects with a lot of financial benefits, but with a low probability of success and a long lead time for completion. Failing projects and waiting a long time for results create a big risk of failure.

Eight steps of change (Kotter)

Managing change requires a lot of soft skills which often are not present in all Green Belts and Black Belts. In this paragraph we will review an approach that can be used to manage change. It can also be useful in the policy deployment process or even in single improvement projects.

Without the ability to adapt continuously, organizations cannot thrive. For this reason, organizations need to be successful in management of change. For all the money and effort that go into change initiatives, they have a decidedly mixed success rate. According to John Kotter, 70% of programs of change fail (Kotter, 1996). After thirty years of research, this is a very demotivating conclusion. Why do changes fail? Because organizations often do not take the holistic approach required to see the change through.

“70% of all major change efforts in organizations fail.”

John Kotter

In his book ‘Leading Change’ (1996), Kotter outlines eight critical success factors from establishing a sense of extraordinary urgency, to creating short-term wins, to changing the culture. According to Kotter, organizations can reduce the risk of failure by following the 8-Step approach. By improving their ability to change, organizations can increase their chances of success in an ever-changing world. Following these eight steps in this particular order will smooth the peaks and valleys in the process of change. Kotter also states that none of these 8 steps should be skipped.

Figure 29 – Eight steps of change (Kotter, 2015)

We will explain these 8 steps briefly:
(Source: www.kotterinternational.com)

1. CREATE Sense of Urgency:
   Help others to see the need to change and they will be convinced of the importance of acting immediately.

2. BUILD Guiding Coalition:
   Assemble a group with enough power to lead the effort to change and encourage the group to work as a team.

3. FORM Strategic Vision and Initiatives:
   Create a vision to help direct the effort to change and develop strategies for achieving that vision.

4. ENLIST Volunteer Army:
   Communicating the Vision for Buy-in and make sure as many as possible understand and accept the vision and the strategy.

5. ENABLE Action by Removing Barriers:
   Empowering and remove obstacles to change. Change systems or structures that seriously undermine the vision and encourage risk-taking and non-traditional ideas, activities and actions.

6. GENERATE Short Term Wins:
   Plan for achievements that can easily be made visible, follow-through with those achievements and recognize and reward employees who were involved.

7. SUSTAIN Acceleration:
   Use increased credibility to change systems, structures and policies that do not fit the vision. Also hire, promote and develop employees who can implement the vision. Finally, reinvigorate the process with new projects.

8. INSTITUTE Change:
   Incorporating the changes into the culture. Articulate the connections between the new behaviors and organizational success and develop the means to ensure leadership development and succession.

Stakeholder analysis

A stakeholder analysis is a way to map out the different opinions and attitudes that people have with regard to a particular project. Knowing these attitudes helps to develop a strategy and to deal with the different attitudes. Stakeholders are people who have an interest in or an influence on a particular project. These can be managers, employees on the shop floor, customers and suppliers. Some of these stakeholders may oppose or hold back changes. Others could help to successfully implement the change. Mapping the stakeholders and understanding their attitude is therefore important in the development of the change strategy. For some Green and Black Belt projects it may be useful to perform a stakeholder analysis. However, it is not necessary in all cases. If you expect resistance in a certain project, it is recommended to perform a stakeholder analysis. This is specially recommended for larger projects or transformation programs.

"If you want to go fast, go alone.
If you want to go far, go together."

African Proverb

To conduct a stakeholder analysis, you have to make a list of all people in the project environment. You then need to find out the interests of each of them, which could be supporting or conflicting. You also need to find out the interest and influence of each stakeholder. An estimate should then be made of the relationship this stakeholder has to the project followed by the risk or opportunities for the program. A communication plan needs to be set up that describes how you will inform and approach all stakeholders.

Step 1 – Map the project environment (List of stakeholders):
You first need to map the project environment. This results in a list of all individuals and companies that are involved in the program in one-way or another. It is possible to have many different types of stakeholders, like policy makers (e.g. management), project members (e.g. employees, colleagues), input providers (e.g. suppliers, governance) and output-users (e.g. customers, external individuals).

Step 2 – Determine influence and interest (Direct, Indirect, Invisible):
Some of the stakeholders are directly involved in the program (e.g. Champion, team members, employees), while others have an indirect role or have no role at all in the program. In this step you have to define the role of each of the stakeholders identified in the previous step.

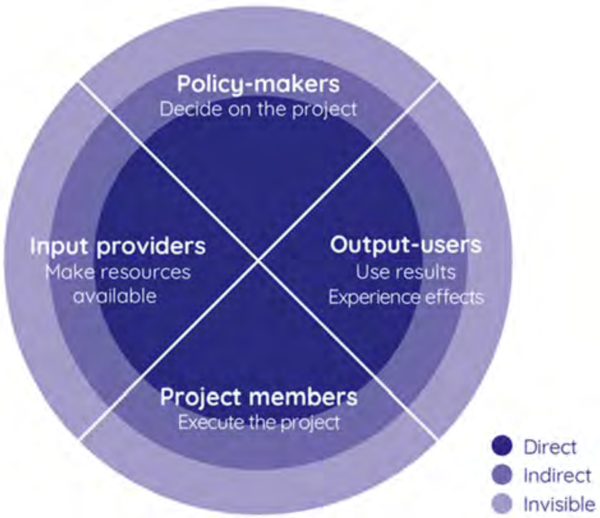


Figure 30 – Stakeholder influence and interest

Step 3 – Estimate relationships (contribution or opposition):
During this step, the relationship of all stakeholders to the project or program is defined. In this approach, six different relationships are distinguished from 'Ally' to 'Enemy' of the program. To classify the correct relationship, first the attitude of each person with regard to the content of the project plan is considered and secondly, the trust that this person has that the project team will achieve the results.

For example, a person who disagrees with the content of the plan (–) and is not confident that the team will achieve the project objectives (–) is classified as 'Enemy' of the program. A person who partially agrees with the plan (–/+), and has moderate confidence that the team will achieve the objectives (–/+) is called a 'Skeptic'. Based on the Figure below, each relationship is given a certain score from (1 to 6).

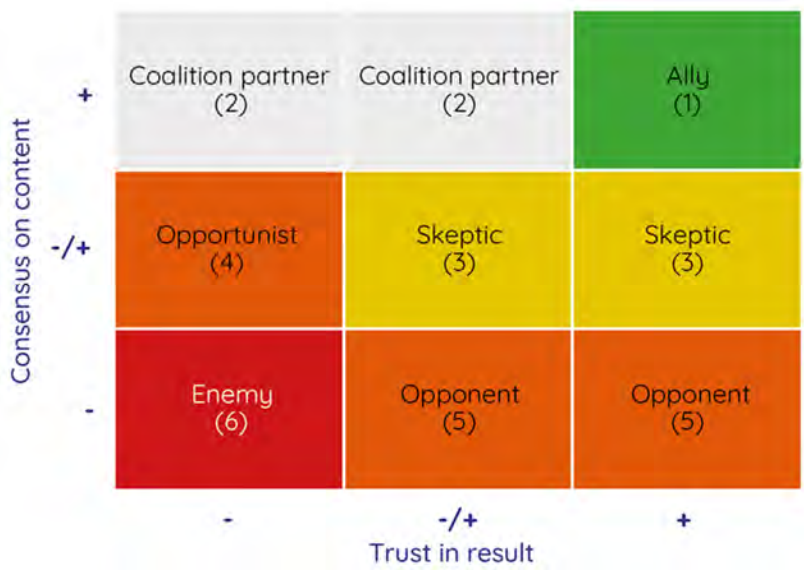


Figure 31 – Stakeholder contribution or opposition

Step 4 – Define opportunities and threats:
In this step, you have to determine the impact that each stakeholder has on the program. This can be achieved by multiplying the 'Relationship' from the previous step with the 'Level of influence' in the organization. For example, an opponent (level 5) who has much influence (level 3), is a big risk for the program (5 x 3 = 15), while an enemy (level 6) who has no influence (level 1), is a low risk for program (6 x 1 = 6).

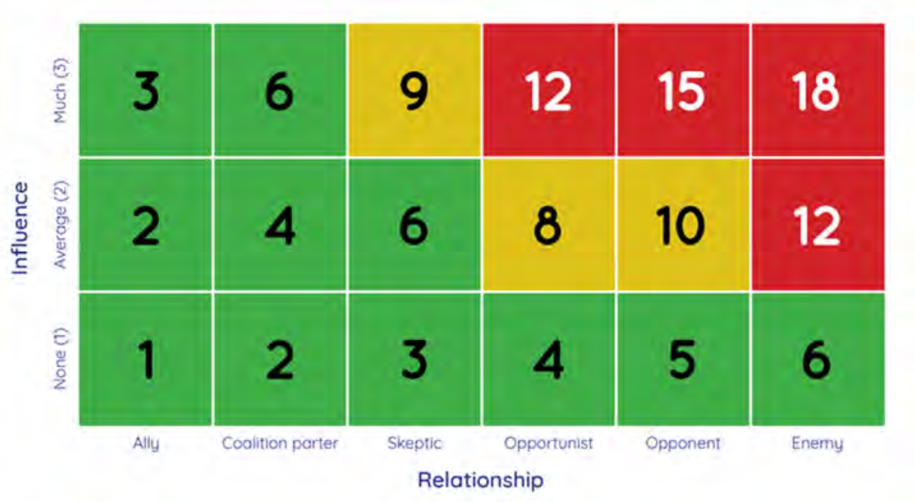


Figure 32 – Stakeholder opportunities and risks

Step 5 – Set up a communication plan:
A concrete result of the stakeholder analysis is the communication plan. On the basis of the results of the risk assessment, it is determined how the various relationships are communicated to. This is called the communication strategy. High risks should receive special attention in the communication plan.

In the 1960s and 1970s, communication was typically deployed at the end of a policy or production process when decisions were already made. Only then, outsiders were informed of what has been decided. At that time, communication science was mainly concerned with unfocused and uncontrolled one-way communication. Our way of dealing with people and the way we treat each other, has changed in recent decades from a command system to a negotiation system (Swaan, 2000). People have become freer and in fact the norm has become that everything must be discussed and negotiated. This is also referred to as the democratization process of society. However, sometimes it may still be important to communicate decisions in a direct way. The communication strategy is a choice that management or the project manager must make.

For our Western society, we have to take others into account as well as greater diversity, than previously. As a result, we need to get in touch with more people who also show great differences in interests and opinions. The management and the project manager must take this into account in a transformation or change process. When communicating with stakeholders a certain strategy must be chosen, where a different strategy can be chosen for different relationships. Do we inform employees about an imminent transformation, or do we first enter into a conversation after which the change is defined? Does management determine the course of the organization and should employees and individuals participate in this, or is management open to input? This is also seen as the problem of one-way communication or two-way communication, or asymmetry or symmetry in the relationship (Ruler, 1998).

In 1998, Betteke van Ruler, professor of Communication Science, introduced the so-called 'Communication grid of tactics', a handy tool for determining the main features of the communication strategy. The intersection assumes that two basic choices must be made. First, it must be determined whether there is room for a dialogue and whether communication can be conducted in two directions or not. Secondly, it must be determined whether it is a statement or whether the target group must be influenced and convinced. These two choices result in four basic strategies for communication.

We will briefly discuss the four communication strategies:

- Information:
  This form of communication aims to disclose information and policy. The form of communication is one way. Newsletters, memos and mass communication such as TV can be used to get the message across. The facts and decisions are presented and the opinion is left to the audience. Examples of this are the publication of policy rules and decisions.
- Persuasion:
  The emphasis of this form of communication is on influencing the target group. The form of communication is one way. Examples include sales and advertisements on radio and TV. Another example is a presentation in which management indicates why a transformation or reorganization is important.
- Consensus building:
  The emphasis of this form of communication is on getting the target group along. You have an opinion that you want to convince the other person. The communication is a two-way process. You listen, but it is mainly intended to convince the other persons of your point of view. An example is lobbying.
- Dialogue:
  With this strategy you enter into a conversation with the target group. There is an open dialogue in both directions. For example, the government uses consultation rounds for this and a manager does this when he is in a meeting with his employees.

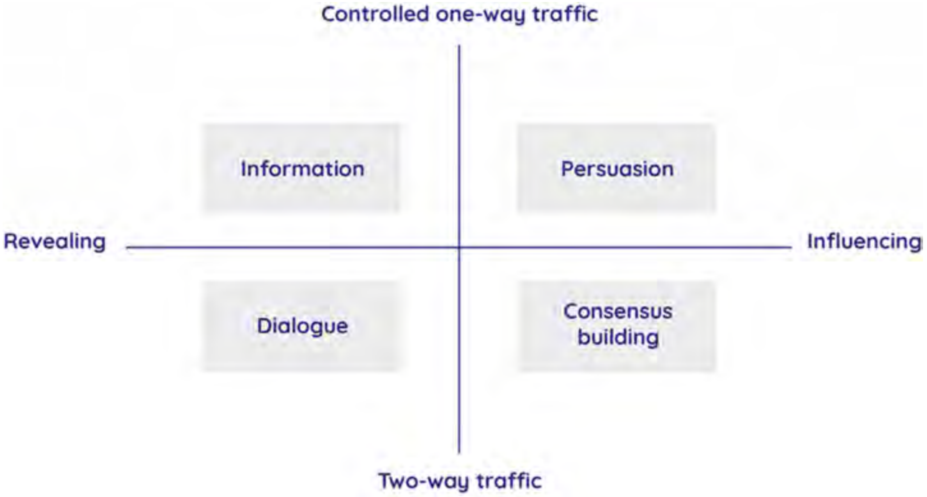


Figure 33 – Communication grid of tactics (Ruler, 1998)

Keep in mind that it is hardly possible to change a person's level of influence, but you can influence the relationship to the program. This starts with listening and understanding. Interaction is key in any communication plan; think in two directions. If you can turn an enemy or opponent into a coalition partner, you have achieved a lot.

2.2.2 Leadership

Continuous Improvement should not focus on efficiency and first time right only because there is more to life than profit and happy customers. Continuous Improvement should include long term and meaningful objectives such as sustainability, dignity and creating an inspiring and healthy work environment. Continuous Improvement consists of both visible and invisible aspects. The visible aspects are the techniques and activities, such as improvement boards, projects and analyzes. The invisible aspects are leadership, communication and competences, but also responsibility, ownership and discipline. It is not only about improving the processes, but also about developing the organization and the employees. Research reveals that most Lean implementation programs focus on the visible elements only. Invisible aspects such as leadership, management strategy, financial capability, employee competencies and organizational culture are critical success factors for Lean and Six Sigma implementation (Achanga et al., 2006). It is important to pay more attention to re-building the organizational strategy and culture, as well as to increase employee engagement, rather than simply adopting tools.

In a Continuous Improvement environment, employees should be encouraged to continuously strive for a good result and to act if it appears that the goals are not met. This requires an open and action-oriented workforce. Managers need to make employees responsible and accountable for their own performance and encourage them to be proactive in taking actions. This also implies that results must be shared openly with the entire organization. The facts and results should not only be known to management, but everyone in the organization must be aware of the performance to ensure that everyone can contribute to improvement initiatives. In an open organization, there is a constructive dialogue between management and employees. Employees are involved in important decisions and projects, and employees feel involved and connected with the organization and their work. An effective Continuous Improvement organization is also result-oriented. Result-oriented leadership is a combination of task-oriented leadership and human-oriented leadership. A manager should realize that, on the one hand results must be achieved, while on the other hand they need the trust of their employees to achieve this.

Different phases within a Lean or Six Sigma deployment program have different roles and requires different styles of leadership. In this paragraph, we will describe the difference between a Leader, a Manager and a Coach.

“Management is efficiency in climbing the ladder of success;
Leadership determines whether the ladder is leaning against the right wall.”

Stephen Covey

Leader
First of all, somebody needs to take the initiative to start the deployment program. This is a strategic decision and not an organizational decision, because it changes the direction of the organization and will have an impact on all departments and employees. This should not be underestimated. The choice of becoming a Lean or Six Sigma organization has a huge impact on the organization.

'Leadership' affects culture rather than 'Management' (Burman and Evans, 2008). A Continuous Improvement organization depends very much on culture and leadership. Whether Continuous Improvement within the organization will become successful or not depends very much on the organizational culture and the role that leadership plays. The leader’s responsibility is to develop the organization’s strategic objectives and to initiate and encourage ideas and improvement initiatives. A leader should also be honorable, visible and trustworthy.

- Style: inspiring; motivating; helping; respecting; leading; encouraging.
- Objectives: strategy; direction; culture; innovation; impact.

Manager (Champion)
After the leadership team has defined the strategy and initiated the improvement program, it is the role of the manager to lead effective execution of the initiatives within his department. Within Lean Six Sigma, the manager is also called Champion. The Champion is selecting the projects within his department in a way that the department will contribute to the organization's strategic objectives. The Champion assigns the project manager (Belt) and together they will develop the project charter. They ensure that the projects get the proper priority and make sure that any barriers for executing will be removed. The role of the Champion during the different project phases and Tollgate reviews is therefore essential.

Being a good manager requires different skills. The manager has integrity, is a role model for others, applies fast decision making, applies fast action taking, coaches others to achieve better results, focuses on achieving results, is effective, is confident, is decisive with regard to non-performers and holds others responsible for their results (de Waal, 2013). The role of a manager is to stimulate creativity and to support and coach employees to achieve short term objectives. Therefore, they should be present during daily standup meetings at the shop floor. Within the role of Champion, it is convenient that the manager masters certain knowledge of Lean and Six Sigma techniques to support and coach Belts in their role of project manager, although in-depth coaching in more advanced techniques is often performed by Master Black Belts or Sensei's.

- Style: planning; implementing; controlling; influencing; scheduling; coaching.
- Objectives: tactics; behavior; efficiency; effectiveness; results; budget; quality; output.

Coach (Master Black Belt / Sensei)
Although the leaders and managers might define what needs to be happen, they may not necessarily know all the Lean and Six Sigma techniques themselves. In the event that freshly trained employees encounter problems during the execution of their improvement projects, it is good to know that they can go to an experienced coach. Within Lean, this role of coach is called Sensei and within Six Sigma, this role is called Master Black Belt. The translation of Sensei is 'Person born before another' or 'One who comes before' and applies to someone who teaches based on wisdom from age and experience. This meaning can be found both in Japanese as in Chinese culture. Toyota had a unique group of Sensei (elderly people) that had the role of trainer, dedicated to help managers think differently.

In addition to the quote of Steven Covey, you might say that the Sensei is coaching the people how to climb from one rung to the next rung.

- Style: encouraging; inspiring; empowering; teaching; asking; demonstrating.
- Objectives: learning; developing; insight; strengthen; self-respect; self-steering.

Situational Leadership
Managers should be able to adapt their way of management to different situations. The 'Situational Leadership' framework describes four leadership styles and demonstrates a set of tools that helps to open up communications, which is an important element in change programs. Situational Leadership is a leadership theory developed by Paul Hersey and Ken Blanchard. The theory was first introduced as 'Life Cycle Theory of Leadership' (1969). As of 1977, both authors continued to develop their own version of the Situational Leadership model.

Figure 34 – Situational Leadership Model (Hersey-Blanchard)

The Hersey-Blanchard Situational Leadership Model rests on two fundamental concepts: leadership style and the individual or group's maturity level. Hersey and Blanchard categorized all leadership styles into four development levels of 'Situational Leadership', named S1 to S4. Each of these four styles is characterized in terms of the amount of 'Task Behavior' and 'Relationship Behavior' that the leader provides to their followers:

- S1 – Telling:
  The manager tells the employees exactly what to do. The manager gives precise instructions and checks the execution of the task. This style is also referred to as management by prescription. A lot of steering and little supportive leadership behavior.
- S2 – Selling:
  The manager supports the employee by sharing responsibilities and by asking a lot of questions, listening actively, consulting and involving the other, complimenting and stimulating. However, the tasks are accurately determined and checked if necessary. This style is also referred to as result-oriented management.
- S3 – Participating:
  The manager and employees decide together how the work is performed. The manager acts in a stimulating manner, and assists the employee with implementation upon request. The manager primarily leads by paying attention to the relationship and by giving recognition. This style is also known as organic management.
- S4 – Delegating:
  The manager leaves the decisions and how to perform the task to the employees. They are responsible themselves and are therefore given the necessary powers. Delegation can be effectively applied when the manager can create the conditions for the employee to perform the assignment. This style is also known as management by exception.

Seven Habits of highly effective people (Covey)
While Lean Six Sigma focuses on improvement from the perspective of customer value or business value, Covey's seven habits focuses on self-renewal of people. The objectives of efficient and effective processes go hand-in-hand with the objectives of effective people and the principles of Continuous Improvement go hand-in-hand with Covey's 'Seven Habits'.

Stephan Richards Covey was born in Salt Lake City and was an American scientist, writer, businessman and speaker and, at the end of his life, a professor at the Jon M. Huntsman school of Business in Utah. His most popular books are: *"The 7 Habits of Highly Effective People"* (1989) and *"The 8th Habit; From Effectiveness to Greatness" (2006)*. In his life he received several awards from both the Eastern and Western institutions. During his studies, Covey became inspired by Peter Drucker, Carl Rogers and other writers of self-help books, that he had read while preparing his thesis. But most of all, he was influenced by his creed as a Mormon. According to some, his book "The 7 Habits" [10.] is a non-religious summary of Mormon values. The book has sold more than 15 million copies in 38 languages worldwide. Covey presents an effective approach for attaining goals by aligning oneself with what he calls, 'True North principles of a character ethic', that he presents as, 'universal and timeless'. He states that, by functioning better yourself, you are also able to make others work better.

According to Covey, until the First World War, success was mainly to be summarized in terms such as humility, integrity, moderation, loyalty and patience. After the First World War, success was defined differently by a more pragmatic attitude to life. Success is mainly measured by personal performance, skills and status. Covey says that lasting success is only possible by pursuing the 7 Habits. The approach consists of seven characteristics that can be learned step by step and can help people to regain control of their lives without affecting their relationships with others. The approach can be seen as a kind of three-stage rocket. The first 3 habits are about Private victory and reaching a state of independence. Habit 4 to 6 are about Public victory and reaching a state of interdependence. Habit 7 is about sustainability and further development. The American president Bill Clinton invited Covey to Camp David, the president's holiday residence, to ask him how the seven habits could be applied into his presidency. That these conversations were fruitful is evident, because, during a conference, Clinton referred to the 7 habits as one of the three books that all employees should read. If that were to happen, this would give a drastic boost to national productivity, Clinton said.

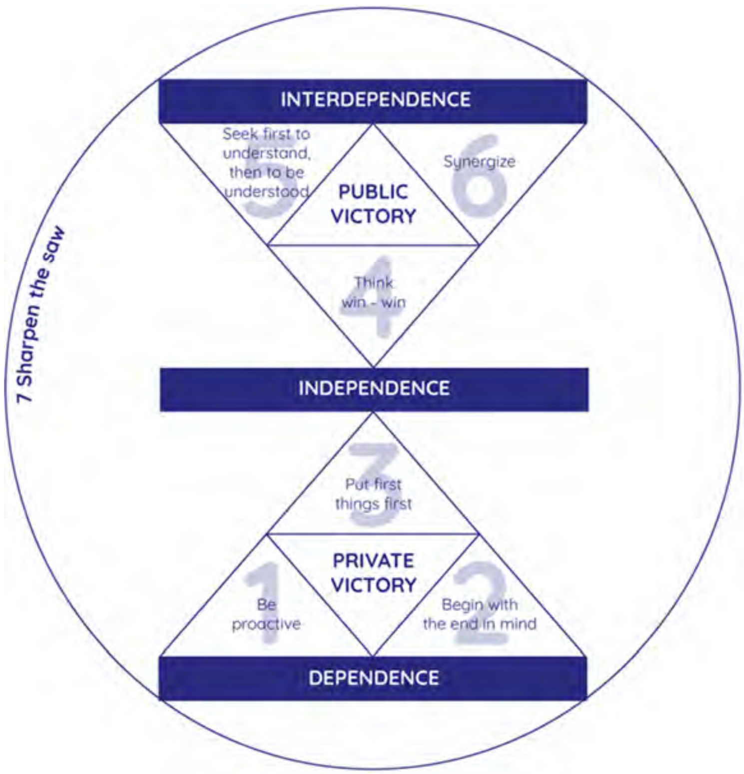


Figure 35 – The 7 Habits of highy effective people

Habit 1 – Be Proactive:

Be Proactive is about taking responsibility for your life. This gives you more influence on what happens to you. This is in contrast to many people who wait to see whether decisions are made for them. A proactive approach means that you focus on your own behavior and your own thoughts. You can't keep blaming everything on your parents, management or society. Proactive people recognize that they are 'Response-able.' It is important to realize that it is not always possible to change everything as an individual. Covey describes this as the circle of involvement and circle of influence. The further from the center of the circle, the smaller the influence we have. Proactive people focus their efforts on their 'Circle of Influence': the things that they can do something about. This self-consciousness helps to choose which subjects we should care about and act on, and which subjects we have to accept or ignore. In other words: "pick your battles". Those things that we cannot influence are the matters that we should not worry about. It is important that we realize that we cannot influence everything, but that we can always determine our reaction. Proactive people realize that they can make this choice and thus gain control over the situation as quickly as possible.

Habit 2 – Begin with the End in Mind:
The second habit is about determine your own destiny, otherwise someone else will do that for you. How do you organize your work, life or department? Do you live in a very opportunistic way and do you see what comes your way, or do you take control and set clear goals? To work and live effectively, it is important to think backwards. Or in other words, first set your goals and then see what it takes to achieve those goals. "To steer the consequences of our choices in the right direction, we must constantly use principles such as justice, kindness, respect, honesty and integrity." Such principles are universal. Without principles, people are disoriented. With principles, people have a compass that guides them into the right direction. Define what you want to become or what you want to achieve. Beginning with the end in mind is about vision. If your ladder is not leaning against the right wall, every step you take gets you into the wrong direction. Develop a 'Personal Mission Statement' that describes your plan of success. Covey asks you to answer the morbid question: "What would you like people to say about you during your funeral?" And if you know that, organize your life in such a way that it actually happens.

Habit 3 – Put First things First:
To prevent overextending yourself, you should only focus on your highest priorities. Realize it's alright to say 'No' when necessary. By setting priorities you can use your time more effectively. It is a waste to spend your precious time on trivial matters that do not contribute to achieving the objectives. If you put first things first, you are organizing and managing time and events according to the personal priorities that you established in Habit 2. If the first three habits are met, people can focus on a more fruitful collaboration with others. After all, being independent in itself is not enough, certainly not in a world where everything is connected with everything.

Habit 4 – Think Win-Win:
Working together effectively does not allow you to think in terms of winning and losing. Success is achieved sooner when we enter a challenge based on a win-win approach. Win-Win is a character-based code for human interaction and collaboration. You should not base your self-worth on comparisons, competition, or success in terms of someone else failing. Win-Win sees life as a cooperative arena, not a competitive one. Win-Win is a frame of mind and heart that constantly seeks mutual benefit in all human interactions. 'If you can't share, you cannot multiply'. A useful tool in this is the abbreviation WIFM (what's in it for me?) When we are able to answer this question for all stakeholders, then we are able to work towards that win-win balance where all involved get the feeling that they get better from the situation. This approach lowers the resistance associated with a change. According to Covey, you should think in terms of abundance rather than scarcity. Don't think that the other must lose so that you can win. Covey states that of the most beautiful things in life – such as love, attention and happiness – is enough for everyone. Don't be afraid to allow other people to win as much as you do.

Habit 5 – Seek first to understand, then to be understood:
To achieve a win-win situation, it is important that people understand each other's needs. Communication is very important. Speaking is one part of communication. Listening is the other part. Most people listen, however, with the intent to reply, not to understand. Truly understanding the other person's mind, however, is very important. It creates an atmosphere of caring and encourages positive problem solving. Despite the fact that we have two ears and only one mouth, many people talk much more than they listen. Project managers of an improvement project often already have a clear idea of how the project will develop. On the other hand, those directly involved do not yet have this image. This can lead to the situation in which managers take too little time to identify the usefulness, necessity and associated backgrounds of their actions and to communicate these to the other stakeholders. If we really understand each other, we will become more creative in solving joint problems.

Habit 6 – Synergize:
When we are able to put the aforementioned habits into practice, we will experience synergy within the group. Synergize is the habit of creative cooperation: 'One plus one equals three'. It is teamwork, open-mindedness and the adventure of finding new solutions to old problems. It is also about mutual respect and appreciation of the differences. If we are better informed about the expectations of the other, we will be more willing to be more flexible and to interpret our views a little more broadly. This attitude creates room for a different perspective that contains the best of both and is therefore perceived as acceptable to both parties. Valuing differences is what really drives Synergy. The capability of inventing new approaches and solutions is increased exponentially because of differences.

Habit 7 – Sharpen the saw:
This habit is about having a balanced program for self-renewal in the four aspects of our lives: physically, mentally, emotionally and spiritually. As you renew yourself in each of the four areas, you create growth and change in your life. Make sure your energy level stays on the right track and stay curious about new possibilities, both mentally and physically. Covey calls this the spiral directed upwards. Keeping the saw sharp goes further than just guaranteeing what has been achieved. It also focuses on making that saw sharper all the time. This habit therefore is fully in line with the principles of Continuous Improvement.

Habit 8 – From effectiveness to greatness:
The 8th habit was added later by Covey. It describes a roadmap to help you find daily fulfillment and excitement. To thrive, innovate, excel and lead in this new reality, it is necessary to reach beyond effectiveness toward fulfillment, contribution and greatness. This habit is not just about the effectiveness to achieve your goals but also about a whole new dimension, the ability of people to live according to their full potential (their inner voice) and to inspire others to do the same. According to Covey, there is a simple reason why so many people are dissatisfied with their work and why many organizations fail to use the talents, ingenuity and creativity of their people. It is because they base themselves on an incorrect paradigm about who they are. People are not things that need to be motivated and controlled, but they are four-dimensional beings, with body, head, heart and soul. Live from your full potential and inspire others to do the same.

2.2.3 Hoshin Kanri (X-matrix)

Excellent organizations continuously work on organizational development, improving their processes and innovating their products and services to generate value for customers and other stakeholders. The process of policy development and policy deployment, as previously described, can be a difficult journey. The road to the top of the mountain is full of obstacles. Do you recognize some of the following situations?

- Objectives between departments are not aligned.
- It is unclear what a given project will contribute to the business goals.
- Long Lead Time of projects; many projects are never completed.
- The priorities are unclear and change frequently.
- Employees do not identify themselves with organizational objectives.
- Employees feel that they are not involved in the process.
- The contribution of individuals to business objectives is unknown.
- Progress and results are not concrete or not transparent.

Many organizations will recognize several of the problems listed above. The main reason is that companies do not perform strategic planning to achieve their goals and do not have enough focus on a limited number of key improvement priorities.

No organization has unlimited resources to work on all improvement and innovation opportunities. Nevertheless, many organizations make the mistake to pick too many opportunities or development projects to work on. As a consequence, projects will be delayed or never get finished at all. To prevent this from happening, choices need to be made in order to maintain focus. A powerful technique to support the project selection and prioritization process at a business level is the 'Hoshin Kanri' technique.

"Hoshin Kanri is the shining of the compass' metal needle.
The one leading all individual units of the fleet toward the same goal."

Kaoru Ishikawa

Hoshin Kanri is a Japanese strategic planning process designed to communicate the organization's strategy, long-term objectives, annual objectives and breakthrough priority projects throughout the organization. Hoshin Kanri is a simple but very powerful tool to define and focus on the key improvement priorities that remove the roadblocks in the organization. Hoshin Kanri is used to:

- Communicate the strategy to the organization.
- Align all projects with the strategy and prioritize projects.
- Identify clear ownership and give insight into an individual's contribution.
- Focus and apply necessary resources for success.
- Make progress and results measurable and transparent.

Top level X-matrix

Hoshin Kanri is visualized by means of a number of matrices. The main matrix is called the Top-level X-matrix. To compose this matrix, you should follow the five steps listed below, which will take a few sessions with the entire management team. In between these sessions, the manager should deploy objectives with his department and debate about the roadblocks and improvement priorities.

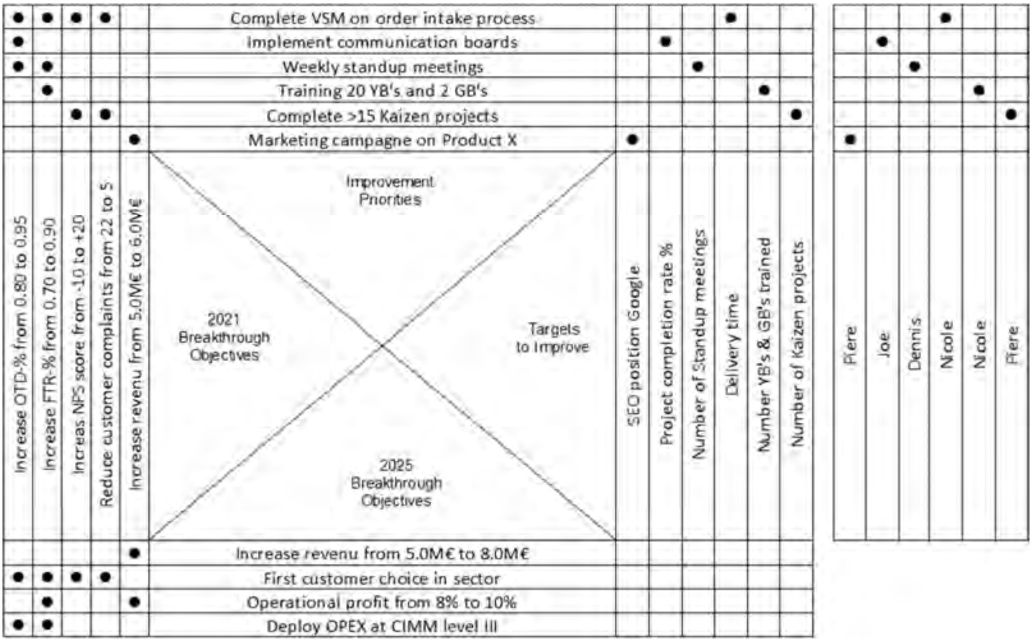


Figure 36 – Top level X-matrix

Step 1 – Long term goals

The first quadrant defines the long-term goals and breakthroughs. Both KPIs and CSFs can be mentioned here. Also state clearly for what year these objectives are intended, for example in five years' time. As a rule, there are a handful long-term goals in this quadrant.

Step 2 – Objectives for the coming year

In the second step, the long-term objectives are translated into objectives for the coming year. These should be measurable objectives and if possible be presented in the following way: 'Verb – Item – From – To', so for example 'Increase NPS score from -10 to +10'. It is therefore important to know what the current value is for a particular objective. That turns out to be not always the case. Each long-term goal from the first quadrant has at least one short-term goal.

Step 3 – Breakthrough projects
The breakthrough projects are shown in the third quadrant. Before we can define these, it is important to organize a brainstorming session for each objective from the second quadrant to identify roadblocks. For each objective, ask the question: "What will stop us from achieving this objective?" Roadblocks can be clustered, even across different objectives. A breakthrough project must then be formulated to remove the most important roadblocks. Furthermore, the third quadrant only shows real breakthrough projects and not all kinds of projects that are already ongoing, but will not lead to a breakthrough. Usually there are about 10 breakthrough projects in the third quadrant, no more. This third step is the most challenging, but also the most important step in the Hoshin Kanri approach.

Step 4 – Targets to Improve (TTI)
In the fourth step, measurable goals are defined to monitor progress and results for breakthrough projects. While lagging KPIs are mentioned in the second quadrant, the leading KPIs are mentioned in the fourth quadrant.

Step 5 – Responsible person
In the last step, a responsible person is assigned to each breakthrough project. For the top-level X-matrix, the responsible persons are all managers. For the second level X-matrices, this can be the department manager, but it can also be the project manager of the concerning breakthrough project.

For each of the items mentioned in the first three quadrants, it is important to note that the most important item is placed closest to the X is in the center of the matrix. This therefore applies to the long-term objectives, the annual objectives and the breakthrough projects. Prioritization can take place at every step, but it can also take place at the end. Setting up the X-matrix is not a fill in the blank exercise. It is a process that takes time and discussion. It is also a recurrent process, sometimes going back and forth between the different quadrants.

Second level X-matrix
After the Top-level X-matrix has been compiled by the management team, it is possible to apply the same approach on a lower level in the organization. This is called a 'Second level X-matrix', and can be set up for each department or business unit. It is advisable not to do this immediately the first year that an organization starts with Hoshin Kanri, but to gain experience with the Top level X-matrix first. Although the technique itself does not look complicated, it is quite a challenge to deploy the process of Hoshin Kanri well. So first gain one or two years of experience using only the Top level X-matrix.

We will now successively go through the five steps to develop at the 2nd level. When we talk about business units, we also mean departments or product groups.

Step 1 – Long term goals
The long-term goals of the organization are translated into long-term goals for the different business units. For example, if a revenue target has been specified for the organization, it can be translated into revenue targets for each business unit. It is clear that the addition of the various sub-objectives should count up to the main objective as stated in the Top level X-matrix. Not every objective from the Top level X-matrix needs to be translated to the second level. Specific objectives can also be mentioned at the second level, but it is important that these sub-objectives contribute in one way or another to the objectives at the top level. If not, the business unit must ask why the sub-objective is actually important.

Step 2 – Objectives for the coming year
Similar to the top level, the long-term objectives for the second quadrant are translated into objectives for the coming year. Here too, we choose to should to describe this using: 'Verb – Item – From – To'. It is useful if the same type of KPIs and terminology are used as in the top level matrix, but it is not required. In case of a deviation, it is again important to check whether steering on this sub-KPI is important for the organization at the top level.

Step 3 – Breakthrough projects
In the same way as the breakthrough projects are determined at the top level, we will determine breakthrough projects at the second level. Again, this process is not a fill-in exercise by listing all current projects. The objective of a breakthrough project is to remove roadblocks that prevent us from realizing the KPIs mentioned in the second quadrant.

The breakthrough projects may also be a derived project from a top-level breakthrough project. For example, a breakthrough project at the top level, which is related for example to quality improvement, can be translated into various breakthrough projects at the second level matrices. If a particular breakthrough project in a business unit is important to the entire organization, it may be listed on the top level instead of the second level. Optionally, the project is mentioned on both levels, but it is not recommended to do this too often. At the second level it is also important to keep the number of projects manageable. It is important to ensure that the projects listed can actually be completed in the relevant year. If you can already predict that the list is not achievable, more focus is needed.

"The essence of strategy is choosing what not to do."

Michael Porter

At the end of this step, it remains to be considered whether projects have also been included in the matrix, for which their contribution to the top level objectives is not clear. It will not be the first time, business units and departments are working on projects that do not contribute to the overall goals. Don't forget the meaning of Hoshin Kanri, which is the shining needle of the compass pointing towards the True North. It means that each department should only concern about projects that contribute to the right direction. If a particular project in a department is nevertheless important, it must also be possible to convince management at a top level that a certain project or objective should be added.

Step 4 – Targets to Improve
In the fourth quadrant, the targets to improve or the leading KPIs are mentioned here. This step is the same as for the top level.

Step 5 – Responsible person
Finally, employees who are responsible for realizing the breakthrough projects and providing the KPIs are listed. Sometimes the whole team is mentioned here. This is a nice addition, as long as it is clearly indicated who the project manager of the concerning breakthrough project is.

Bowling chart

Each Hoshin matrix includes a so-called Bowling chart. This is an overview of all lagging KPIs from the second quadrant and the leading KPIs from the fourth quadrant. For each KPI, a measure is shown as a target and the actual performance. As long as the actual performance is better than the target, the KPI is green. If the KPI is not performing as indicated in the Bowling chart, the KPI is marked red. In that case, the responsible project manager as mentioned in the Hoshin matrix should define with actions are needed to ensure the KPI turns green again.

KPI		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YTD
Revenue	Target	€ 400,000	€ 500,000	€ 500,000	€ 500,000	€ 500,000	€ 500,000	€ 450,000	€ 500,000	€ 550,000	€ 550,000	€ 550,000	€ 500,000	€ 6,000,000
	Actual	€ 425,385	€ 496,105	€ 507,076										€ 1,427,566
Customer complaints	Target	0	0	0	0	0	0	0	0	0	0	0	0	0
	Actual	0	0	1										1
NPS score	Target	20	20	20	20	20	20	20	20	20	20	20	20	20
	Actual	15	12	15										14
First Time Right %	Target	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
	Actual	92%	93%	89%										91%
On Time Delivery %	Target	90%	90%	90%	95%	95%	95%	95%	95%	95%	95%	95%	95%	94%
	Actual	88%	92%	92%										91%
SEO position Google	Target	>50	>50	50	25	25	20	15	10	9	8	7	6	6
	Actual	112	78	52										52
Project completion rate	Target	20%	20%	20%	20%	20%	0%	0%	0%	0%	0%	0%	0%	100%
	Actual	0%	10%	10%										20%
Standup meetings	Target	8	8	8	8	8	8	8	8	8	8	8	8	96
	Actual	8	8	8										24
Delivery time	Target	20	20	20	20	15	15	5	5	5	5	5	5	5
	Actual	22	18	20										20
Number YB's & GB's trained	Target	0	0	10	2	0	0	0	10	0	0	0	0	22
	Actual	0	0	11										11
Number of Kaizen projects	Target	0	0	0	2	2	2	2	2	2	2	2	2	18
	Actual	0	0	0										0

Figure 37 – Bowling chart

Performance behavior

Hoshin Kanri's classic approach is often only about process-based KPIs and TTIs and hardly anything about attitude and behavior. Yet, managing behavioral characteristics are at least as managing process-based characteristics. This is also referred to as 'Performance behavior'. Performance behavior is about cascading strategic (annual) goals from the monitoring level (top management) to the management level (middle management) and finally to short-term goals for performance and behavior at the execution level (shopfloor) (Neil Webers, 2010). When compiling an X-matrix, therefore, consider not only the process side when drawing up KPIs and TTIs, but also the behavioral side, especially when translating the top level matrix to the shopfloor. Translate goals into achievable goals for operators that they themselves have control over. Those goals must then be translated into behavioral characteristics. Not: reduce the number of disruptions, but: perform a certain maintenance activity once a week. The best approach for determining the behaviors and activities should preferably not be imposed from above, but rather determined by the employees themselves. From above, the objective of 'fewer disruptions' can be determined, and then the employees themselves determine that the necessary activity 'weekly maintenance'. They are then held responsible for conducting these behaviors and activities. The translation of KPIs at the level of top management and the translation into behavioral activities at the execution level is a modern way of applying Hoshin Kanri.

2.3 Competence development

This section focuses on developing those who need to ensure that the strategy is implemented successfully. This depends strongly on the organizational culture and the role of leadership, such as managers, Champions and Master Black Belts. A leader's responsibility is to facilitate improvement initiatives to achieve better results. This can be done, among other things, by inspiring, motivating and coaching employees, by stimulating ideas and initiatives. Also important is to be visible at the Gemba.

"Learn from yesterday, live for today, hope for tomorrow.
The important thing is not to stop questioning."

Albert Einstein

In this section we will review how to develop a learning organization. We will also review the need of coaching and intervision, as well as a powerful coaching technique called Kata coaching.

2.3.1 Learning organization

A learning organization is the term given to an organization that facilitates the constant development of its employees and constantly transforms itself (Pedler, M. et al). We often talk about the competencies that an employee needs for a certain function or task. Competencies are the totality of knowledge, skills and attitude. So it is made up of three elements:

- Knowledge:
  Knowledge is the theoretical information that an employee has. This can be developed by following training courses, through studies and by talking to colleagues. Sharing knowledge in a learning organization also involves sharing past experiences with other colleagues. Why should we all make the same mistakes if we can avoid this by sharing our experiences?

- Skills:
  Skills are the physical actions with which an employee shows how competent he is. These can be developed by applying knowledge and by practicing. Deploying Lean techniques such as 5S, visual management, short-interval management and by participating in Kaizen projects is a very effective way to achieve the development of individuals and the development of the organizations as a whole.

- Attitude:
  Attitude is the way an employee shows a certain behavior when performing the job. This is strongly influenced by the culture that prevails in an organization and is the result of years of cooperation between colleagues and the way in which employees interact with each other. Different techniques of continuous improvement require a certain attitude. For example, during the daily standup meetings employees are expected to arrive on time, be prepared and participate actively. The CIMM assessment identifies the associated behavior for each technique and . This can be found at the end of Chapters 4 to 8.

When developing employees, attention must be paid to all three elements. When talking about a learning organization, reference is often made to the so-called '70:20:10 development framework', which reflects the relationship between different forms of learning. The framework describes how effective learning can be deployed. The starting point here is that not the learning but the performance is put as the center, which is the result of the learning process. 70 percent of learning and development takes place through gaining experience; 20 percent through coaching and feedback; and only 10 percent through formal classroom training. Reference is often made to Charles Jennings (2002) as the founder of this framework, but the development of this approach goes back further, to Tough (1968), McCall, Lombardo and Morrison (1988).

“Development generally begins with a realization of current or future need and the motivation to do something about it. This might come from feedback, a mistake, watching other people’s reactions, failing or not being up to a task – in other words, from experience. The odds are that development will be about 70% from on-the-job experiences – working on tasks and problems; about 20% from feedback and working around good and bad examples of the need; and 10% from formal courses and reading.”

Lombardo and Eichinger

Jennings stated that research over the past 40 years has shown that learning, which takes place outside of formal training and courses, is not only more common but generally much more effective. This certainly applies to continuous improvement. The best way to learn Kaizen, Lean or Six Sigma is to actually be involved in improvement projects. Learning the theoretical techniques in a formal classroom environment is helpful (10%), but putting the techniques into practice in a concrete improvement project is much more effective (70%). This applies to the different Belt levels, but also to employees on the shop floor. For the (Master) Black Belts, who already have a lot of experience in the techniques, it is important to realize that they play a crucial role in coaching other employees (20%).

In order to properly guarantee improvements in the organization, it is necessary that everyone follows the new working standards and that there are no employees who still follow the old working methods. In the industry, some improvements lead to the use of a custom tooling or machine setup. In transactional environments, many improvements lead to a system or software update. In such cases, employees are more or less forced to follow the new standards. Sustaining improvements is then relatively simple. However, there are also improvements that depend on the working methods of employees. In such cases, it is much more difficult to properly sustain the improvement, because it depends on communication, instructions and discipline. There is a good chance that there are employees who still follow the old standards or after a while fall back into ‘old behavior’. To prevent this, it is important that improvements are adapted in the DNA of the organization. However, this is the most difficult part of a transformation process. Even if it is obvious that a new way of working is better, it will be difficult to change the DNA from the old culture to a new one. It is the responsibility of management to work on this to ensure that improvements become sustainable.

Lessons learned
Some say that people don't learn the lessons from past projects. This must be true; otherwise why would we keep making the same old mistakes? Some of the most important lessons we learn come from failures made on earlier projects.

“If we don't take time to learn the lessons of past projects, and moreover act upon them, we will continue to commit the same project management sins again and again.”

Duncan Haughey

In a learning organization, employees are not blamed for making mistakes. An error is seen as an opportunity for improvement. You can make mistakes as long as you learn from this. This does not mean that mistakes are concealed by an employee or penalized by the manager. Errors must be made visible, without putting the employee in question in the spotlight. By making the error visible, not only the employee concerned, will ensure that all will learn from the mistake.

Getting it right the first time is cheaper and easier than doing it now and fixing it later. Defining and documenting lessons learned can make all the difference on future projects and help them to succeed. Capturing lessons learned from projects, therefore, is key for any organization. Lessons learned sessions are traditionally held during project close-out, but it is strongly advised to identify and document lessons learned at any point during the project's life cycle. There is no predefined way of defining lessons learned. However, the questions in Table 4 might be helpful.

What have you learned about the methodology that you didn’t already know?
What were the ‘ah-hah’ moments in the project?
What were the strongest points of this engagement?
What were the weakest points of this engagement?
What surprises did the team handle during the project?
What project events were not anticipated?
Were there any areas that you wish you had a deeper understanding of for this project?
What would you have done differently?
Were you provided with all necessary tools to accomplish the project objectives?
What other positive outcomes came out of this project?

Table 4 – Lessons learned

Four stages of learning

When we talk about developing competences for a person, it is crucial to understand where this person currently stands. In the process of developing competences, each person has to go through a number of stages. We can distinguish four consecutive stages for developing competences [Figure 38]:

1. Unconscious Incompetence:
   This is the phase where you don't know what you don't know. You are not aware of missing certain skills. Or even worse, you think you know but it is not correct. This stage is therefore a vulnerable and dangerous one. Of course, no person in the world is able to know everything, but when it comes to perform certain tasks or social aspects at work, it may be catastrophic to not even know what skills we are missing. At the same time, we must acknowledge that there will always be things about our jobs and ourselves that we don't know yet. Each personal development aspect starts here.
2. Conscious Incompetence:
   This is the stage where you realize there is a gap. Something is missing, you don't know certain knowledge or you are not able to perform certain tasks. The next step is to identify what the gap exactly looks like and what knowledge or skill you need to develop. You will then investigate where the knowledge can be found and what training can be done. You may also try to find a colleague that is able to explain or show you how it should be done.
3. Conscious Competence:
   You will now start your learning process. Conscious competence is the stage where you are actively working on the skill, but you are still a novice. You can learn by trying and failing, like a baby that is learning to walk. You can also attend training or learn the skill from a colleague. During this process, you keep getting better but it will not become part of your DNA yet. Your competences grow slowly and surely, but it doesn't come naturally yet. You have to be persistent and determined and not give up.
4. Unconscious Competence:
   Only in the fourth stage you can say that you have mastered the new skills and that it has become instinctual. You can apply the skills without hesitating or risk. While you're still learning and growing, you've established a strong foundation and can be confident about your competency in that area. Moreover, you can teach others that are still at the phase of incompetence.

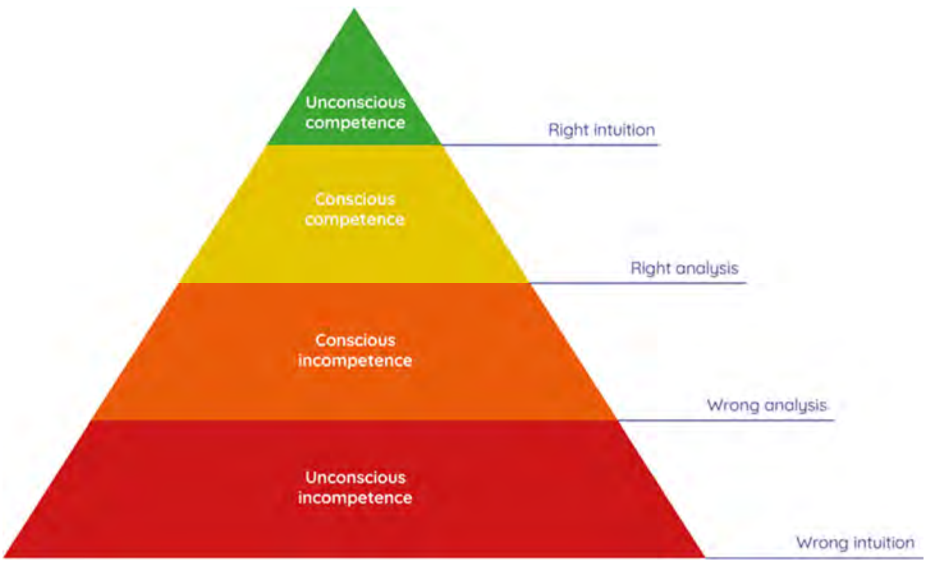


Figure 38 – The four stages of learning (Martin M. Broadwell, 1969)

2.3.2 Coaching and intervision

Team performance and motivation

Green and Black Belts should be able to demonstrate team progress in relation to goals that support team success and reward. It is also important to recognize the team for their accomplishments. The level of motivation applied toward project efforts has a direct impact on the project results. Motivation can inspire, encourage and stimulate individuals and project teams to achieve great accomplishments. Motivation can create an environment that fosters teamwork and collective initiatives to reach common goals or objectives (Tonya M. Peterson, 2007).

Motivation is generally defined as an internal state that induces a person to engage in particular behavior. There are various work motivation theories that are typically concerned with the reasons, other than ability, that some people perform their job better than others. Depending on the situation, these theories can predict people's choices of task behavior, their efforts or their persistence. If people have the necessary ability and constraints on performance are relatively low, high levels of motivation should lead to good performance. We will review two work motivation theories: 'Two-Factor theory' and the 'Goal Setting theory'.

The 'Two-Factor theory' (Frederick Herzberg, 1959) states that one set of factors cause job satisfaction, while a separate set of factors cause dissatisfaction. The first set of factors include organization policies, salary, status, security, fringe benefits, work conditions, vacation, etc. These so called 'Hygiene factors' do not give positive satisfaction or lead to higher motivation. However, the absence of these factors will lead to dissatisfaction. The second set of factors includes challenging work, responsibility, respect, do something meaningful, involvement in decision-making, importance to an organization, etc. These so called 'Motivator factors' lead to positive satisfaction, arising from intrinsic conditions of the job itself, such as recognition, achievement, or personal growth. Herzberg theorized that job satisfaction and job dissatisfaction act independently of each other.

Figure 39 – Motivation Factors

The 'Goal Setting theory' (Locke & Latham, 1990) states that People perform better when they are committed to achieving certain goals. The basic idea is that people's behavior is motivated by their internal objectives and goals. People can vary in their goal orientation or in achieving certain levels of job orientation. This theory is widely used in organizations. Goals can be individual or common. Examples of individual goals are amount of sales for an account manager and output per day for an operator. Examples of common goals are net revenue, customer satisfaction and performance rate. Goals should be linked to the organization's strategic objectives, CSFs and KPIs.

Black Belts and Champions, but also Green Belts, should be able to apply techniques that stimulate team performance and motivation. If we combine the Two-Factor theory, the Goal Setting theory and principles of Continuous Improvement, the following 10 guidelines can be derived that will support team motivation:

1. Shared vision:
   People are more engaged and motivated by why they do things than what they do. A burning platform like a serious customer complaint or organizational crisis may help very well to establish one common vision and goal.
2. Goal setting:
   People perform better when they are committed to achieving certain goals. Goal setting involves the development of clear goals and an action plan that is designed to guide the team members toward this common goal. Goals should be defined SMART.
3. Inspire:
   Short-term and specific goals can be achieved by motivating team members. Long-term aspirations and commitments can be achieved by inspiring team members. Your reputation, character and behavior should inspire people more than anything else. The best way to receive the best out of others is to expect the best from yourself.
4. Emphasize progress:
   Harvard's Teresa Amabile's research stated that nothing is more motivating than progress. Of all the positive events that influence inner work life, progress is very powerful in meaningful work. This is in line with execution of multiple small iterative improvement projects (Kaizen), rather than large step change projects (Kaikaku).
5. Walk the Talk:
   You can tell people what you expect from them. However, if you yourself are not giving the proper example, you cannot expect it from others. Take responsibility without blaming others. "We must become the change we want to see" (Mahatma Ghandi). This is called leading by example.
6. Go to Gemba:
   Don't solve problems by sitting in your office, directing others what to do. Go to the shop floor where the action is. Roll up your sleeves like Alexander the Great leading his men into battle, just as the great Lean leaders Imai and Ohno did.
7. Empower:
   Inspiring people is not about telling them exactly what to do or giving them precise directions. Getting the best out of people is to trust and empower team members to take the proper actions to achieve the defined objectives. Encourage an atmosphere in which people can focus on their core strengths.
8. Kata Coaching:
   Coaching is about supporting and involving team members to make them more effective. It is a key element in the Continuous Improvement journey. Coaching is based on asking questions and giving guidance rather than telling people what to do.
9. Building consensus:
   Listen and ask questions. You'll receive valuable insights and set a tone that encourages a healthy dialogue. Then make decisions based on consensus within the team. Building consensus is also known as collaborative problem solving or collaboration.
10. Recognition:
    Highly effective leaders energize others by noticing and recognizing achievements. They thank, appreciate, recognize and celebrate accomplishments with the team.

Coaching
Training, coaching and intervision are important elements in the deployment process. The objective of training is to impart basic knowledge, mind set and skills. Without the proper knowledge of tools and techniques, people cannot lead or take part in a project. As mentioned earlier, training is only part of the story. Attending Lean and Six Sigma training alone does not deliver adequate Green or Black Belts. This requires a lot of practice and coaching. It is like driving a car. Getting your license does not make you an excellent driver. This will come over time. It is the same for becoming an outstanding Green or Black Belt. It takes time and practice.

Most fresh Green and Black Belts are facing similar problems and are making similar mistakes when doing their first project. Some common issues are:

- Insufficient focus or a scope that is too broad.
- Including the solution in the problem description.
- Continuing the project without a proper Measure phase.
- Starting a project that is not in line with the business objectives.
- Starting a project without available time.
- Starting a project without the Champions commitment.
- Picking the incorrect tools or following the incorrect approach.
- Facing problems with statistical analysis and deriving proper conclusions.
- …

To minimize these kinds of issues and to prevent the consequences of incorrect conclusions, coaching by an experienced (Master) Black Belt or Sensei is a key element in the Lean Six Sigma deployment process. Coaching is an inseparable extension of training. Coaching is about supporting and involving ‘fresh Belts’ to make them more effective at leading future improvement projects. Coaching influences adaptability, productivity and retention. The benefit for both the Champion and the Belt is that they will gain better use of their time and have a higher success rate in achieving project objectives.

An effective way of coaching employees and team members involved in improvement initiatives is Toyota Kata. ‘Kata’ is Japanese for ‘detailed choreographed patterns of movements practiced’. It is commonly known in martial arts like judo and karate. The basic goal of Kata is to preserve and transmit proven techniques from the teacher (Sensei) to his pupil. Sensei can literally be translated as ‘Person born before another’. The Sensei will practice with his pupil in a repetitive manner. In the end, the learner develops the ability to execute the techniques and movements in a natural, reflex-like manner and in unpredictable situations.

According to Toyota, true leaders are Senseis, teaching others continuously. Instead of telling people what to do and how to do it, they will encourage people to find solutions themselves. They do this not by giving the answers but by asking questions, challenging people to find the answers themselves. In other words, Senseis coach their pupils in becoming masters in their field. Mike Rother explains in his book, ‘Toyota Kata’ [18.], how Toyota used the Kata approach in achieving Operational Excellence in its factories. Toyota Kata defines management as, ‘The systematic pursuit of desired conditions by utilizing human capabilities in a concerted way’. Rother proposes that it is not solutions themselves that provide sustained competitive advantage and long-term survival, but the degree to which an organization has mastered an effective routine for developing solutions again and again, along unpredictable paths. This requires teaching the skills behind the solution (Rother, 2009).

There is an ‘Improvement Kata’ for those who climb the mountain, and a ‘Coaching Kata’ for the mentor who coaches the mountain climber and keeps them on the right route. We will explain both.

Improvement Kata

In most organizations there is a lack of creative possibilities. The traditional approach for improvement tries to predict the path of the implementation steps. It is therefore almost impossible to make progress, because trial and error is necessary, to a certain extent, in order to be able to respond to unexpected circumstances and problems. Rother summarizes this nicely: "How would you feel as a passenger if the pilot were obliged to determine the landing route in advance, after which no adjustments were allowed?" The Improvement Kata does not plan but discovers along the way what action is needed and what obstacles appear. Teams can use the Improvement Kata as they strive to reach a target condition and adapt their actions based on what they learn. The improvement Kata is a routine for moving from the current situation to a new situation in a creative, directed and meaningful way. It is like climbing the mountain in the dark with a flashlight. The approach is based on the following steps:

1. Understand the direction.
2. Grasp the current condition.
3. Establish the next target condition.
4. Move toward that target condition iteratively.

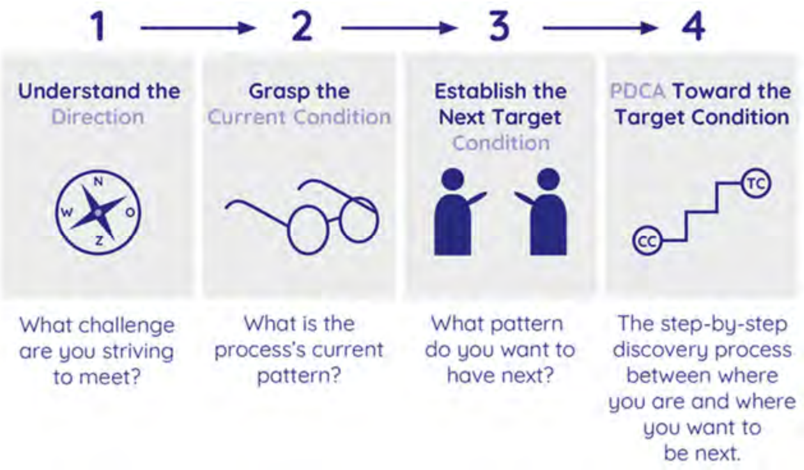


Figure 40 – Toyota improvement Kata (Rother, 2009)

The team will be using a Kata Storyboard as shown in Figure 41. The team stands around the board to discuss the status of the improvement project. The step-by-step discovery process follows the Kaizen PDCA roadmap. PDCA stands for Plan-Do-Check-Act [paragraph 3.2.1].

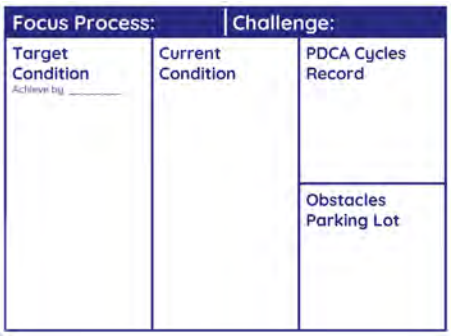


Figure 41 – Kata storyboard

Coaching Kata

Once you have learned to bring the 'Improvement Kata' into practice, you can start to develop your 'Coaching Kata' skills to become the coach of the learner. Coaching cannot be separated from teaching. First of all, the coach needs to train the learner in the practice and secondly the coach has to coach the learner in practicing the practice to a high level of excellence. The Improvement Kata should be practiced under periodic observation and correction by an experienced coach. The purpose of coaching is to achieve a change in the mindset of the learner.

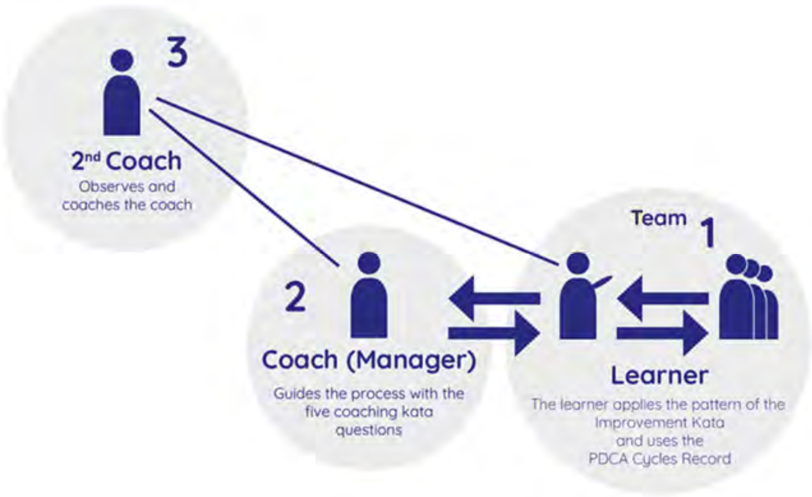


Figure 42 – Toyota Coaching Kata (Rother, 2009)

A coaching cycle is done once a day at a scheduled time and should not take more than 10 to 15 minutes per cycle. The coaching cycle involves the coach asking the 'Five Coaching Kata Questions' to the Learner:

1. What is the target condition?

2. What is the actual condition now?
    a. What did you plan as your last step?
    b. What did you expect?
    c. What actually happened?
    d. What did you learn?

3. What obstacles do you think are preventing you from reaching the target condition?
    a. Which one are you addressing now?

4. What is your next step?
    a. What do you expect?

5. How quickly can we go and see what we have learned from taking that step?

Coaching, however, is about influencing visible behavior. A coach should not be confused with a psychologist, as they can only coach on what they perceive.

Intervision

What makes a certain approach work in one organization and not work in another? Why is it so difficult to hold a certain level? Why do we revert to old behavior at some point? To implement improvements, regardless of which improvement method is applied, it is necessary that the mindset and techniques become part of the DNA of the organization. This is the most difficult part of a transformation process. Even if it has been demonstrated that a particular method fits the organization well and even if it has been proven that the application of certain techniques work, it is still difficult to embed continuous improvement in the DNA of the organization. Edgar Schein defines culture as "*A pattern of shared basic assumptions that was learned by a group as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems.*" Although today's culture has worked well enough to perpetuate itself, it does not mean that it is the best way.

Within organizations there are direct and indirect working mechanisms, according to Schein. Organizational culture is directly influenced by direct working mechanisms. This includes example behavior, views, status and appointments. Indirect acting mechanisms do not directly influence the organizational culture, but they do determine it. This includes the mission and vision of an organization, processes, rituals and design. Several studies have shown a strong correlation between the success of implementing continuous improvement and the attention paid to the cultural aspect of change. Organizational culture is an abstract concept and therefore difficult to understand. Schein developed a model that provides insight into the culture in an organization. This model is compared to an onion and consists of three layers. The outer layer consists of the artifacts and symbols within an organization such as structures, processes and house style. These are still fairly easy to change. The second layer consists of the norms and values within the organization that have been formed over a longer period of time. Changing this is already much more difficult. The core of the onion consists of assumptions. These are about "the truth" that has been shaped by the people in the organization over the years. They arise from experiences and perception. These assumptions have partly become unconscious and are therefore taken for granted and can hardly be discussed.

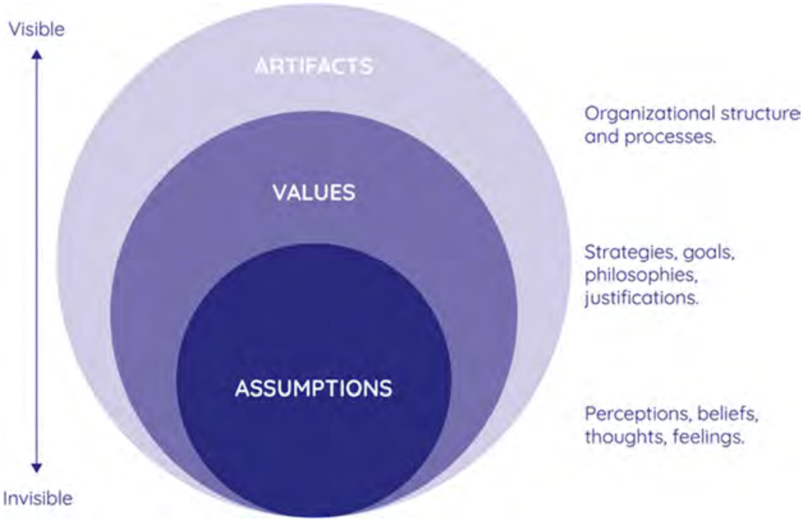


Figure 43 – Organizational culture (Edgar Schein)

It therefore depends on how deep we have to go with realizing changes in order to achieve the desired result. If it is only about changing a process or working method, this is still fairly easy to do. But often adjusting only the visible artifacts and symbols is not enough. Before new behavior can be learned, old behavior must first be unlearned. Realizing a continuous improvement organization is a process of transformation and an integrated approach. Schein's model offers tools for achieving such a cultural change. An important part of this is conducting interviews with employees to find out which deeper backgrounds and aspects underlie to the organizational culture. Why do we work the way we do? Why do we accept things the way they go? What motivates individual employees and what do they suffer from every day?

Interventions should take place if a difference is observed between the desired and the prevailing culture during the transformation process. Schein describes ten principles that are important in carrying out interventions:

1. Always be helpful. If possible, all contact should be aimed at providing assistance.
2. Always keep in touch with the current reality. Knowledge of your own reality and that of the employee you speak to are necessary to provide help.
3. Expose your ignorance. Think about what you know, what you think you know and what you don't know.
4. All you do is an intervention. Therefore, estimate the consequences of everything you do.
5. Remember that the employee you approach has both the problem and the solution. Do not answer every problem and do not take the employee's burden on your own shoulder.
6. Go with the flow. Every employee has elements where he is open to change. Locate it and build on it.
7. Timing is crucial. A particular intervention can work at one time and fail at another. Be alert when an employee is receptive to an intervention.
8. Create a safe situation in which the employee can talk openly. Also make sure that the employee obtains a status, by enabling him to solve his problem.
9. Not everything will go well. But every wrong intervention produces a response that you can learn from. This way you understand the employee's reality better and better.
10. Be open if you don't know it yourself. Discuss this with the employee and decide together which next step is the best.

2.3.3 Effective communication

While some may embrace the efforts of continuous improvement, it may be a threat for others. A comment frequently heard is 'Why do we have to do things differently? We have done it this way for more than twenty years, so why do we need to change it now?' This is one of the questions that management, Champions, but also Green and Black Belts should be able to answer. It is crucial to include a carefully constructed communication strategy that identifies and addresses potential risks and concerns employees and other stakeholders. A proper communication plan will significantly increase the chances of a smooth deployment process. It helps to address and remove barriers that may become a hazard to the program.

Some of the most frequently asked questions are the same for each organization, so it is possible to be prepared for these questions. Some of the most common questions are:

- What is Lean Six Sigma about?
- We are not in manufacturing, but in services. Will this work for us?
- We have tried something like this before. It didn't work. Why will it work now?
- How will it impact my work / our department?
- Is there a plan for laying off people?
- I do not have the time to take additional work. How will this affect our daily work?
- …

Fortunately, not all questions are negative. Some positive questions may be:

- Can I participate in a project?
- Can I attend training?
- Can I manage a project?
- To whom do I submit potential projects?
- …

The answers to these questions will obviously depend on the specific objectives of your organization. Regardless the answers, it is important to prepare answers upfront. Green and Black Belts have an important role in the communication process as they are managing improvement projects and often are part of the policy deployment process. Communication about progress and achievements will remain a key factor during the execution of improvement projects.

Unclear communication, the Wastes of seeking clarification, confusion over the product or service use, wasting time finding a location; these are all issues that may result in misuse or duplication (Bicheno and Holweg, 2009). It sounds so simple: 'Say what you mean'. But all too often what we try to communicate gets lost in translation despite our best intentions. We say one thing, the other person hears something else and misunderstandings, frustration and conflicts ensue… How is that possible?

Communication is more than exchanging information. Communication is about understanding the intentions and emotions behind the information. Effective communication is a two-way process. This process always consists of at least two people, the Sender and the Receiver. Communication is not only about conveying information, but also about the receiver understanding in exactly the way you intended. This is called the Interaction Model of Communication (Wilbur Schramm, 1997). The communication process can be described as follows:

1. Encode information:
   Put the information together.
2. Send the encoded information (Sender):
   Transmit the information.
3. Receive the encoded information (Receiver):
   Hear / perceive the information.
4. Decode the received information:
   Interpret and understand the information.
5. Feedback / React:
   Take action.

It gets even more difficult when talking different languages or dealing with different cultures. Make sure you understand each other. This includes more than just asking the standard question: ‘do you understand?’. If the answer is ’yes’ it does not mean the loop is closed. It is advisory that you make sure that the communication process is a closed way, meaning that you will ask the receiver to repeat what the intention was and the action should be. By checking if your message came across and letting the other person feedback the information you can avoid miscommunication and cooperation will be more pleasant.

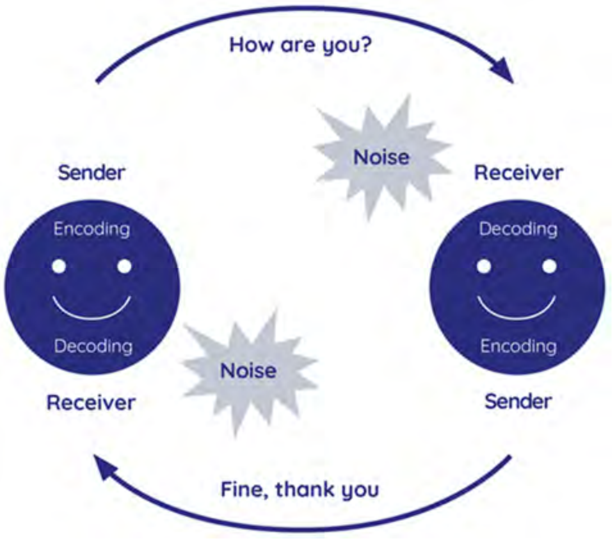


Figure 44 – The Interaction Model of Communication

Communication in project meetings

It is the team leader's responsibility to ensure the smooth running and success of team meetings. An important aspect of this is to facilitate team members to start and take actions, not only showing up in meetings for sake of exchanging ideas. Some generic rules should be agreed at the start of the project and all team members should maintain the expectation that the rules are adhered to by all involved. The following list is a starting point that can be augmented with additional points developed and agreed by the team to create more support:

- Be outcome focused:
  The objective of each meeting should be clear and well communicated so that the whole team is focused on creating a meaningful outcome.
- Be prepared:
  The agenda for each meeting should be sent out in advance to allow team members to prepare. Team members should come to the meeting prepared in order to prevent unnecessary discussion.
- Be punctual:
  Arrive on time. Start the meeting on time. Do not get into the habit of 'waiting for latecomers'. Latecomers should not disrupt the flow of the meeting.
- Be time conscious:
  Pay close attention to the time and, if necessary, appoint a team member as time keeper to ensure that the agenda is fully progressed prior to the end of the meeting timeslot. Use team-based techniques that are 'time-boxed' i.e. designed to achieve a result in a given time frame.
- Be polite and respectful:
  Introduce new people to the team. Do not talk over each other. Do not allow inappropriate language regarding people inside or outside of the meeting.
- Concentrate:
  Don't answer emails and put phones on silent. Give all of your attention to the meeting for the period of the meeting. Should it be necessary to take a call, then leave the room so as not to disrupt the rest of the team.
- Be engaged:
  Ask questions and add comments at the appropriate point of the meeting. It may help to make bullet notes of ideas as they come to you and as prompt when it is your turn to speak, so as not to forget any points.
- Be action oriented:
  Ensure that all actions that are agreed at the meeting are understood by the individual responsible for carrying out the action. Ensure that the owner of the action knows what is expected and when the action should be completed.
- Plan to finish early:
  Be aware that team members may have back-to-back meetings or appointments. Allow them enough transit time to arrive on time to their next meeting. Ensure that the room is tidy and ready for the next meeting.

RACI Matrix
The RACI Matrix is a responsibility assignment matrix that describes the various roles of team members in completing tasks or deliverables within a project. The acronym RACI is derived from the four key responsibilities most typically used within a project: Responsible, Accountable, Consulted and Informed.

- Responsible:
  The team members that do the work to achieve the project's tasks.
- Accountable:
  The person who is ultimately responsible for the result (deliverables) of the project. In most cases this is the department manager or Champion.
- Consulted:
  Those who are consulted during the project. These typically are subject matter experts.
- Informed:
  Those who are kept up-to-date on progress. These may include management and employees.

	Manager	Engineer	Planner	Purchaser
Develop drawing	A	R		C
Release drawing	A	R	I	I
Audit supplier	A	C	I	R
Submit purchase order	A		R	R
Perform tests	A	R		

Figure 45 – Example RACI matrix

Making decisions by Consensus
One of the Toyota principles is Nemawashi, which means: 'Making decisions slowly by consensus, thoroughly considering all options and then implement decisions rapidly'. It can be very conflicting to the culture of managers who prefer to make decisions rapidly, not considering all options and hazards, thereby running the risk that problems have to be solved later on. Consensus is a very noble aspiration. Consensus means that all people concerned will be involved and discuss the possible options and best choices. If the decision is not unanimous, the minority will comply with the decision of the majority, without complaint or rejection. A simple and straightforward approach, especially for bottom-up initiatives, is the '3D-process':

- Discuss: involving all concerned.
- Decide: by consensus.
- Do: following the group decision without repining.

This process requires that there is time given to all involved so that they can contribute to define the solution or new situation. After a certain period of time it is necessary to come to a decision. The best way to reach an agreement is by 'Consensus'. This means that the minority of the group will conform to the opinion of the majority of the group, without starting a new discussion. The entire workforce now contributes to the implementation of the agreed actions without repine.

Six Thinking Hats (de Bono)
Black Belts often chair team meetings or moderate brainstorm sessions. Black Belts, therefore, should master some basic concepts on how to guide such sessions. Especially in problem solving and innovation projects with multidisciplinary teams where each member is contributing their unique strengths to the conversation, a strong guide is necessary to maintain direction. Several studies have examined the effectiveness of such group meetings and, in general, results are disappointing. One of the reasons for this is that people come biased and prepossessed and have difficulties to listen to the opinion of others. Another reason is that the loudest voices in the room hold court and squeeze out others. Some brilliant ideas may never get heard. It is the task of the moderator to assure everyone contributes ideas and to create an environment to share ideas before someone starts thinking critically. One technique that is very powerful to guide opinions in the room is the use of the 'Six Thinking Hats' as described by de Bono.

Dr. Edward de Bono has written numerous books that have been translated into 34 languages and has lectured in 52 countries around the world. His book 'Six Thinking Hats' streamlines the decision-making process of the mind. According to de Bono, the thinking process is split up into six thinking levels represented by six imaginary thinking hats. This originates from the 1960s and 1970s when everyone wore a hat. The type of hat represented who you were and, above all, the way that you behaved. The establishment of a specific thinking hat determines the manner in which you participate in discussion.

The six different character rolls are symbolically represented by six thinking hats, each with a different color. Why must we be 'forced' to work with thinking hats? This comes from the chemical conditions in our brains. Our brains cannot take on multiple thinking roles at the same time. Our brains also have difficulties switching quickly from one thinking role to another. Everyone has a preference for a particular thinking roll. However, for the most optimal discussion, it is necessary that we briefly discuss all of the rolls.

1. White Thinking hat:
   Information thinking: facts, figures and information. The white hat is related to objective facts and figures. Thinking like a computer, without emotions or opinions.
2. Red Thinking hat:
   Emotional thinking: feelings, suspicions and intuition. The red hat symbolizes the emotional standpoint. It is the opposite of neutral, objective information.
3. Black Thinking hat:
   Negative thinking: why something will not work. The black hat symbolizes the negative aspects, the reasons why something cannot be done.
4. Yellow Thinking hat:
   Positive thinking: brightness, positive and constructive. The yellow hat symbolizes optimism, the hope for a positive way of thinking and constructive thinking. It is the opposite of Black thinking.
5. Green Thinking hat:
   Creative thinking: 'Out of the box', innovative and provocative. Green is the color of growing vegetation. The green hat symbolizes creativity, new views and stepping back from existing ideas.
6. Blue Thinking hat:
   Structured thinking: overview, structured and detached. Blue is 'Cool'. The blue hat is associated with steering and organizing the thinking process, as well as the use of the other hats. With the blue hat on, you can determine which thinking hat needs to be put on next.

The six hats can be paired in three sets:

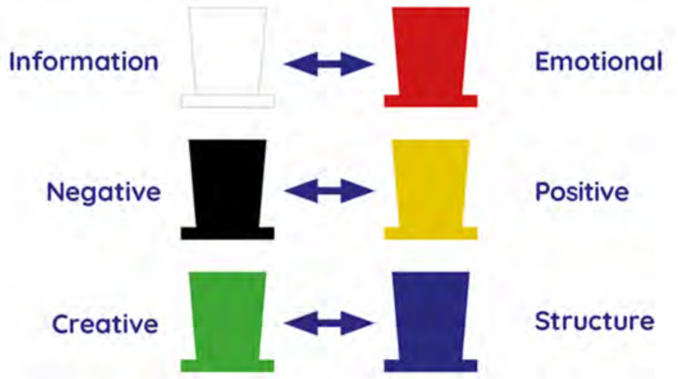


Figure 46 – Six Thinking hats

How can we use thinking hats? First of all, keep the following in mind:

- Anyone can put a hat on.
- Anyone can ask another person to put a hat on.
- Anyone can ask another person to take a hat off.

Eventually the six colors come together to make up a comprehensive map of the topic being discussed. The color order is not entirely fixed, however the sequence of using the colors does guide the order in which the discussion progresses. It is also important to realize that you should avoid forgetting a colored hat during the discussion.

The following sequence is recommended to follow (in almost any type of discussion):

a. White thinking: start with facts and status overview;
b. Green thinking: generate new creative ideas;
c. Yellow thinking: be positive to these new ideas and add elements to it;
d. Black thinking: not to be negative, but to identify potential risks;
e. Red thinking: add the emotional factor;
f. Blue thinking: summarize and determine actions.

If, as a Belt, you have to chair a brainstorm session, you can follow this structure even if not all participants in the room are familiar with this approach. As a Belt, you should ensure that the meetings start with facts, numbers (White) and a clear objective. Then all participants should express creative and positive ideas (Green and Yellow). The use of colored Post-Its are a great help to encourage Green and Yellow thinking. When people start thinking negatively and emotionally (Black and Red), you should ask them to hold it in for a minute. Don’t forget to make time to review risks and management of change and make room for Black and Red thinking.

“You do not have to see the whole staircase.
Just take the first step.”

— Martin Luther King Jr.—

3 Project Management

A deployment program consist of multiple projects. These initiatives must also be managed and implemented as such. This means that a project manager is appointed and a team is formed. During the project execution there will be project meetings and progress must be reported.

Most improvement initiatives are executed as a project by a team of people, guided by a Green or Black Belt as the project manager. Therefore, it is essential for Green and Black Belts to review how to manage a project. They are responsible for applying effective project management techniques to ensure projects are carried out on time, within budget and with minimal disruption to the operation.

In this chapter, we will review the way improvement projects should be managed. We will take a look at the responsibilities of the project manager, project selection, project planning and execution. We will also review a number of project management roadmaps, like PDCA and DMAIC, that are specifically used in process improvement projects.

3.1 Managing a project

In general, project management can be defined as the application of knowledge, skills, tools and techniques to project activities to meet the project requirements (Project Management Institute, Inc., 2008). It is outside the scope of this book to review every aspect of project management in detail, but in this section, we will review some of the main aspects.

Setting up the project:
Every project starts with a clear description of the project objective. In case of solving a problem, a problem description also needs to be developed. Furthermore, the scope, timing and budget will be defined. Within Lean Six Sigma projects these elements are described in a project charter, which will be reviewed in detail in paragraph [3.1.2].

Resource management:
After agreement on the project charter, it is important to identify and allocate the proper resources that are able to work on the activities. The project manager must look for the proper team members, with the right skills and available time. The project manager has to organize this with the department managers. If the team is not equipped with the right people, the project is doomed to fail. Managing resources is also about making sure the team has the right budget, tools, space and equipment needed to get things done.

Time management:
The first thing you probably think of when talking about ‘managing a project’, is making sure the right actions have been defined and are assigned to the right team members. Making a proper plan, with the right actions and accompanying timing is crucial for managing a project successfully. It is the task of the project manager to monitor the overall action list and to ensure that all team members carry out the activities within time and budget.

Leading the team:
Managing a project successfully is not about telling team members what to do and when. Managing a project is also about setting the vision, inspiring and motivating the team, as well as guiding and coaching the team members during the execution. It is therefore crucial that the project manager has leading, guiding and coaching capabilities. When something unexpected happens or if things don't work out, it is the task of the project manager to cheer up the team and get it back on track again. It is also the task of the project manager to help the team to resolve road blocks that pop up during execution.

Communication:
Great communication is the key for many things in live. It is the same for managing a project. Without proper communication you will not be able to manage a project successfully. Communication does not only have an impact on the team, but also on clients and stakeholders. Most of the issues in project execution, like attendance, performance and behavior, can be tied back to poor communication. This however is not a task of the project manager alone. Every internal and external stakeholder plays a role in the communication process. It is, however, the responsibility of the project manager to assure smooth and effective communication.

3.1.1 Project selection

Project, Program or Portfolio
Most improvement projects are part of a bigger program or portfolio. Below you will find the definitions of a Project, Program and Portfolio. (Source: 'Project Management Institute').

Project:
A project is a unique process consisting of a set of coordinated and controlled activities, with start and finish dates, undertaken to achieve an objective conforming to specific requirements including the constraints of time, cost and resources. The project is focused on a single objective and has a narrow scope. The project is executed according a specific, detailed and bounded plan. Benefits are determined in advance and deliverables and timescale are clearly defined. In a project, changes to the scope should be minimized. In general, a project is a temporary endeavor undertaken to create a unique product, service or result. The project manager directly monitors and controls the activities and deliverables.

Program:
A program is a group of related projects, managed in a coordinated way to obtain benefits and control that would not be available from managing them individually. Individual projects will have their respective schedules. A program is focused on business strategy and has a cross functional scope. A program is executed with a high-level and evolving plan. Programs may include elements of related work outside of the scope of the discrete projects in the program. A program is used to make decisions during the program and therefore, mainly initially, has many undefined deliverables and a less strict timescale. The program manager uses program governance mechanisms for monitoring and control.

Portfolio:
A portfolio is collection of projects or programs and other work that are grouped together to facilitate effective management of that work to meet strategic business objectives. The projects or programs of the portfolio may not necessarily be interdependent or directly related. Project portfolio management helps the organization to make the best use of its resources, and ensures that all new and existing projects are aligned with the organization's mission, goals and objectives. 'Project Portfolio Management' (PPM) is the centralized management of multiple processes, methods and technologies. The portfolio manager monitors the aggregated performance and value indicators. PPM develops a bigger picture and a deep understanding of the project collection as a whole. It creates an objective methodology for identifying, ranking, prioritizing and selecting new projects. It also ensures that a healthy balance across different types of projects with different cost, schedule, complexity and risk profiles is maintained.

Figure 47 – Example of software to manage projects, programs and portfolios

Low Hanging Fruit

Within each organization there are large projects that last several months, but also small projects that are completed within a few days. In addition, there are projects with a high risk of failure and projects with a low risk. There are easy projects and there are difficult complex projects. In all cases, resources are limited and choices must therefore be made. We will discuss a number of techniques that can support the process of making choices.

A commonly used metaphor for doing the simplest or easiest work first is called ‘Low-hanging fruit’. The low-hanging fruit presents the most obvious opportunities because they are readily achievable and do not require a lot of effort. In process improvement initiatives, this may refer to problems with known solutions and low required investment, so problems that can be solved with very little effort.

But sometimes it can be even easier ... Sometimes there are problems that everyone knows and that should have been solved long ago. These problems are presented here as ‘Apples, rotting on the ground’ or CIMM-level 0. No complicated methods are needed to solve these problems. It just needs to be picked up. Examples of these are repairing broken cables and removing junk.

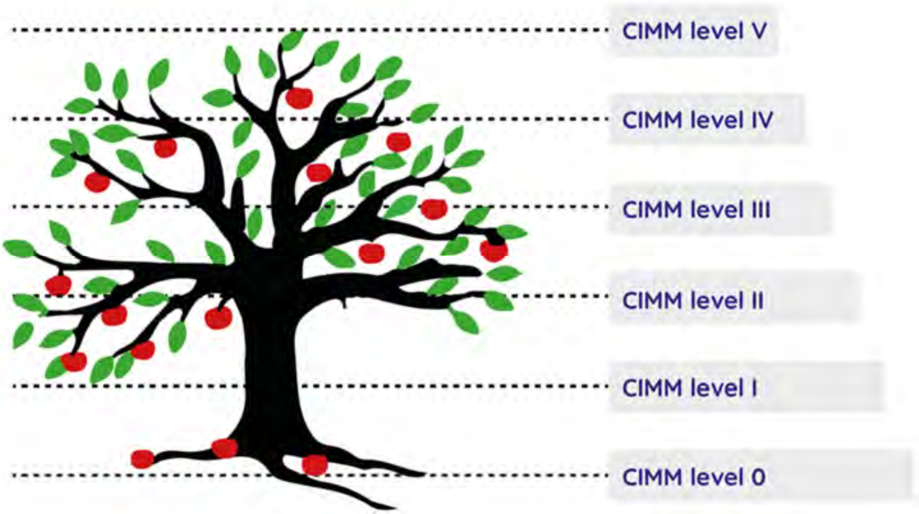


Figure 48 – Low-hanging fruit

Project Priority Diagram

The Project Priority Diagram is a simple but powerful technique that helps you choose which project to prioritize and which ones to drop. The diagram uses one dimension for 'Impact for the organization' (benefit) and a second dimension for 'Effort to achieve results' (amount of time and money). All improvement opportunities should be graded for both dimensions on a scale of 1 to 5 and will be visualized in a matrix.

1. Quick Wins (High Impact, Low Effort):
   These are the opportunities to choose first, as they give good return and require relatively little effort. These projects are called 'Low-hanging fruit' projects.
2. Major Projects (High Impact, High Effort):
   These opportunities give good returns, but require a lot of effort. They take a long time to complete and can be complex to execute.
3. Not now (Low Impact, Low Effort):
   Do not worry too much about these opportunities until resources become available. There are better opportunities to work on.
4. Don't do (Low Impact, High Effort):
   Avoid these opportunities because they give low returns and they Waste time which would be better used on something else.

In addition, a third dimension can be added to indicate if the team (or department) has the competencies to find the solutions and if it is empowered to implement the required solution. If this is the case, you can make the circle green, while the circle should be made red if this is not the case.

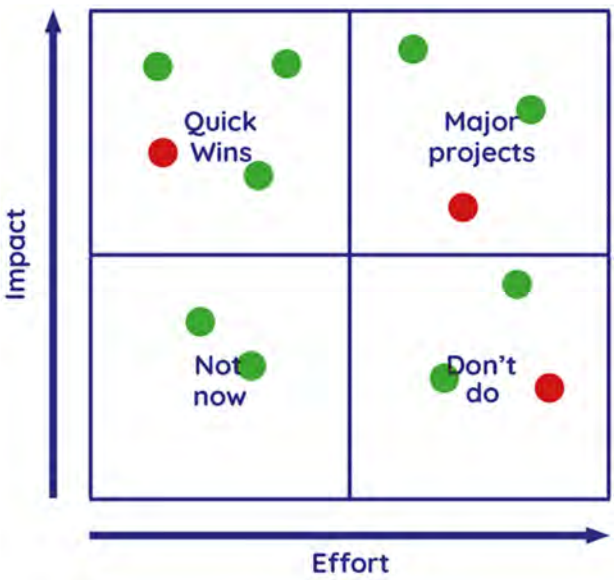


Figure 49 – Project priority diagram

Pugh Matrix

The 'Pugh-matrix' is a decision-matrix method constructed by Stuart Pugh (1991). Pugh-selection is a quantitative technique used to rank multi-dimensional options. It is frequently used in engineering for making design or concept decisions. Typically, a Pugh-matrix is used to evaluate various alternatives against a baseline. For example, an organization has five alternative processes to the one it is using and it wants to know if any of the five is better than the current one, or not.

The same approach can be used for project prioritization and selection. If you look around in your organization, you might identify many opportunities for improvement, both small and large. Every external and internal issue is an opportunity for improvement. This makes the number of opportunities so big that you might not know where to start. Solving problems is a process on its own and needs to be treated as such. Management needs a practical and robust approach to easily determine which projects are valuable. As a starting point, a system needs to be defined to register problems and to identify opportunities. Subsequently, projects should be prioritized to ensure resources are allocated appropriately. A criteria-based selection matrix based on the focus points (Quality, Delivery, Costs) helps to standardize the project prioritization and selection process. A number of possible selection criteria are listed below, but each organization should define its own criteria:

- Urgency: safety risk; Urgent from a customers' perspective; Risk of losing business?
- Impact: how big is the impact on the (external) customer?
- Strategy: does the problem contribute to a higher organizational objective?
- Benefits: is there a lot of COPQ involved? Will there be a lot of hard or soft benefits involved?
- Effort: does it require a lot of resources, investment or effort to solve the problem?
- Ability: is the team able to achieve results and empowered to implement the change?
- Change: is there any potential resistance to change from the internal or external customers?
- . . .

In addition, a weighting factor can be applied to determine the importance of the different criteria. In Table 5, six projects are ranked against the different criteria using a score of 1, 3 or 9. However, a different ranking can be applied. Also keep in mind that not all criteria have to be used and that different criteria can be used. This is just an example of one possible selection matrix.

	Urgent	*Impact*	*Strategy*	*Benefits*	*Effort*	*Ability*	*Change*	*Score*
Weighting	5	3	3	5	3	3	1	
Project 1	1	1	1	1	9	3	1	53
Project 2	1	3	3	9	3	9	3	107
Project 3	3	1	3	1	1	9	9	71
Project 4	9	9	9	3	9	9	9	177
Project 5	3	1	9	3	1	9	9	99
Project 6	1	1	9	1	9	3	9	85

Table 5 – Project selection matrix

3.1.2 Project charter

At the start of larger projects, generally at level III to V, a project charter will be produced. This is a document agreed between the Champion and the project manager that includes the problem description, scope, objectives, timing, budget and resources. The project charter should clarify the business case and the need of the specific project. It should mention the product or service and the customer concerned.

Although you should not skip the step of composing a proper project charter, you should also be careful not to lose yourself in this phase. I have seen Belts and Champions discussing the problem description and objectives for months. There are two reasons why this phase could subvert the process of problem solution. The first reason is that the problem is not urgent or is not addressing a higher departmental or business objective. As a consequence, there is always something else that requires more attention. This happens a lot though, especially when the Belt is identifying his own project or if there is no real serious Lean Six Sigma deployment program. The second reason is that the scope of the project is too wide. You should ask yourself: ‘How do you eat an elephant?’ The answer is ‘Piece by piece’. What I mean by this is that it is best to pick a manageable part of the problem and to start solving it. An experienced project manager that I used to work with once said that an improvement project should never last more than three months. If it takes more time, the scope is too wide.

Problem statement
Green and Black Belts are expected to develop and analyze the problem statement in relation to customer requirements (external customers) and business goals (internal customer). The problem description should never mention a solution to the problem, because if a solution is known, a problem-solving project is not needed. Lean Six Sigma projects are focusing on solving problems, not on implementing known solutions like buying a new piece of equipment. Ensure that the problem statement is SMART:

- Specific: Precise statement of the problem and goal.
- Measurable: Ability to measure the performance (both problem and solution).
- Attainable: Objectives are reasonable and goals can be achieved.
- Relevant: The problem is urgent or has an impact on the organization.
- Timely: Solutions can be achieved in reasonable time.

If the problem description is not SMART, the project is likely to go down the path of fixing the wrong things causing additional pain to the organization. Example: “Ever since John came to work here, the organization has been going down-hill” or “We can solve the quality issues by buying a new machine.” These are examples of ignorant problem definitions, not likely to build consensus or to chart a course for solving real problems. Although regularly the Champion, Black Belt and Green Belt are responsible to compose the project charter, even the Yellow and Orange Belts should understand the importance of defining the problem specifically and quantitatively before blindly going down a path of fixing the wrong problem or not fixing anything at all. Using structured methods like DMAIC and simple guidelines like SMART will help you achieve success and avoid disappointing results.

Project Scope and Goal

For both large improvement projects and small Kaizen projects, it is important to reach agreement at an early stage about the scope of the project and the intended objectives. It is relevant to agree on expectations among all concerned to ensure that the project will be completed within the agreed time and budget. The scope of the project describes what is included in the project and what is left out. To manage expectations, it is advised not only to define what is within scope, but also to record what is out of scope and what the team will not focus on. If this is not properly described, it may happen that the project manager thinks that the team should focus on one specific product or customer, while the Champion thinks that the team focuses on different products and customers.

A change in scope may cause problems, especially when the Champion and the project manager have different perceptions of what is in scope. For instance, the project manager might believe that the team should focus on a specific area (e.g. product, machine, department, client, etc.), while the Champion thought that the team was working on a different area. The scope of a project may be changed during the progress of the project, but only if all stakeholders are involved in the redefinition of the new scope. All should realize that a change in scope will have an impact on time and budget of the project.

The same applies to the intended objectives. At the beginning of the project, the Champion and project manager must try to determine as clearly as possible the intended objectives and the results to be delivered. If it becomes clear halfway through the project that the result will be different than previously defined, this can be discussed. However, if nothing is defined, a discussion about this may be difficult.

Project Charter

Business unit:
Department

Project Leader:
Name of project leader

Belt level / Method:
GB/BB & DMAIC/DMADV

Project title:
Short name of the project

Project Number:
Project number assigned

Problem Statement:
Short description of the problem / Reason for the project

Product / Service:
What is delivered?

Process:
Operational process

Customer:
Who receives the product?

Hard Benefits:
Direct bottom-line savings

Benefit Enabler

Benefit Realisation

Hard Benefits /yr:
Direct Monetary savings

Budget:
Estimated investment costs

Net Savings /yr:
Savings minus Costs

Soft Benefits:
Risk avoidance and Nonmonetary benefits

Interface with other projects:
Is the project part of another project? Will the project impact another device or customer?

Start Date:
Date the team will start

Target Completion Date:
Completion of Control / Verify

Actual Closure Date:
Release of team

Figure 50 – Example project charter (LSSA, 2009)

Project Charter

Benefit description:

VOB: Benefit for the Business?

VOC: Benefit for the Customer?

Goal Statement:

What are the improvement objectives?

What are the targets / How are these measured?

Project Scope:

What is in scope?

What is out of scope?

Characteristics to be improved:

What is the main CTQ to improve?

How is it measured?

Project deliverables:

Products, documents and photos that are delivered

Type of deliverable

Main Risks:

What are the project main risks?

What is the mitigation plan?

Project Planning:

Milestone?

Completion date of deliverable:

Figure 51 – Example project charter (LSSA, 2009)

3.1.3 Project team

Personality types

Continuous Improvement is about improving processes, but also about creating a fulfilling work environment so that products and services are delivered effectively. Every employee involved in Continuous Improvement is expected to actively contribute towards initiatives. Continuous Improvement therefore is a ‘people business’, especially when it comes to management of change. Black Belts should understand how different people face challenges in different ways and react differently to change. Some people will like the structured DMAIC approach, while others prefer a more personal approach.

The ‘Myers–Briggs Type Indicator’ (MBTI)® assessment is a psychometric questionnaire designed to measure psychological preferences. It investigates how people perceive the world and make decisions. The MBTI assessment, developed by Katharine Cook Briggs and her daughter Isabel Briggs Myers, was first published in 1943 and has a long and prestigious history. The use of MBTI is recommended for both teams and individuals to better understand their strengths. The starting point is that being familiar with one's personal preferences is useful in finding the most suitable job. Today it is one of the world’s most widely used and recognized personality tools. Globally about two million people complete the MBTI questionnaire every year.

The MBTI assessment is based on the typological theories proposed by Carl Gustav Jung, a Swiss psychiatrist and psychotherapist who founded ‘Analytical Psychology’. His work is described in the book, ‘Psychological Types’. The original German language edition, ‘Psychologische Typen’, was first published in 1921. Jung theorized that people are engaged in one of two mental activities: Perceiving and Judging. Jung also stated that there are four principal psychological functions (or mental processes) by which humans experience the world: Sensation, Intuition, Feeling and Thinking. According to Jung, people use all four cognitive functions. However, one function is generally used in a more conscious and confident way. Jung also noted that people could focus their energy in two orientations: Extraversion and Introversion. He called these the two orientations of energy. Based on the combination of the two orientations and the four mental processes Jung described eight basic patterns of behavior.

Myers and Briggs make use of four separate scales. Each scale consists of two preferences. The one preference is not better than the other, but different. You use both of them, but there's one that you prefer. The MBTI assessment is scored by evaluating each of the answers in terms of what it reveals about the taker. Each question is relevant to one of the following cognitive learning styles [15.]

Extraversion ←→ Introversion (person’s Energy preferences):
Extraverted types learn by talking and interacting with others. They prefer to draw energy from the outer world of activities, people and things. Introverted types prefer quiet reflection and privacy. They prefer to draw energy from the inner world of thoughts, feelings and ideas.

Sensing ←→ Intuition (person’s Learning preferences):
Sensing types enjoy a learning environment in which the material is presented in a detailed and sequential manner. They prefer to focus on information obtained through the five senses and on practical applications. Intuitive types prefer a learning atmosphere in which an emphasis is placed on meaning and associations. They prefer to focus on patterns, interrelations and possible meanings.

Thinking ←→ Feeling (person's Decision preferences):
Thinking types desire objective truth, logical principles and deductive reasoning. They prefer to base decisions on logic and objective analysis of cause and effect. Feeling types prefer to base decisions on valuing processes taking into account what is important to other people.

Judging ←→ Perceiving (person's Lifestyle preferences):
Judging types prefer information to be organized and structured. They will be motivated to complete assignments in time. Perceiving types prefer a flexible environment; they are stimulated by new and exciting ideas. They like a spontaneous approach and prefer to keep options open.

Experienced and certified MBTI administrators can conduct an assessment. This assessment helps you to become aware of your personality preferences; what you like, you may like, or prefer. Based on your preference in each category, you will find your own personality type, which can be expressed as a code with four letters. There are 16 different personality types.

ISTJ	ISFJ	INFJ	INTJ
ISTP	ISFP	INFP	INTP
ESTP	ESFP	ENFP	ENTP
ESTJ	ESFJ	ENFJ	ENTJ

Figure 52 – MBTI Type Table (source: http://www.myersbriggs.org)

At the MBTI website you can find a short description of each of these 16 personality types. The description of the ENTP type is:

'Quick, ingenious, stimulating, alert and outspoken. Resourceful in solving new and challenging problems. Adept at generating conceptual possibilities and then analyzing them strategically. Good at reading other people. Bored by routine, will seldom do the same thing the same way, apt to turn to one new interest after another'.

(Source: http://www.myersbriggs.org)

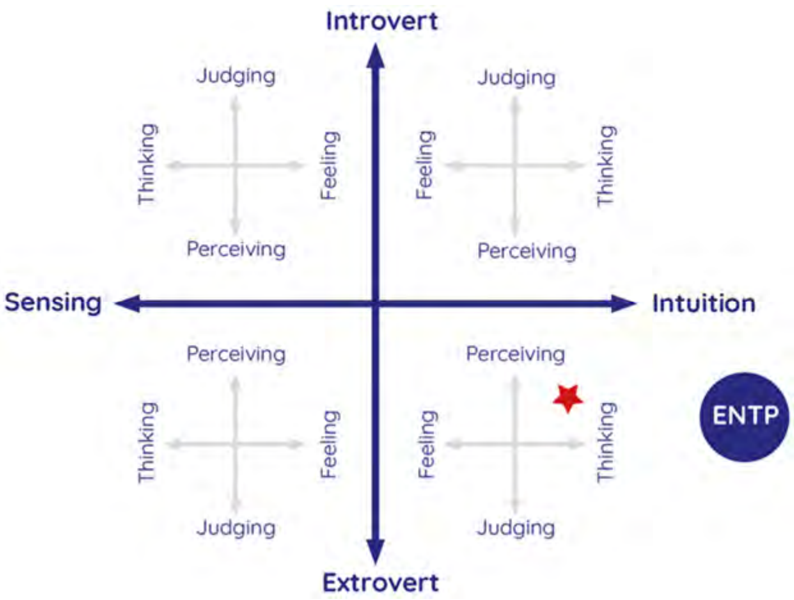


Figure 53 – Example of the ENTP type

Team member selection
Working as a team means a group of individuals working collaboratively on achieving the same objective. Each of the team members is doing a part of the work while all of these sub-tasks contribute to the whole. Working with teams is a crucial part of an organization. Teamwork means that people will cooperate using their individual skills and provide constructive feedback, regardless of any conflicts between individuals. Working with multi-disciplinary teams brings together knowledge and skills from different individuals.

It is essential that team members are subject matter experts and that the collective sum of their expertise at least covers the whole of the process that is being improved. It is often helpful to also have on the team a subject matter expert who is a supplier and one who is a customer. If this would make the team too large (say more than 8 people including the team leader), then these last two might be part time team members who are invited just to the specific meetings where their input is valuable.

The selection of team members does not only depend on the type of a project, but also on the maturity level at which the organization is operating. Starting the first projects on the next maturity level requires different competencies in order to maintain a certain level. Since starting at a new maturity level is a project on its own, it requires a senior project manager. For instance, implementing 5S is not something to be managed by a junior employee or by an operator. Although the 5S tool itself is very simple, the process of implementing the 5S philosophy across a department or an organization requires Lean knowledge expertise and skills of project management and management of change.

The team formation and duration of projects depends very much on the type of project, the scope of the project and the state within a certain level. Implementing 5S across multiple departments in an environment that has no experience with 5S can take half a year or even longer, while implementing 5S in one department within an organization that has already got experience with 5S in other departments can be done in a few weeks. Implementing a new strategy, changing behavior of people, transforming processes or deploying new techniques will take much longer than sustaining a certain level or executing a single project. In general, single projects on a higher level take more time than single projects on lower levels. In Table 6, an overview of possible team formations and timings for the different maturity levels is listed. These are just guidelines because they will differ from organization to organization.

CIMM Level	Project type	Project leader	Team members	Duration indication
Level-V	DfSS deployment	MBB	GB, BB, Engineers	1 to 3 years
	DMADV project	Lean Six Sigma GB/BB	GB, BB, Engineers	3 to 6 months
Level-IV	Six Sigma deployment	MBB	GB, BB, Process owners	1 to 3 years
	DMAIC project	Lean Six Sigma GB/BB	YB, OB, GB, employees	3 to 6 months
Level-III	Lean transformation	Lean BB	YB, OB, GB, employees	1 to 3 years
	VSM project	Lean GB/BB	YB, OB, GB, employees	3 to 6 months
Level-II	CI Culture	Lean GB/BB	YB, OB, employees	1 to 3 years
	PDCA project	Team leader, OB	YB, OB, employees	Few days to 2 weeks
Level-I	5S, QMS and Standards	Lean GB/BB	Employees	1 to 3 years
	Sustaining	Department leader	Employees	Continuously

Table 6 – Deployment and Team formation

Team roles (Belbin)

Leading a Continuous Improvement project is all about working together in a multidisciplinary team. Black Belts should be able to manage the dynamics in such a team. In order to improve a team's effectiveness, it is useful to know the behavioral strengths and weaknesses of individuals in a team. Team Roles help to build high-performing teams, maximize working relationships and to enable people to learn about themselves. Belbin Team Roles are used to identify people's behavioral strengths and weaknesses in the workplace. This information can be used to build productive working relationships; select and develop high-performing teams; raise self-awareness and personal effectiveness and build mutual trust and understanding.

"A team is not a bunch of people with job titles, but a congregation of individuals, each of whom has a role which is understood by other members. Members of a team seek out certain roles and they perform most effectively in the ones that are most natural to them".

Dr. R. Meredith Belbin

Dr. Raymond Meredith Belbin is a British researcher best known for his ground-breaking research in the field of team effectiveness. His research became the basis for the classical book, 'Management Teams' (1981). One of the most important conclusions of the research was the proposition that an effective team has members that cover nine different team roles. This doesn't mean that a team needs nine individuals, each with one strong Team Role. A team member can play two or three Team Roles well [5.].

- Role 1 – Plant:
  Highly creative and good at solving problems in unconventional ways. Also tends to keep ideas to themselves for a while.
- Role 2 – Resource Investigator:
  Provides a logical eye, makes impartial judgments where required and weighs up the team's options in a dispassionate way. Is also energetic, creative, innovative and a networker.
- Role 3 – Coordinator:
  Focuses on the goals of the team; encourages team members and delegates work appropriately. Has a strong will, but is also reactive at the same time. Collects opinions and drives a decision.
- Role 4 – Shaper:
  Provides inside knowledge on the opposition and makes sure that the team's idea would carry to the world outside the team. Has ambition, takes initiative, shows courage and likes to set goals.
- Role 5 – Monitor Evaluator:
  Is a thinker and often reactive. Often wait to see what others will do. Subject each plan to its critical eye. Carries it out as efficiently as possible.
- Role 6 – Team worker:
  Would rather work together than alone. Can turn individual individuals into a team. Is optimistic and can motivate well. Often relies on his feeling. Scrutinizes the work for errors, subjecting it to the highest standards of quality control.
- Role 7 – Implementer:
  Identifies the work required and completes it on behalf of the team. Is accurate, efficient, persistent and purposeful. Is disciplined, collegial and takes responsibility.
- Role 8 – Completer / Finisher:
  Senses when things are about to go wrong and signals when things are not in order. Keeps the team moving and doesn't lose focus or momentum. Is accurate, collegial and involved.
- Role 9 – Specialist:
  Is a researcher and provides the team with in-depth knowledge of the main area of the project. Is independent and well able to organize his own work.

Not all team roles are required at every stage of the project. As projects progress, different team roles are required. Introducing a certain role at the wrong stage may have adverse consequences on the project. For example, a Monitor Evaluator should not be present at the initial ideas stage, since there is a risk that they might dampen enthusiasm and cause a potentially strong idea to be rejected too early. It is recommended to consider flexible teams where team members join the team to make their contribution and drop out again when their stage of the project is at an end.

Define	Coordinator, Shaper
Measure	Resource Investigator, Implementer
Analyze	Plant, Monitor Evaluator, Specialist
Improve	Implementer, Completer/Finisher
Control	Monitor Evaluator, Coordinator, Implementer, Team worker

Table 7 – Preferred Belbin roles in Lean and Six Sigma projects

Team stages

The development of a team during a project is not a linear process. A different approach and behavior will be needed in different stages of a project in order to optimize the team's productivity. Having a way to identify and understand causes for changes in the team's behaviors will be useful as a basis for conversation. This will help to avoid ending up in a clash and misunderstanding.

A useful model to review the development of a team is the 'Forming – Storming – Norming – Performing' model. This model was first proposed by Bruce Tuckman (1965). Later, after the review of 22 studies, that appeared since the original model was published, a fifth stage was added called 'Adjourning'. According to Tuckman, each of these stages are necessary and inevitable in order for the team to grow, to face up to challenges, to tackle problems, to find solutions, to plan work and to deliver results. Tuckman's descriptions of the stages provide a useful framework for looking at your own team.

Bruce W. Tuckman's model of the developmental sequence in small groups has rightly been adopted as a helpful starting point about possible stages or phases within different small groups. When the original article was written, it was an important summary of the existing literature – and its longevity reflects Tuckman's ability to categorize and synthesize – and to get it right. While there may be all sorts of debates around such approaches to stage theory, and around the need for a model that reflects the flux of groups, there does seem to be some truth in the assertion that small groups tend to follow a fairly predictable path (Source: http://www.academia.edu).

Stage 1 – Forming:

During the first stage of team building, the forming of the team takes place. The individual's behavior is driven by a desire to be accepted by the others and avoid controversy or conflict. People focus on being busy with routines, such as team organization. At this stage, much of the focus is placed on gathering information and impressions about each other and learning about the scope of the task and how to approach it. This is a comfortable stage to be in, but the avoidance of conflict and threat means that not much actually gets done.

Stage 2 – Storming:
Different ideas compete for consideration. Team members open up to each other and confront each other's ideas and perspectives. The storming stage is necessary for the growth of the team. This stage can be unpleasant and even painful. There is a risk that the team will never develop past this stage.

Stage 3 – Norming:
The team manages to have one goal. At this stage the team comes to a mutual plan. Some may have to give up their own ideas and conform to others. At this stage, all team members are responsible for the performance of the team and have the ambition to pursue the team's goals.

Stage 4 – Performing:
Only few teams reach the performing stage (high-performing teams). This involves finding ways to get the job done smoothly and effectively without inappropriate conflict or the need for external supervision. Team members are now competent, autonomous and able to handle the decision-making process without supervision. In certain circumstances, the team might revert to an earlier stage.

Stage 5 – Adjourning:
Adjourning involves dissolution. It entails the termination of roles, the completion of tasks and reduction of dependency (Forsyth 1990: 77). Some commentators have described this stage as 'mourning' given the loss that is sometimes felt by former participants. The process can be stressful – particularly where the dissolution is unplanned (ibid: 88). In many respects, Tuckman and Jensen's addition of 'adjourning' was less an extension of the model, more an after word.

When leading improvement teams, Black Belts require the ability to diagnose the stage of development of these teams. Black Belts should also be able to make appropriate interventions that move the team forward. Tuckman defined the most appropriate types of interventions that will move the team forward, for each of the stages a team is in [Table 8]. Using a different type of intervention will be less effective. At worst, the incorrect intervention may well destroy the good teamwork that already exists. Therefore, it is important to use proper interventions in each stage.

Intervention Type	Forming	Storming	Norming	Performing
Overview	Set objectives	Resolve conflicts	Facilitate processes	Coach
Direction	High	High	Low	Low
Support	Low	High	High	Low
Leader focus	Individual tasks	People interactions	Task interactions	Self-development
Persuasion style	Tell/push	Sell/Consult	Listen/advise	Observe/support
Team Interaction	Leader provide links	Facilitate relationships	Facilitate team processes	Dynamic grouping
Summary	Individuals	Relationships	Processes	Self-development

Table 8 – Intervention types a leader should make

3.1.4 Project planning

Project planning or project scheduling refers to the management of projects. The objective is to achieve the predefined project goals within time, budget and quality. It is the responsibility of the project manager and the team that project deliverables will be completed within a certain time frame (start date and completion date) by means of resources and activities. The task of the project manager involves monitoring and reporting the status of milestones, tasks, activities, results and outcomes. A project manager is like a doctor who leads the trauma team and decides the course of action for a patient, both at the same time.

Time management is the process of planning and execution of activities needed to complete certain deliverables within a certain time frame. Time management include the following elements:

- Defining deliverables that need to be derived.
- Setting priorities.
- Defining due dates for deliverables.
- Defining the quality level of deliveries.
- The process of balancing activities and available resources.
- Carrying out activities to compose deliverables.
- The process of monitoring progress.
- Team meetings to review status and dividing actions.
- The process of increasing efficiency of execution.
- Incentives to modify behavior to ensure deliveries within time.

Many books have been published that deal with time management. Earlier in this book, we already identified Covey's Seven Habits. Another well-known book is 'Getting Things Done' (David Allen, 2001). Getting Things Done is part tools and techniques and part psychology. This approach has helped many people improve their personal effectiveness in today's hectic times. According to David Ellen, a person is most productive when his mind is clear and free from things that people tend to do that remain undone and become an obstruction on the unconscious mind. The advice is therefore to keep your mind clear, for example by writing actions on a to-do list, so that you can clear your head afterwards.

"The key is not to prioritize what's on your schedule, but to schedule your priorities."

Stephen Covey

The most disturbing factor in office environments is the email inbox. New emails appear every few minutes and bring new information or requests for new actions. If you're not careful, your inbox will completely determine your daily schedule while your head keeps track of all this information. It is therefore recommended to set fixed times during the day for checking new emails. If you need less than 2 minutes for an action, do it right away. If the activity takes more time than 2 minutes, add it to your to-do list. If possible, prioritize the items on your to-do list and add the amount of time it takes to complete the activities. Adding actions to your to-do list will clear your mind, ultimately making you more productive.

Gantt Chart
Gantt charts are most often used to support time management and to visualize the time schedule of a project. The Gantt chart was developed by Henry Gantt in the 1910s. The left side of the Gantt chart contains a vertical tree of project elements at different levels of granularity. The tree can be collapsed or expanded. The elements can be represented in two different ways. The first is a list of activities, which is called a 'Work Breakdown Structure' (WBS). A second option is to make a list of deliverables that are the result of the activities. This is called a 'Product Breakdown Structure' (PBS).

Most software programs that are available to manage projects can generate Gantt charts. These programs offer the possibility to show the dependencies and relationships between activities and milestones. The horizontal axis on the chart shows the schedule with the total duration of the project. A horizontal bar represents each element in the project from the start to the finish. Arrows between bars indicate dependencies between activities. Milestones are usually represented by diamonds and are points in time with zero duration.

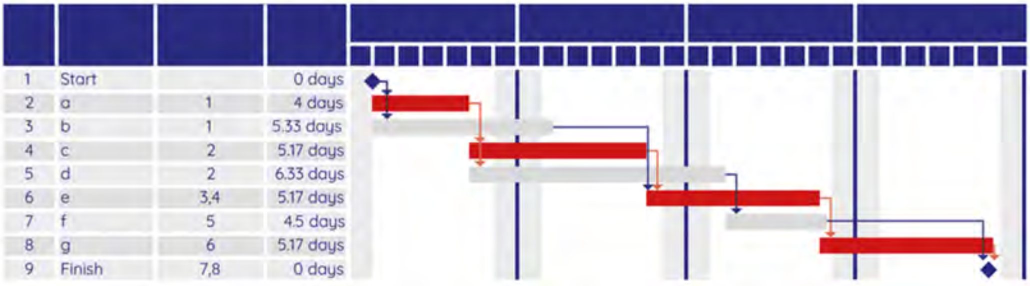


Figure 54 – Example Gantt chart

The Gantt chart is developed during the planning stages of a project and gives the project manager the opportunity to visualize and manage progress. Software programs calculate the project's critical path, using the 'Critical Path Method' (CPM). The critical path should be highlighted (in this example in red). The total float is also calculated and depicted in this case by a black line that extends after the task bar. Activities on the critical path become key areas of focus during project progress review meetings. Non-critical path activities that contain a large amount of 'Slack' or 'Float' may need less attention. Naturally, if the slack time is small, then care should be taken to maintain focus on these activities as well, to ensure that lack of progress does not cause the completion of these activities to be delayed more than the 'Total float'. If this happens, the activities will become part of a new, longer critical path, and the project as a whole will be delayed.

Program Evaluation and Review Technique
'Program Evaluation and Review Technique' (PERT) is a technique that was designed to analyze and represent the dependencies and duration of tasks and to visualize the critical path of a project. PERT is a method to analyze the activities within a project (the tasks), the order in which they must be completed (the dependencies), the time needed to complete each task (the duration) and to identify the minimum time needed to complete the whole project. PERT uses task-on, arrow-diagram notation to document the project. For instance, a project comprising six activities A to F, each with its expected duration in months might look like Figure 55.

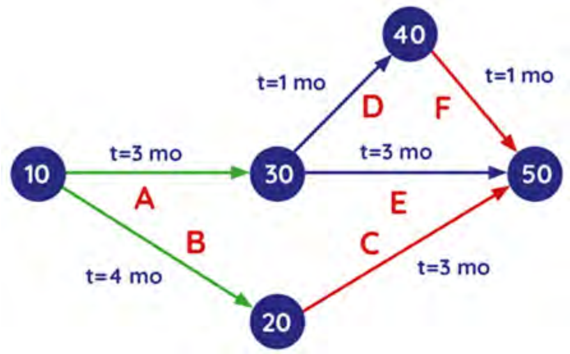


Figure 55 – Example PERT

In this example we see there are three possible paths from the start (node 10) to the end (node 50): ADF, AE and BC. The duration of each path is calculated:

- ADF = 3 + 1 + 1 = 5 months.
- AE = 3 + 3 = 6 months.
- BC = 4 + 3 = 7 months.

Focus on the critical path is key to successfully managing the project. The minimum time required to complete the project is equal to the longest path duration. In this example, path BC forms the critical path of the project and it will take 7 months to complete the project.

PERT is a visual method for identifying the critical path and is good enough for simple projects. For complex projects with many tasks and paths it is not recommended to use this technique.

3.1.5 Project execution

DMAIC Tollgate reviews

The DMAIC methodology for Lean Six Sigma projects is accomplished in five phases (Define, Measure, Analyze, Improve and Control). Regularly a Tollgate review session is scheduled between each phase by the project manager (Green Belt or Black Belt) to present the progress to the Champion or Project board. During this meeting, all results within a certain phase are presented. At the end of the meeting, the Champion (or Project board) confirms that the team has successfully completed the phase and may 'pass the Tollgate'. This approach is similar to other project management methods like PRINCE2.

This means that the phase is officially closed and the team gets permission to move to the next phase. Tollgates are usually attended by a Master Black Belt to support the Champion in the decision-making process. This is especially important if the Champion does not have the Six Sigma skills of interpreting and challenging the statistical analysis and conclusions that the project manager is presenting.

Figure 56 – Tollgate reviews for a DMAIC project

In many Six Sigma literatures, the use of Tollgates is explained in a way that the team can only prepare for a Tollgate review if it is ready to complete a phase and that the team cannot start the next phase until a phase has officially been completed. This implies that the team cannot work in different phases simultaneously. This can result in undesirable effects such as difficulties to adjust the approach when needed or to start certain steps of the next phase to save time. It is also difficult to get the project board together when a Tollgate meeting is scheduled only at the time the team is ready to complete a phase. Nowadays, most organizations follow a more Agile approach and schedule regular progress meetings between the Champion and the project manager (every two weeks for instance). During this meeting, it will be decided if it is possible to complete a phase and move on to the next one.

Tollgate reviews should take the form of a formal review of progress against project objectives. This should take place with the Champion at the end of each phase. The specific content of each review naturally varies by project and phase; however, the generic agenda should follow the same pattern:

- What has been achieved against objectives and plan?
- What, if anything, remains to be completed?
- What has been learned and what conclusions have been drawn?
- What does the team plan to do next and what support will be needed?

Risk management
Project risk management is an important aspect within project management. A project risk is defined as an unintended event or condition with a certain probability and a certain negative effect on the project's objectives. Project objectives are often related to time, costs, quality or technology.

Risk management is the identification, assessment and mitigation of risks. Risks can be identified in a brainstorm session by the team. The assessment can be done to qualify the probability and severity of each risk. A tool that can be used for the risk assessment is demonstrated in Figure 57.

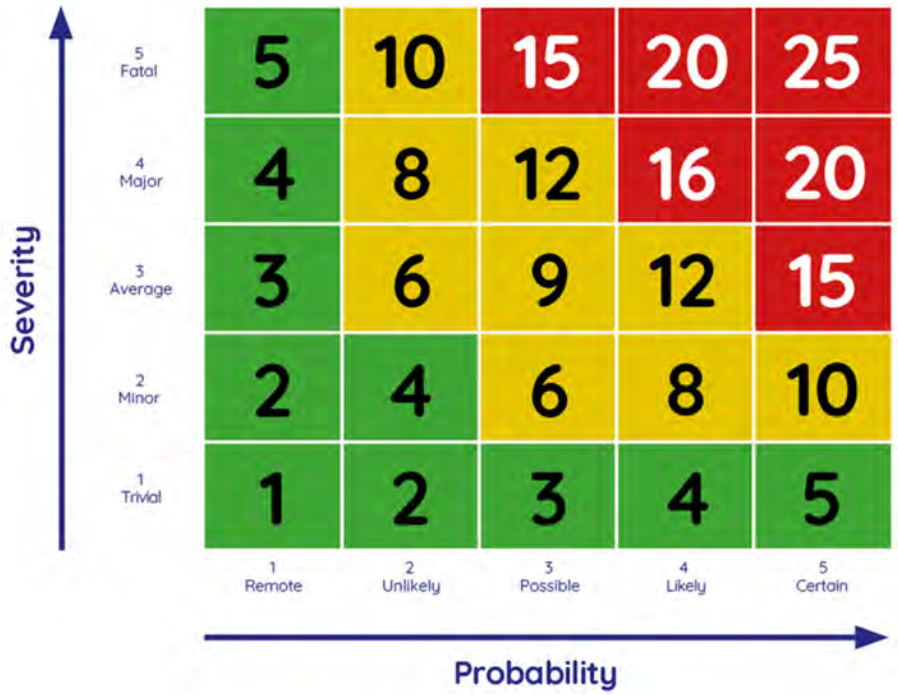


Figure 57 – Risk Matrix

During the project, the team should try to mitigate the risks. Mitigation is the set of actions to either:

- Reduce probability: Reduce the likelihood of the event to occur.
- Reduce severity: Eliminate the negative effect of the event.

In many occasions it is not possible to reduce the severity of the event (effect). In that case, the team should focus on taking actions or measures to reduce the probability of the event occurring.

Project documentation

Project documentation is an important part of Project management. Proper documentation ensures that project requirements are fulfilled and that they are traceable with regard to what has been done, who has done it and when it was done. The project manager is responsible for ensuring that project documentation is developed and maintained. It is important that documentation is arranged correctly and that it is understood by people both inside and outside the team.

It is the responsibility of the project manager to follow the standard procedures and templates that are available in the organization. Any organization will have its own set of project templates. Templates that are pretty common include:

- Project Charter or 'Project Initiation Document' (PID):
  Describes the business case, need, scope, time frame, global finances and objectives of the project. This document also mentions the names of the Champion, Project manager and Team members.
- Work Plan:
  Sets out the activities, timing, status and the responsible resource(s) needed to perform the task. This is often presented in a Gantt chart.
- Project Review Template:
  DMAIC template, used for Lean Six Sigma projects, containing the 14 steps [3.2.4].
- Issue Log:
  Maintains the list of issues and includes the assigned responsible person and status.
- Change Management Report:
  Maintains a list of (proposed) changes, the status of those changes and the approval process.
- Data Collection Sheets:
  Sheets that are used for data sampling or collecting data during a test [6.3.2].
- Quality Documents:
  These are various documents related to the quality management system [4.3.1], but also to FMEA and Control Plan [6.9.2] and documents related to product development, like PPAP [8.1.2].
- Work Instructions:
  Instructions for the operators or employees, also called 'Standard Operating Procedure' (SOP).
- Lessons Learned:
  A document that describes what we have learned from what we have done.

Project documentation is the foundation for quality, traceability and history so it is essential that this documentation is well arranged, accessible, easy to read and adequate.

3.2 Process Improvement roadmaps

In this paragraph, we will review a number of commonly used project approaches and roadmaps. We will also review the differences and coherences between bottom-up projects and top-down projects. Considering the process improvement maturity model from the previous chapter, CIMM Level-I and CIMM Level-II projects tend to follow the PDCA roadmap and A3-report. The DMAIC approach is applied for CIMM Level-III and CIMM Level-IV projects, and the DMADV approach is used for CIMM Level-V projects. In addition, some organizations (e.g. Automotive) follow the 8D problem-solving process for customer complaints and Scrum for Innovation projects.

3.2.1 Kaizen roadmap (PDCA)

Many small improvement projects, like Kaizen events and other Level-II initiatives, follow the PDCA approach. The PDCA abbreviation stands for Plan-Do-Check-Act and is also known as the Deming or Shewhart Cycle. As shown in Figure 58, the Plan phase consist of five steps. This implies that a good preparation is (more than) half the work.

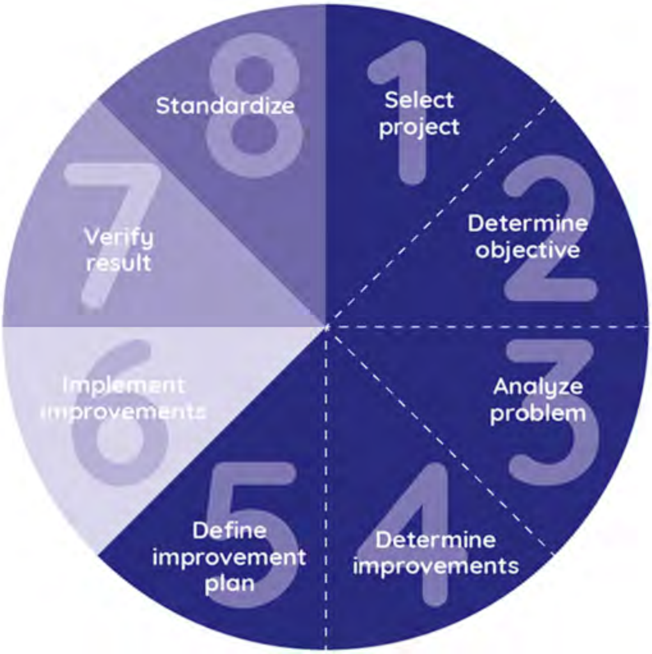


Figure 58 – PDCA roadmap

We will briefly review each of the four phases:

Plan

Within the Plan-phase, we will identify a relevant issue, followed by forming a team that has the knowledge and time to work on the problem and is empowered to implement the solution. We will define the problem description and establish the objectives. Then the problem will be analyzed and possible causes will be determined. Quality tools and brainstorm techniques like the Ishikawa (or Fishbone) diagram or 5-Whys can be used in this phase. Finally, the team will generate a solution and an implementation plan. The plan will be presented to the department leader to get approval to execute the plan.

Do

Within the Do-phase, the team will execute the implementation plan and put in place the solutions that will take away the root cause. Data of the improved process will be collected.

Check

Within the Check-phase, the team will compare the data of the improved process with the initial data. The team will measure the effect of the solution and verify if the root cause has indeed been eliminated. The team will also verify if the output of the improved process is what would be expected.

Act

Within the Act-phase, the team will review whether the actions taken have achieved the right effect and if any additional actions need to be initiated. Second, the team has to sustain the established improvement. This is an important step to ensure that the process performance will not deteriorate over time again. This step is the wedge as shown in Figure 59. Without securing the improvement properly, we will be certain to face the same problem again in the future.

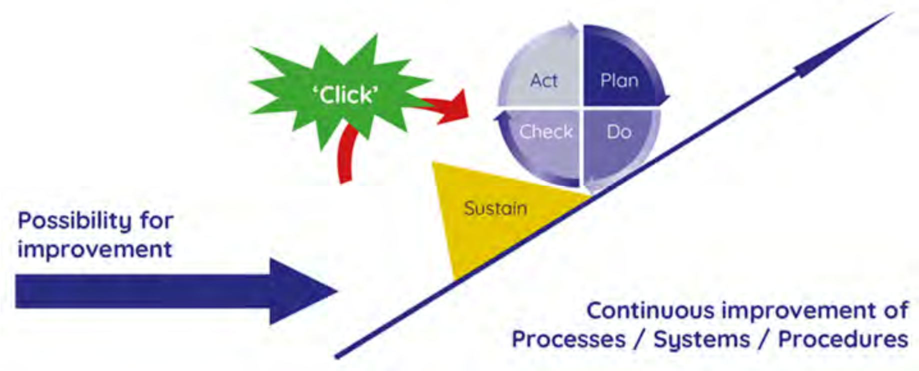


Figure 59 – Continuous Improvement PDCA

A3-report

One of the tools Toyota has been using to manage people to achieve operational learning and to present project results is the A3-report. The report is named after the international paper size (A3) on which it fits. It is a key tactic in sharing a deeper method of thinking that lies at the heart of Toyota's sustained success.

An A3-report is composed of a number of sequential boxes arrayed in a template. Often, the four steps of the PDCA process are followed and visualized in the A3-template. In Figure 60, an A3 is presented concerning problems encountered within the translation process of documents. The project manager used the A3-approach to attack the problem while being mentored by his supervisor.

1. Describe problem background.
2. Describe the current problem conditions.
3. Set the desired goals.
4. Analyze the situation to establish causality.
5. Define possible countermeasures.
6. Define the action plan to implement solution.
7. Define follow-up actions.

The objective of using an A3 is twofold. The first is to solve the problem at hand. The ultimate goal, however, is to make the process of problem solving transparent and sharing the solution with others. It will create an organization full of thinking, learning problem solvers. The danger is that organizations do not use the tool in the proper way, but use it for window dressing. Keep in mind that the purpose is not to fill in the A3, but use it to communicate the solution to others in order to share knowledge.

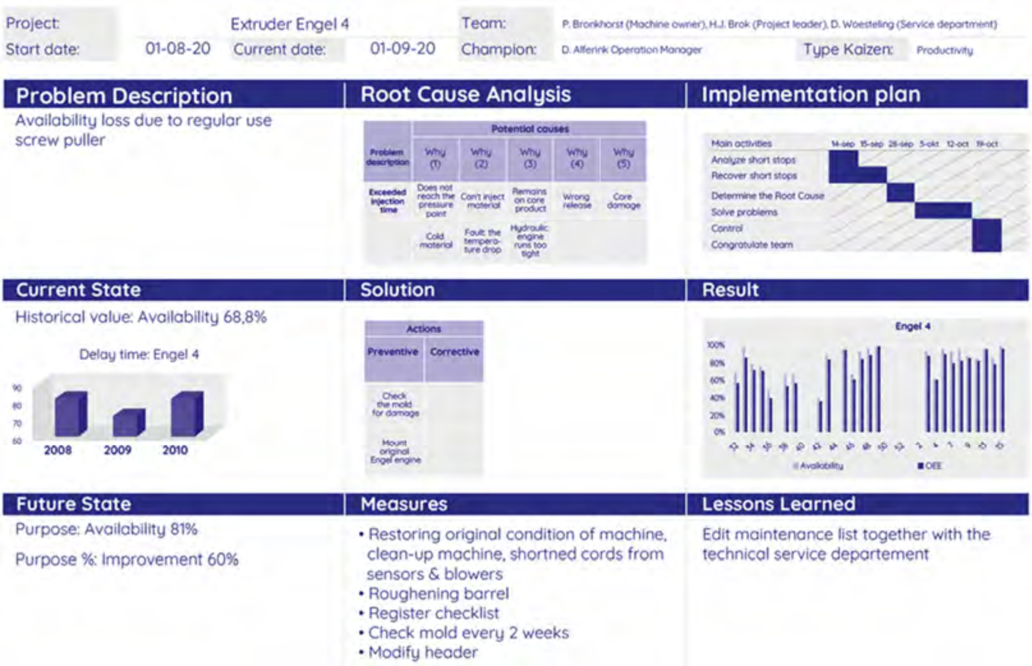


Figure 60 – Example A3 report (John Shook, 2008)

3.2.2 Lean Six Sigma roadmap (DMAIC)

DMAIC is an abbreviation for Define, Measure, Analyze, Improve and Control. DMAIC refers to a data-driven improvement initiative used for improving, optimizing and stabilizing business processes and products. The DMAIC roadmap offers a focused and structured approach to improve processes and solve problems in an organization. The roadmap is used mainly for Six Sigma projects (Level-IV). Lean projects (Level-III) use both PDCA and the DMAIC roadmap. Kaizen projects (Level-II) are advised to follow the PDCA roadmap because it is less complicated.

In the Define phase of the roadmap, the operational problem is defined and the project charter [paragraph 3.1.2] is written, as well as the 'Critical To Quality' metric (CTQ). In the Measure phase, the measurement system that needs to measure the CTQ is validated. In the Analyze phase, the current process is analyzed and potential factors of influence are identified. In the Improve phase, improvements are defined, implemented and verified. Finally, in the Control phase, measures will be put in place to sustain the improvements. Each of these phases will be discussed in more detail in the following paragraphs.

Project selection is formally not part of the DMAIC roadmap, but should be done prior to the start-up of a Lean or Six Sigma project. The Champion or management selects a project based on selection criteria such as size, impact and urgency. However, it might be that during the evaluation in the first phases the project scope or team will be changed. Sometimes a quick DMA is done prior to the actual start of a full DMAIC project. Portfolio management and project prioritization are also not part of the DMAIC roadmap itself, but are managed at a higher level by the Champion or by the Master Black Belt.

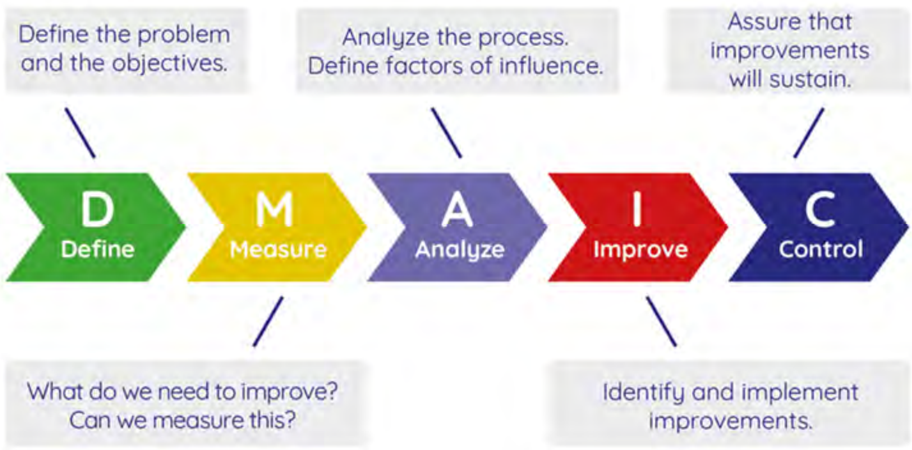


Figure 61 – Lean Six Sigma DMAIC roadmap

Define:
Every Lean and Six Sigma project starts with the Define phase. General Electric added the Define phase to the original MAIC methodology. Based on the problem statement and the scope of the project, a team is formed and a project manager is assigned. The Champion is the project owner. The purpose of the Define phase is to clearly define the problem statement, the goals, the scope and the high-level project timeline. These elements will be combined in a project charter. The Define phase helps to clarify the understanding of why the problem is actually a problem. This is expressed as a financial measure. This is important before resources and effort are invested in the project. The problem definition is done from the perspective of the external client (Voice of Customer) and / or from the perspective of the organization (Voice of Business). In the Define phase, it is determined which metric can be linked to the problem of the customer. These so-called "Critical to Quality" (CTQ) measures are the common thread throughout the DMAIC project. Each

project focuses on a limited number of CTQs. To determine the CTQs, a CTQ Flowdown is composed [paragraph 1.2.2]. Within Lean, the CTQ is often related to quantities or time (lead time, delivery time, processing time, capacity utilization, etc.). Within Six Sigma, the CTQ is often related to measurements that are out of specification.

Measure:
Within the Measure phase, the gap between the current performance and the required performance is defined. The purpose of the Measure phase is to make customer requirements tangible and measurable. Determining the measurement procedure is the main purposes of this phase. It is decided what should be measured and how it is measured. In the Measure phase, it is determined what the measurement procedure is and how well the measurement system is able to measure the CTQs. It is important that the team ensures that the measurement system, and the data collected, are valid and reliable before proceeding with the Analyze phase of the project. It is very important to clearly define the definitions of the CTQ and the source for the data so that there is no debate about the performance. Also, within the Measure phase, the difference between the current performance (Baseline performance) and the desired performance is determined (Target performance). Often people rate the Measure phase as the most difficult stage in a DMAIC project because reliable data is sometimes difficult to collect.

Analyze:
Within the Analyze phase, we will identify reasons why the CTQ is not performing on target. Within Lean projects in this phase, a ‘Value Stream Map – Current State’ or ‘Spaghetti Diagram’ of the current state is drawn to highlight Waste and opportunities for improvement. Within a Six Sigma project, we will look for possible root causes that are the reason for high variation of the CTQ. The purpose of the Analyze phase is to identify, validate and to identify factors that have influence on the variation. In the Analyze phase, the relationships are established between the CTQ (also called ‘Key Process Output variables', Responses or ‘Ys’) and the ‘Key Process Inputs variables’ (also called ‘Xs’). Often, a large number of potential influence factors are identified at the beginning of this phase, for example, by a brainstorm session. The number of potential factors of influence is then reduced by carrying out screening experiments. Next, a hypothesis is determined and experiments are performed in order to test the hypothesis. The result is a (mathematical) model that represents the relationships between the factors of influence ($X_{1..n}$) and the CTQ.

Improve:
The purpose of the Improve phase is to implement and verify solutions to the problem. Within Lean, a ‘Value Stream Map – Future State’ will be composed. This is a design of a new process flow or factory layout. TPM or 5S initiatives and Kaizen projects can be performed to eliminate Waste or to resolve quality issues. Within Six Sigma, we will perform experimentation to determine the optimum settings for the process. Several tools can be utilized in this phase, e.g. Regression analysis or Design of Experiments [7.8]. Within Six Sigma projects, often a Process Capability Analysis [7.7] is performed to investigate the performance of the improved process.

Control:
The purpose of the Control phase is to sustain the achieved results. Although the problem has been fixed by now, the team should not forget to take this phase seriously to prevent the problem from occurring again. The best way to accomplish this is to capture the improvement by applying 'Poka Yoke' [paragraph 6.9.1] to guarantee that the process is independent of the way of working. Improvements should be monitored to ensure sustainable success. To achieve this, a Control plan should be composed, work instructions should be updated and employees should be trained. The team should verify if the forecasted savings have been met and should report the ‘Lessons Learned’, so the next project can benefit from this experience. Then, the assignment is formally returned to the Champion. Finally, the task of the Champion or department manager is to appreciate the team for their achievements.

DMAIC 14 step roadmap
The five DMAIC phases are followed by all Lean Six Sigma Belts across the world. Because all of the phases are very comprehensive, they are split into a number of steps. There are many different variants of these roadmaps. In Table 9, a 14 step DMAIC roadmap is demonstrated (Source: Minitab Quality Companion).

Define	1	Define and Scope project
	2	Define defect and CTQs
	3	Plan and document project
Measure	4	Evaluate measurement system
	5	Establish baseline
	6	Set improvement goals
Analyze	7	Map process and identify inputs
	8	Isolate key inputs
	9	Develop *Y=f(X)* function
Improve	10	Determine optimum settings
	11	Implement proposed improvement
	12	Validate proposed improvement
Control	13	Implement control strategy
	14	Close out project

Table 9 – 14 steps DMAIC roadmap

Both Lean and Six Sigma projects can follow the DMAIC roadmap. The techniques used, though, are different. A graphical presentation of some of the techniques used in a Lean project is shown in Figure 101 and a graphical presentation of those used in a Six Sigma project is shown in Figure 174.

3.2.3 Problem-Solving roadmap (8D)

The 'Eight Disciplines Problem Solving', also called '8D' or 'Global 8D', is a problem-solving method. Its purpose is to identify, correct and eliminate problems. The 8D method is ideally suited to supply brief and concise reports to the customer in order to demonstrate how the problem was solved. The 8D methodology was originally created by the U.S. Department of Defense (1974). The methodology has been widely used by Ford in the automotive industry. Later on, the methodology was applied in the entire automotive sector. If a series of components did not meet specifications, the customer would request an 8D from its supplier. Nowadays, the 8D approach is applied more and more in other sectors as well.

Typically, an 8D request is triggered by a 'Non-Conformity Report' (NCR), which is raised by the customer and received by the supplier of the problem. Because the steps in the process are defined, it is clear to the supplier what is expected. During the problem-solving process, the customer and supplier can communicate about expectations and progress following these steps.

Step	Description
D0	Determine Emergency Response Action (ERA)
D1	Establish the team
D2	Describe the problem
D3	Develop Interim Containment Actions (ICA)
D4	Identify & Verify Root Cause
D5	Identify Permanent Corrective Actions (PCA)
D6	Implement & Validate the PCA
D7	Prevent reoccurrence
D8	Congratulate the team

Table 10 – 8D Problem-solving process

D0 – Emergency Response Action (ERA):
When a problem occurs, it is recommended to shut down the line immediately to prevent the production of huge piles of products that have the same failure. The 'Emergency Response Action' describes supplier actions on items already produced. These items may be found in several locations like the customer, plant or warehouse. ERA requires checking for errors in already manufactured items. Checked items should be marked in such a way that it is evident that these have been checked. The checked results should be documented. This activity is often 'quick and dirty'.

D1 – Establish the team:
When you receive a complaint from a customer, or a problem is experienced in the normal work environment, the first step is to establish a (multidisciplinary) team that has knowledge and is empowered to solve the problem.

D2 – Describe the problem:
The problem has to be described from the viewpoint of the problem holder as objectively and clearly as possible. It is important that no solutions are mentioned in the problem description. The problem should be sustained with data. Sometimes a separate form is used to report the deviation from the standard. This form is called a 'Non-Conformity Report' (NCR).

D3 – Develop 'Interim Containment Actions' (ICA):
The 'Interim Containment Action' (ICA) describes activities preventing material, produced after detection of the problem, from reaching the customer (in contrast to ERA (D0) describing material produced before detection of the problem). Especially for high volume production, this is an important step. Shutting down the line, however, would mean that the customer, or the next line in the process, would not receive any parts. To prevent a total shut down, an Interim Containment Action needs to be defined to guarantee that good products are still going to be delivered, while at the same time no bad products will be delivered.

D4 – Identify & Verify Root Cause:
In this step, we determine the Root Cause. Sometimes simple problem-solving techniques can be used such as the Fishbone diagram, Cause & Effect matrix or the 5-Whys technique. In the case of persistent and complicated problems, a full DMAIC project can be started to identify and eliminate the Root Causes.

D5 – Identify 'Permanent Corrective Action' (PCA):
The cause of the problem is now known. The next step is to establish corrective measures: the root cause must be eradicated. Permanent Corrective Action is the solution you finally want to implement in order to avoid the problem happening again. This is contrary to ERA and ICA where the solution is often limited to inspection and sorting of produced parts.

D6 – Implement & Validate the PCA:
The team now knows the solution to the problem. In this step, the solution will be implemented and validated. Validation can be achieved by removing the solution and verifying if the problem expresses itself again. If you can switch the problem on and off, you know that you really have found the root cause as well as the solution.

D7 – Prevent reoccurrence:
To avoid the problem occurring again in the future, additional measures are usually necessary. In this step, the team should define a plan to ensure that the same problem will not reoccur in the future. This may result in changed specifications, operator training and updating quality documentation like PFMEA, Control plan and work instructions.

D8 – Congratulate the team:
The last step in the 8D methodology is to congratulate and reward the team. Delivering a good performance is worth a pat on the back.

3.2.4 Scrum

Scrum finds its origin in product development and is commonly used in software development. Nowadays, Scrum is used more and more in development projects outside the IT-sector. A product development project that is applying Scrum will progress via a series of iterations that are called ‘Sprints’. The duration of a Sprint may vary between different organizations, but is commonly one to four weeks. The advantage of Scrum is that it is very appropriate at handling changes in requirements and that it focuses on delivering an operational or shippable version of the product at the end of each Sprint.

Scrum teams are supported by specific roles, like the ‘Scrum Master’ (SM) and the ‘Product Owner’ (PO). The Product Owner is responsible for the product or service and is representing the Voice of the Customer. His most important task is prioritizing the product requirements that must be achieved. For this, the Product Owner is in constant contact with the customer, the business and other relevant stakeholders. The Scrum Master guides the team towards building the right product by creating a compelling vision and functional requirements for the product. The priorities and requirements will result in a Product backlog. This is a list of the functionalities that remain to be added to the product. At the start of every Sprint, the Product Owner will work with the team to define which activities from the Product backlog will be transferred to the Sprint backlog. This is the team's to-do list during a certain Sprint. The number of items will be aligned with the available resources.

It is the task of the Scrum Master and the team to complete the Sprint backlog items functionalities within the Sprint timeframe. The role of the Scrum Master is to ensure that goals, scope, and product domain are understood by everyone on the Scrum team as well as possible. It is also the role of the Scrum Master to ensure the team follows the Agile values and principles. The responsibilities of the Scrum Master include preventing distractions, removing obstacles, finding resources and skills, establishing an environment where the team can be effective, addressing team dynamics, and ensuring a good relationship with the Product Owner as well as with other stakeholders. The role of the Scrum Master differs in many ways to the traditional project manager role. The role of the Scrum Master is not to provide day-to-day direction to the team and not to assign tasks to individuals. Instead, the Scrum Master is a coach to the team and shelters the team from outside distractions. This allows the team to focus during the Sprints on achieving the defined goals.

The Scrum project management is done by the Scrum team itself. As a self-organizing team, they are responsible to complete all Sprint items during the Sprint. Each person contributes in whatever way they can and helps other team members if needed to complete their deliverables. Scrum teams consist of skilled and motivated team members, who have a high sense of ownership, decision-making power, take ownership, communicate regularly, share ideas and work together on the same objective. Self-organizing teams prove to work very efficiently because they spend less time on project management and more time on development activities and completing work.

Each Sprint begins with a brief planning meeting and concludes with a test or review. Scrum expects the team to bring the product to an operational or shippable state in the end of each Scrum Sprint. The teams and the Scrum Master have daily stand-up meetings in front of the Scrum board to review progress and roadblocks. If there are any external roadblocks, the Scrum Master will take the lead in removing these roadblocks. At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly.

Below the main Scrum elements are listed:

- Product:
  The final product according to customer specification (after a number of Sprints).
- Sprint:
  Period of 1 to 4 weeks, during which the team is working on the Sprint backlog items.
- Sprint Planning meeting:
  Before a Sprint, the team will review what needs to be done.
- Sprint Review meeting:
  After a Sprint, the team will review the results and what can be learned from the past Sprint.
- Daily Scrum Meeting:
  During this daily scrum meeting, three questions are asked:
  - What did we finish yesterday?
  - What will we finish today?
  - What are some of the obstacles we came across?

Within Scrum, we also recognize so-called artifacts:

- Product backlog:
  Complete list of functionalities that remains to be added to the product.
- Sprint backlog:
  The team's to-do list during a certain Sprint. The number of items will be aligned with the available resources.
- Burn down chart:
  A chart to track progress with respect to hours planned and spent.

Some of the elements and artifacts are illustrated in Figure 62. There are a few additional artifacts and guidelines that are outside the scope of this book.

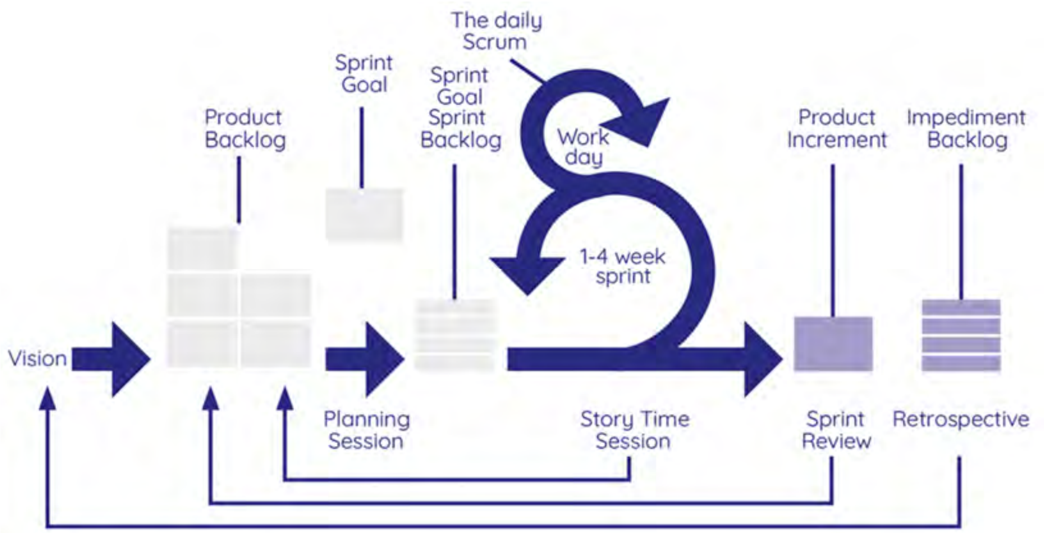


Figure 62 – Graphical representation of SCRUM

When If organizations start with daily Scrum meetings, it is recommended to use magnetic boards first. Software tools can be used at a later stage. There is many professional software and apps available, both paid as free. Two examples are shown below.

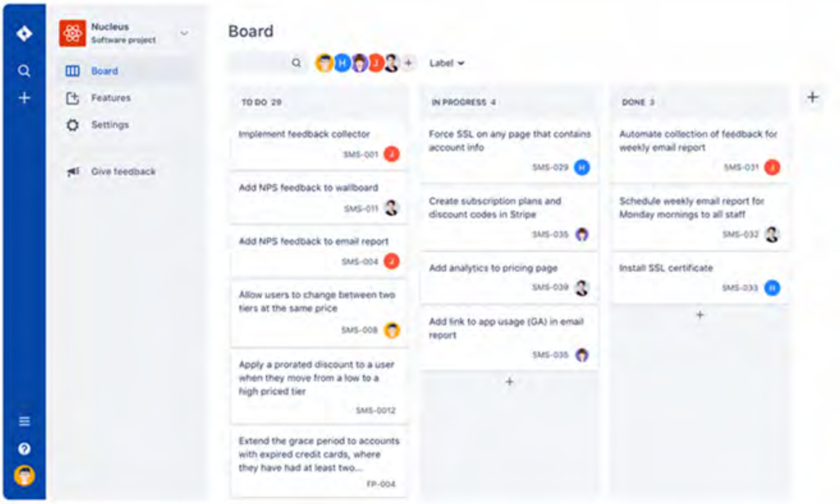


Figure 63 – Example Scrum software tool (Jira)

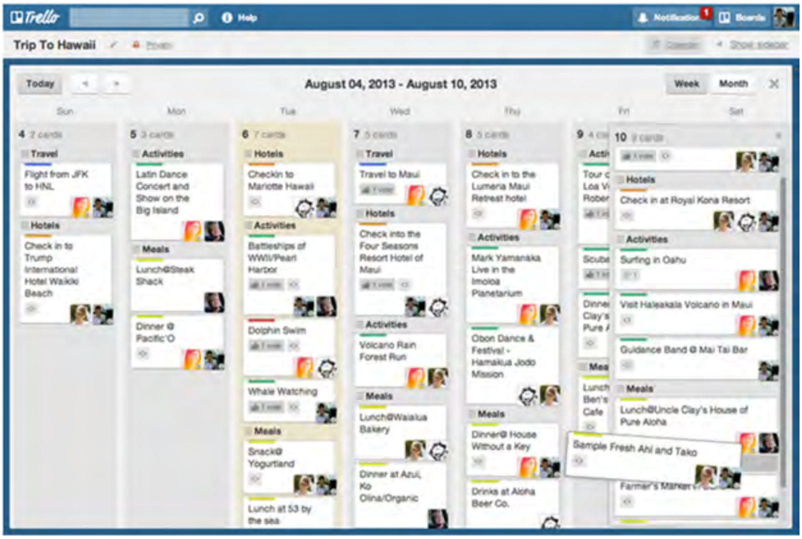


Figure 64 – Example Scrum software tool (Trello)

3.2.5 Design for Six Sigma roadmap (DMADV)

According to Bob Galvin (former CEO of Motorola), process improvement is needed due to an ineffective design process. It is much better and cheaper to prevent problems rather than solving them. Design for Six Sigma follows a different roadmap than the regular Six Sigma DMAIC roadmap. One possible roadmap is the DMADV, which is an abbreviation for Define, Measure, Analyze, Design and Verify. While the DMAIC is applied in breakthrough projects (Level-III and IV), the DMADV is applied in problem prevention, development and innovation projects.

"If I would ever start a new six-sigma initiative again,
I would focus on the design rather than on manufacturing."

Bob Galvin

As DfSS projects very often start from a risk perspective, the project is very often initiated by an outcome of the Design FMEA [see paragraph 8.2.3]. These projects are therefore called Risk Avoidance projects. A development project can have several risks that need to be investigated so one development project might initiate several DMADV projects.

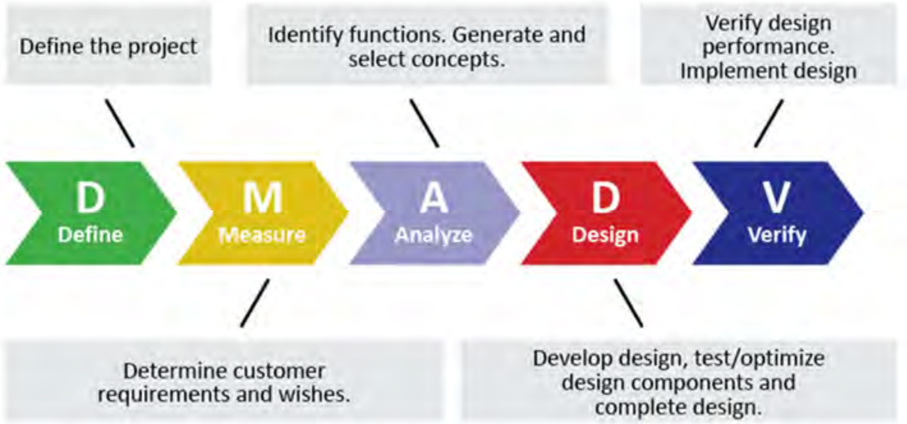


Figure 65 – DMADV roadmap

There are a number of similarities between the DMAIC and DMADV roadmaps. Both are data-driven approaches, they use similar tools and techniques and are used to drive defects to a minimum. To achieve this, both roadmaps use the same tools (e.g. MSA, Hypothesis testing, DOE). Therefore, all tools and techniques that have been explained in Level-IV of this book can also be applied in Level-V.

Alternatively, to the DMADV roadmap, some Design for Six Sigma projects follow an IDOV roadmap (Identify, Design, Optimize and Verify) or a CDOV roadmap (Concept, Design, Optimize and Verify). In practice, there is not much difference between each of these roadmaps. It depends more on the preference of the organization.

Below we will review each of the five DMADV phases:

Define:
The Define phase is similar to the DMAIC Define phase. Most DMADV projects start with a risk or requirement that is new to the organization or difficult to achieve. The purpose of a DMADV project is to investigate this risk and define solutions to mitigate it. If the solution for the risk is already known, there is no need to start a DMADV project. Like DMAIC projects, the Champion will form a project team and assign the project manager. During the Define phase, a project charter will be composed that includes the problem statement (risk), the goals, the scope and the timeline. These should all be in line with the bigger development or innovation project, the Voice of the Customer and the Voice of Business.

The Define phase should also include an estimate of the Hard benefits associated with the risk, when it will arise multiplied by the estimated likelihood. It is often not possible to define the exact values as the risk never arose before. Therefore, a best guess given by the team and the Champion is sufficient in order to justify the time, resources and budget to start the project. Some customers demand that certain requirements are established before the business can provide products or services. In this case, the Hard benefits of the project may include the potential 'Loss of business'.

Measure:
Within the Measure phase, the risk or customer requirement is made tangible and specific. The specific measures are called critical characteristics or Critical to Quality (CTQ). CTQs describe what is important to the quality of the process or service to ensure the requirements that are important to the customer. Each DMADV project focuses on a limited number of CTQs that are reflecting the risk or requirement. As in DMAIC projects, it is necessary to determine what the requirements would be for the CTQs and how they should be measured. The team should assure that the measurement system is adequate to measure the CTQs by performing a Measurement System Analysis (MSA). This phase includes specification limits, measurement equipment and procedure. This can be difficult because in a development project there is no prototype to perform measures. In this case, a Monte Carlo simulation can be used to analyze the sensitivity of a prototype system and to predict yields and/or C_p and C_{pk} values. The Monte Carlo method is a probabilistic technique based on generating a large number of random samples. A detailed explanation of Monte Carlo simulations is outside the scope of this book.

Analyze:
In order to achieve a certain value for the critical characteristic or CTQ, it is necessary to identify which factors have an influence on the performance of the CTQ. The purpose of the Analyze phase is to identify, validate and determine these factors of influence ($x_{1..n}$) that need to be controlled in order to achieve a stable and capable CTQ (Response or Y). There are several ways to identify potential factors of influence. In general, the same tools can be used as in the Analyze phase of the DMAIC. Potential factors of influence will be investigated in order to compose the Transfer function, which is the mathematical model that characterizes the relation of the factors of influence ($x_{1..n}$) on the CTQ (Response or Y). Tools that can be used for this are Regression Analysis and Design of Experiments (DOE).

Design:
When the Transfer function is characterized, the values of the factors of influence can be determined in an optimum setting. In addition to the Design of Experiments, another tool called Response Surface Modeling can be used to determine these optimum settings. Some projects focus on Product Lifecycle Management. Within these projects, Reliability Engineering can be applied. This is a very specific and extensive field of expertise. Therefore, it is outside the scope of this book.

Verify:
When the CTQ requirements are determined and the optimum settings for all significant factors of influence are defined, we have two more steps to take. First, we need to verify if the performance of the CTQ can, indeed, lie between its defined limits. To test this, we have to construct or produce a number of samples that can be analyzed. In some cases, we will need to pass special test requirements or duration tests. In most cases, we will use the samples to perform a capability analysis on the CTQ to verify if the performance of the samples will be far from the risk that was initially defined. Finally, we will need to ensure that the factors of influence will be controlled in a way that the risk will not appear.

DMADV 14 step roadmap
Like the DMAIC roadmap, the DMADV phases can be split into a number of steps. There are many different variants of these roadmaps. Table 11 demonstrates an example of a 14 step DMADV roadmap.

Define	1	Define project & Determine project Scope
	2	Determine functional requirements
	3	Plan and document project
Measure	4	Translate into technical requirements
	5	Establish objectives
	6	Evaluate measurement system
Analyze	7	Develop concept design
	8	Identify potential influence factors
	9	Develop $Y=f(X)$ function
Design	10	Determine optimum design
	11	Prototyping / concept
	12	Design validation plan
Verify	13	Design validation
	14	Close out project

Table 11 – 14 steps DMADV roadmap

“Quality is everyone's responsibility.”

— W. Edwards Deming —

4 CIMM level I – Creating a solid foundation (Structured)

Before organizations can really work on process improvement programs like Lean and Six Sigma, it is required that a proper foundation is put in place. The first level of any Continuous Improvement scenario starts with the objectives of a professional and safe work environment, standardized work and a solid quality management system. These three elements will guarantee a stable foundation for further improvement initiatives.

In this chapter we will review how to implement these three elements. We start by creating a professional, organized and safe working environment using the 5S method. Then we discuss the importance of standardized work. There is no possibility to improve if there are no standards. We briefly discuss 'Training Within Industry' (TWI), a method to realize standardized work. Finally, we discuss the three elements of quality management (quality planning, quality control and quality assurance).

4.1 Professional Work Environment

The workspace is the mirror of the organization. If the surroundings are not organized, it reflects poorly on the organization and represents the way it regards its customers and its products or services. A tidy workspace leads to quality and is therefore the starting point for every improvement. This section is about good housekeeping and how to set up a proper and safe work environment in a structured manner

4.1.1 Organized Work Environment (5S)

Good housekeeping is about creating an organized and safe work environment, also called '5S'. Employees are made familiar with the methodology and companies are assisted in the actual realization of a more structured workspace. As mentioned earlier: the workspace is the mirror of the organization and is the starting point for every improvement initiative. All employees directly or indirectly involved in the improvement project on the work floor should be involved in this process. The 5S technique itself is not very complicated, but because all employees will be involved and it requires a change in behavior, it will take quite some effort to implement 5S properly.

The 5S technique exposes Waste and prevents it from reoccurring in the future. It supports the communication process of operational standards of the organization to all employees. It will result in improved workplace efficiency, a professional representation to clients and a safer and more pleasant work environment. The process of implementing good housekeeping consists of 5 consecutive steps:

Japanese	English	Description
S1: Seiri	Sort	Only necessary items are at the workplace
S2: Seiton	Straighten	Everything has a fixed place
S3: Seiso	Shine	Everything is constantly kept clean
S4: Seiketsu	Standardize	Procedures and standards are visible
S5: Shitsuke	Sustain	Procedures are followed with discipline

Table 12 – 5S steps

Figure 66 – Organized work environment 5S

S1 – Sort (Seiri):
The goal of the sorting step is to distinguish between what is necessary and what is superfluous. What is necessary, what can we get rid of? In this first step you make sure that only items that you regularly need are present at the work location. Items that are superfluous get in the way of the real work and potentially make the workplace unsafe. These items should be thrown away or removed to other areas.

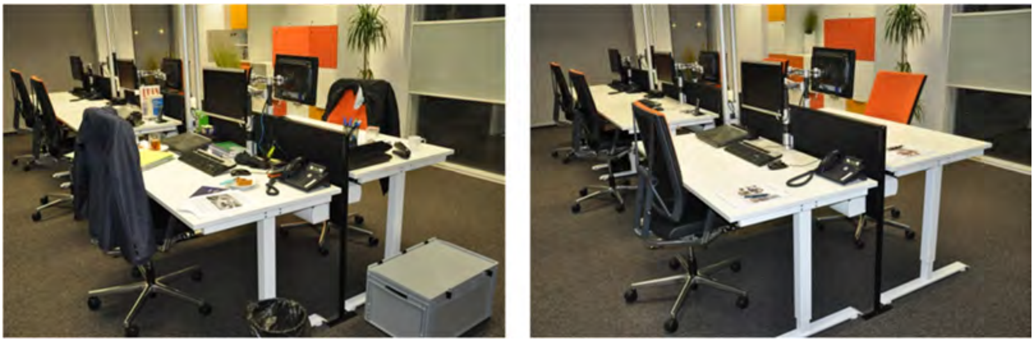


Figure 67 – 5S example office environment (before and after)

The 'Red tag procedure' can be used to support this process. A Red tag will be attached to items that are identified to be superfluous and to items for which it is not clear what to do with them. Anyone can change the description on the tag. After a few days, when each person has had the chance to modify the remarks on the red tag, the decision can be made to throw away or to remove the item to a designated location. After this first cleaning action, the remaining items and tools should be cleaned. Also broken lighting, furniture and equipment should be repaired. In service environments this step will focus on emptying the desk by throwing away documents and by cleaning out archives and cabinets. Secondly, we can focus on deleting unnecessary data on computers and servers.

Figure 68 – 5S Red tag cards

The Sort step is an important step and it certainly will make a significant difference. However, some might think that after this first cleaning action 5S is completed and implemented, but it is just the beginning.

S2 – Straighten (Seiton):
After the cleaning out process in the first step, we will continue with the second step called 'Straighten'. The objective of this step is to identify a permanent location for each item. The work location should be organized in a way that everyone can find everything needed quickly and easily. Items that belong together, such as pencils, documents and tooling, should be combined and grouped. Items should be placed in the correct order (e.g. next to each other) to improve the flow of the process and to reduce errors.

"A place for everything and everything in its place."

Benjamin Franklin

It should be clear for everyone where to find an item and where to put it back in place after use. Especially important is that everything has a defined place and the most frequently used items are at hand. Locations of items should be visualized by means of outlining /marking. Visualization can be used such as lines, markers, signs, arrows, color codes etc. Labels are often used to explain the system at a glance. A shadow board is often used in manufacturing and operation rooms. This makes it visually obvious when items are missing.

Figure 69 – 5S example organized workplace

Also, in this step we will arrange items based on the frequency of use. Items that are needed several times a day should be closer to the work location than items that are only used once a week. Items that are used even less frequently should be stored in a closet, separate department or warehouse.

Frequency	Where to keep	Maximum distance
Continuously	On the body	Max. 50 cm
Every hour	At the workplace	Max. 1 meter
Every day	Close to the workplace	Max. 5 meter
Every week	At the department	Max. 10 meter
Every month	Central warehouse	Max. 250 meter
Every year	Regional warehouse	-
Less than once a year	Do you need it?	-

Table 13 – 5S where to keep items

S3 – Shine (Seiso):
This Shine step means that everything is in its place. The objective of this step is not to make everything clean, but to keep everything clean and orderly. Keeping a computer clean is not a physical thing necessarily, but involves keeping the directories organized and free of unnecessary or 'dirty' files.

The cleaning of the workplace should become routine. This means that it is necessary to define what should be cleaned, in what way it should be cleaned, when it should be cleaned and by whom it should be cleaned. Cleaning is a task for everyone, not just for the cleaning department. Why is this important? In a clean environment problems or faults become visible faster. By keeping the workplace clean you see deviations and you can prevent errors and mistakes. A clean environment also results in a safer work environment. Cleaning actually also means 'make it shine'. A shiny floor or a fresh painted wall will improve the working atmosphere and a person's mood. You probably recognize that you are more careful if you wear white clothes. White is very prone to dirt and that's exactly the point. Any contamination should be cleaned immediately. Every source of contamination will become visible and should be removed. A workspace should look like an operating room. Everyone knows that inside an operating room the people keep the workplace pristine.

"Take 5 minutes at the end of each day for cleaning and organizing."

In the Shine step, the illumination of the working area, noise and ergonomics should also be given attention. Flickering lights, working in an environment with insufficient illumination or working in a very noisy environment can result in overlooking items, stress and fatigue. Broken chairs, bad computer screens and or bad ergonomics can cause health complaints or even sickness.

Figure 70 – 5S ergonomics & safety

S4 – Standardize (Seiketsu):
The Standardize step addresses the question: *'How do we ensure constancy?'* Standardization and guidelines for 5S is of great importance. In this step we will determine the rules and standards. This involves standards for cleaning and defining responsibilities.

After the first round of cleaning in step one, it is good to consider what you would do in the future and what should be in the cleaning program. Keeping a workplace clean only takes a few minutes a day. For example, introducing a routine to clean up every last 5 minutes of a working day or shift.

To improve safety, fire extinguishers, first aid kits and exits should be marked clearly. Also, standards should be defined for operator clothing like wearing safety glasses, hand gloves, sound protection and protective footwear.

Figure 71 – Example Standardized industry environment (before and after)

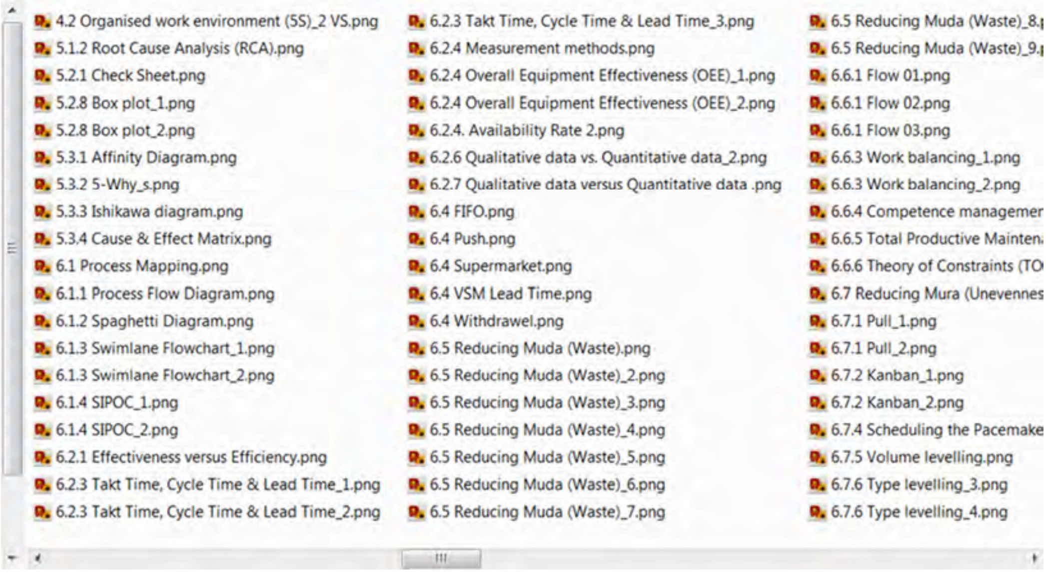


Figure 72 – Example Standardized transactional environment (file naming structure)

S5 – Sustain (Shitsuke):
The final step is about sustaining all previous steps and actions. Without this step everything will revert to the original situation within a short space of time – untidy and potentially unsafe. Measures should be taken to guarantee that the new behaviors are maintained.

Everyone is required to follow the agreed disciplines and procedures. Obviously, management should lead by example. All employees have the obligation to indicate to others if the agreed procedures are not being followed.

Using an audit checklist ensures that objective monitoring can take place regularly and that results are measurable with a point score. Audit results and targets should be reported and published. The 5S score for a department is often represented by a spider diagram on the visual management board.

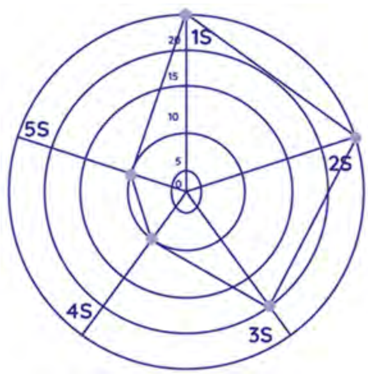


Figure 73 – 5S audit spider diagram

4.2 Standardized Work

Taiichi Ohno, the father of the Toyota Production System, once said, "Without standards there can be no improvement." Also, people like Deming, Juran and Imai made similar statements. If you think about the Continuous Improvement cycle, it makes a lot of sense. How can you move from a certain current situation to a better situation if the current state is a moving target? Standard work documents the current best practice for performing a task or process and ensures that everyone is applying the same way of operating a certain task. As such it creates a stable and predictable outcome. Therefore, it is a prerequisite for improvement.

4.2.1 Standard Operating Procedure

Standardized work is paramount for organizations that want to eliminate waste, improve efficiency, maintain quality, and practice continuous improvement. The difficulty about standardized work is the cultural behavior in an organization and the discipline that people work according the standards. It is therefore important people really understand the principles of standardized work and how it benefits a good work environment for everybody.

The Japanese method of Continuous Improvement is pretty straightforward. A Japanese auditor will ask you: 'Has a standard for this process been defined?' If the answer is no, the auditor will tell you that a standard need to be defined. If the answer is yes, the next question will be: 'Are you working according the standard?' and 'What is your plan to improve the standard?'

1. If we have no standards, we need to develop them.
2. If we have standards, we should work according to the standards.
3. If we work according to the standards, we should continuously try to improve the standards.

Don't confuse standardized work with rigidity or slowness. Standardized work allows organizations to scale rapidly. One-off processes and individual judgment are difficult to scale. Standardized work makes it possible to get the same results with one person once, or 100 people, thousands of times. It also makes improvements easier and faster. It's hard to improve a process that is not well understood or consistently applied. Once standardized work is in place, opportunities for improvement become apparent, and there is an easy way to implement them.

Standardized work also encourages flexibility and creativity. While it may seem counterintuitive, standardized work promotes innovation. That's because the standard is only the best practice for today. Creative ideas for improvement are always welcome, and the standard changes whenever a successful PDCA proves that there is a better way. Following this philosophy, it is important that standards defined in the quality management system are not just listed in a dusty book that is only brought out for audits. They should be visible and attainable for everybody in the organization. Standardized Work is applicable everywhere and necessary to create a solid foundation.

"Without a standard there is no logical
basis for making a decision or taking action."

Joseph Juran

When using standardized work, we define who is trained and permitted to operate the process and how many people it takes to operate the process. Standardized work also documents what is needed to start the process. For each operation step a 'Standard Operating Procedure' (SOP) is composed. In some organizations this is called 'Standardized work Instructions' (SWI) or 'Protocol'. The SOP is more than a work instruction document. The SOP is created by the employees by agreeing on the best way to operate the process. They should all agree, by applying consensus if needed, on the best way. Then this will become the standard and all will follow accordingly. Managers should generally defer to employees when determining the content of the SOP, as employees are usually more knowledgeable about the process than anyone else. They are also the ones who have to commit to the standardized work.

The SOP describes what items or tools are required and the sequence of the process activities. The SOP also clearly describes what the final product should look like and what quality checks need to be performed on the product. This will prevent the need for each employee to determine by himself what quality criteria the product or service should meet. The SOP procedure mentions the Cycle Time for the process step, which means that it is defined how long the employee is expected to work at their operation step before the product should be passed on to the next operation step. Standardized work also includes how much raw materials or components should be on hand at the operational step and how often component levels must be replenished. It also includes how often products are retrieved from the work cell and how they should be packed or stored. For service organizations Standardized Work includes how information should be documented and archived at the server. It also includes what standard documents, templates and revision numbers should be used.

The SOP documents the best practices to the current moment, but it can always be questioned and employees should always look for further improvement opportunities. Lean and Kaizen encourage the questioning of standardized work and looking for improvements. If an employee thinks he has found a better way, he should discuss this with his colleagues in order to update the current standard if his proposal should become the new standard. Standardized work does not have to be in conflict with flexibility or customization. On the contrary, a good example is the design of a new hospital. Each patient room was designed and shaped exactly the same, to use it for all types of treatment and care, in order to increase the flexibility of the room. The room was designed in collaboration with experts from different departments to assure all special requirements were incorporated in the final design.

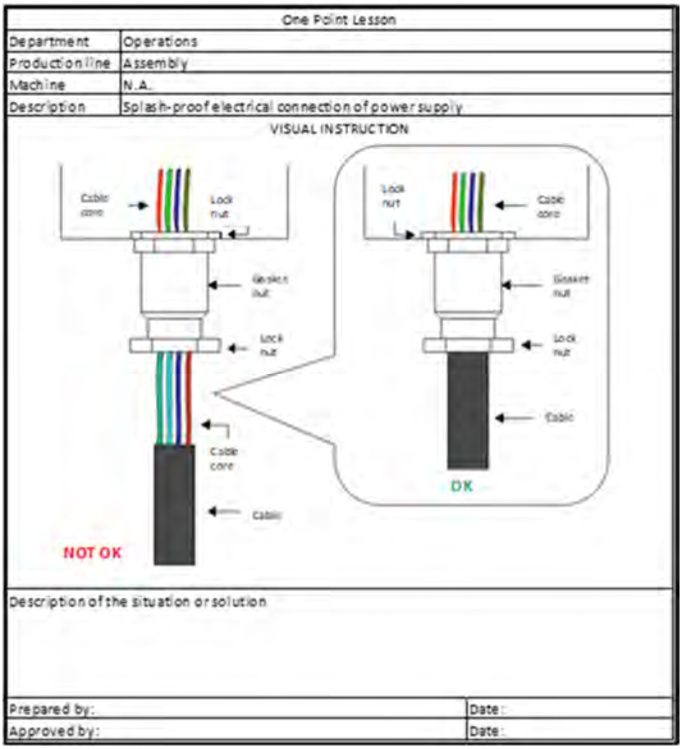
Figure 74 – Example visual work instruction AED

One Point Lesson

SOP documents may be supplemented by One Point Lessons / Single Point Lessons. A ‘One Point Lesson’ (OPL) or ‘Single Point Lesson’ (SPL) is a structured teaching tool at the Gemba, explaining a single topic on one single (plasticized) sheet. OPLs originated from ‘Total Productive Maintenance’ (TPM) as a method to teach, instruct and warn operators. OPLs are an effective training tool. It is important that the OPL is written as simply as possible. Pictures, drawings and diagrams are preferred above texts. OPLs can support and simplify instructions and procedures but it is not the intention they replace work instructions or SOPs.

OPLs are used:

- to warn about a dangerous situation;
- to explain the setup or maintenance of equipment;
- to describe the approach and measurement of an improvement initiative;
- to assure that everyone knows about a better way of doing something.


One Point Lesson

Department	Operations
Production line	Assembly
Machine	N.A.
Description	Splash-proof electrical connection of power supply

VISUAL INSTRUCTION

Description of the situation or solution

Prepared by:	Date:
Approved by:	Date:

Figure 75 – Example One Point Lesson

4.2.2 Training Within Industry (TWI)

A practical approach to create and maintain standardized work is 'Training Within Industry' (TWI). Contrary to what the name of this method suggests, this method is also widely used outside the industry. TWI has a long history of success in both industrial, transactional and healthcare environments and is an essential element of Lean and continuous improvement programs. This method is about hands-on learning and practice, teaching essential skills for supervisors, team leaders, and anyone who directs the work of others. TWI originated during WWII, when many workers went to the front and those who stayed at home (usually the women) started making weapons and ammunition and short and effective training became necessary. The program was later adopted and further developed by Toyota. TWI generates cooperation and positive employment relationships; it teaches team leaders how to train employees quickly and properly and it is used to solve problems quickly and efficiently. TWI consists of the following three pillars: Job Relations (JR), Job Instruction (JI) and Job Method (JM). The second pillar is used the most. We will therefore explain this pilar in a bit more detail than the other two.

1 – Job Relations (JR):
Job Relations teaches us the foundation of positive employment relations. Developing and maintaining these relationships prevents problems from arising and is critical in earning loyalty and cooperation from others.

2 – Job Instruction (JI):
Job Instruction is designed to develop fundamental process stability by implementing 'Standardized Work'. This program teaches the method of teaching employees how to do their jobs correctly, safely and accurately. As is often the case, most processes are performed by different employees using different methods. Job Instruction requires that the 'One best way' be identified and the process adapted to this one best way. This way is described in a Job breakdown sheet, which the team leader uses during the instruction. The basis of stability is created because all employees do the same and in the same way. The core of Job Instruction is to break the training down into small pieces and to demonstrate and repeat until the task is mastered.

3 – Job Methods (JM):
Job Methods develops individuals who are able to divide their job into the parts of which they are composed. Every detail is systematically questioned to generate ideas for improvement. The improved standard is being developed by identifying and eliminating waste. Tasks can also be combined and tasks can be simplified. This pillar from the original TWI program has been replaced by Toyota by Standardized Work in combination with Kaizen.

TWI has developed a card that can be used by the supervisor or team leader to prepare the instruction and then to provide the instruction. The next figure shows a photo of the original flashcard developed during WWII.

HOW TO GET READY TO INSTRUCT

Have a Time Table—
how much skill you expect him to have, by what date.

Break Down the Job—
list important steps.
pick out the key points. (Safety is always a key point.)

Have Everything Ready—
the right equipment, materials, and supplies.

Have the Workplace Properly Arranged—
just as the worker will be expected to keep it.

Job Instruction Training

TRAINING WITHIN INDUSTRY
Bureau of Training
War Manpower Commission

KEEP THIS CARD HANDY
GPO 16—35140-1

Front of the Job Instruction Card

HOW TO INSTRUCT

Step 1—Prepare the Worker
Put him at ease.
State the job and find out what he already knows about it.
Get him interested in learning job.
Place in correct position.

Step 2—Present the Operation
Tell, show, and illustrate one IMPORTANT STEP at a time.
Stress each KEY POINT.
Instruct clearly, completely, and patiently, but no more than he can master.

Step 3—Try Out Performance
Have him do the job—correct errors.
Have him explain each KEY POINT to you as he does the job again.
Make sure he understands.
Continue until YOU know HE knows.

Step 4—Follow Up
Put him on his own. Designate to whom he goes for help.
Check frequently. Encourage questions.
Taper off extra coaching and close follow-up.
16—35140-1

If Worker Hasn't Learned, the Instructor Hasn't Taught

Back of the Job Instruction Card

Figure 76 – TWI Job Instruction card

A more modern version of this flashcard includes the following steps:

Prepare Instruction:

1. Create a training plan:
    a. Which skills must be mastered, at what time?
2. Split the task:
    a. Determine main steps.
    b. Determine key points, including safety.
    c. Determine reasons for key points.
3. Get everything ready:
    a. Correct equipment, materials and supplies.
4. Organize the workplace:
    a. In such a way that you also want the employee to maintain it.
    b. Is safety guaranteed?

Provide instruction:

1. Prepare the employee:
    a. Reassure the employee.
    b. Name the task and check prior knowledge for this task.
    c. Grow interest in the task.
    d. Put the employee in the right position.
2. Demonstrate the task:
    a. Tell and show each major step.
    b. Repeat the task and explain each key point, again with the key point reason.
    c. Be clear, complete, and patient in trainable parts.
3. Let the task be executed:
    a. Let the employee try out the task; correct mistakes.
    b. Let the employee explain the main steps, key points and reasons.
    c. Repeat until the instructor knows the employee can do it.
4. Sustain:
    a. Assign the employee a task; grant help.
    b. Regularly check progress; encourage questions.
    c. Break down the coaching.

To set up, test and train a particular TWI task looks like this:

Phase	Step	Round 1 Concept version	Round 2 Check with workinstruction	Round 3 Check with experienced employee	Round 4 Check with unexperienced employee
Prepare instruction	1. Create a training plan				X
	2. Split the task	X	X	X	X
	3. Get everything ready		X	X	X
	4. Organize the workplace		X	X	X
Provide instruction	1. Prepare the employee			X	X
	2. Demonstrate the task	X	X	X	X
	3. Let the task be executed	X	X	X	X
	4. Sustain			X	X

Table 14 – TWI training plan

4.3 Quality Management

It’s essential for organizations to effectively manage customer satisfaction by meeting the needs and expectations of its clients and applicable legal requirements. Each organization should be able to manage its business processes properly. The quality procedures should be made known to all employees and they should work according to the agreed procedures. The ‘Quality Management System’ (QMS) is a set of policies, processes and procedures required for planning and execution (production/development/ service) in the core business area of an organization, such as areas that can impact the organization's ability to meet customer requirements.

4.3.1 Quality Management System

To give interpretation to quality management most companies implemented a ‘Quality Management System’ (QMS). A Quality Management System is a collection of all kind of business processes focused on achieving the quality policy and quality objectives to meet customer and legal requirements. There are different standards for quality management systems, but ISO 9001 is one of the most widely used systems in the world today. Over one million organizations worldwide are independently ISO 9001 certified.

Quality management can be divided into the following three groups of activities:

- Quality Planning (QP):
  Focused on planning how to fulfill the quality policy and translating that into measurable objectives and requirements. A sequence of steps is laid down for realizing them within a certain time frame.
- Quality Control (QC):
  Focused on detection of mistakes. Inspections and approvals that are applied in the realization process to ensure only good products and services will be delivered to the next process step or the final customer.
- Quality Assurance (QA):
  Focused on prevention. Not only preventing defects in delivered products and services, but also preventing all kind of problems in the company’s processes by preparations and inline control measures.

Quality Planning
Quality Planning defines everything a company is going to do, to ensure the quality to the customer. Creating a Quality Management Plan is the first step in the quality management process. It is essential to provide the customer with confidence that his requirements will be met. Examples of Quality Planning are:

- Formulating the quality policy
- Identifying the customers’ requirements.
- Listing the deliverables to be produced.
- Setting quality targets for these deliverables.
- Defining quality standards for the deliverables.
- Communicating the above items to all employees.

Quality Control
Quality Control is product or service oriented and focuses on defect identification and detection. It is very often planned inspection, installed at the end of the line or process. Examples of Quality Control are:

- Final visual inspection for damage or scratches.
- Functional test on electronics.
- Testing software solutions.
- Management approval or signature on the final document.
- Applying Jidoka when problems occur [paragraph 6.9.1]

Quality Control activities are short term solutions to prevent the customer from defects. Although this is of course a very good initiative, all Quality Control measures mentioned above are classified as ''Non-Value Added' or 'Waste' in terms of Lean Six Sigma. This is because the measures are not adding any value to a product. They only prevent a bad product will be delivered to the customer. The measures result in rework or scrap. Therefore, Quality Control alone is not enough. Organizations should focus on prevention rather than detecting. This can be achieved by implementing Quality Assurance.

Quality Assurance
Quality Assurance is a way of preventing mistakes or defects in products and processes and ensuring Continuous Improvement. Quality Assurance is process oriented and focuses on defect prevention rather than defect identification. Quality assurance activities are to ensure that the process implemented to produce the product or service satisfy customer and legal requirements. It covers all activities from design, development, production, installation, servicing and documentation.

Two principles included in Quality Assurance are: 'Fit For Purpose', i.e. the product should be suitable for the intended purpose; and 'First Time Right' (FTR), i.e. mistakes and damage should be prevented, rather than repaired or inspected. Examples of Quality Assurance are:

- Applying Poka Yoke in product design.
- Composing a risk assessment before implementing a change.
- Validation and verification of software before release.
- Using formats.
- Execution of internal and external audits.

Whereas Quality Control is focused on inspection and blocking the release of defective products, Quality Assurance is focused on improving production and associated processes to avoid issues that led to the defects in the first place. However, Quality Assurance does not necessarily eliminate the need for Quality Control. Some product characteristics are so critical that inspection is still necessary just in case Quality Assurance fails.

Quality Ethics

Besides Quality Planning, Quality Control and Quality Assurance, that is important as well. This can be called 'Quality Ethics'. This is about taking the appropriate actions when you find a mistake. Read the article about General Motors on the next page about how it should not be done. Another bad example of Quality Ethics is the use of 'Emissions-rigging Software' by Volkswagen in 2015.

GM settles criminal case over ignition switches

Associated Press, Sep. 17, 2015 (Summary)

NEW YORK (AP) – General Motors agreed to pay $900 million to fend off criminal prosecution over the deadly ignition-switch scandal, striking a deal that brought criticism down on the Justice Department for not bringing charges against individual employees.

The switches, which can slip out of the "run" position and cut off the engine, have been linked to at least 169 deaths. Despite evidence that GM's legal and engineering staffs concealed the problem for nearly a decade, no employees were charged, though U.S. Attorney Preet Bharara said the investigation is still going on.

"They let the public down," Bharara said. "They didn't tell the truth in the best way that they should have — to the regulators, to the public — about this serious safety issue that risked life and limb."

In this case, court papers showed that GM engineers knew of the problem in 2004 and 2005 when other employees, the media and customers complained. But the engineers left it alone, rejecting a cheap and simple fix, court papers said. Even after the dangers became plain in 2012, GM did not correct its earlier assurance that the switch posed no safety concern. Instead, Bharara wrote, it concealed the defect from regulators and the public "so that the company could buy time to package, present, explain and manage the issue."

Last year, GM recalled 2.6 million older small cars worldwide, including the Chevrolet Cobalt and Saturn Ion, to replace the faulty switches. Amid the scandal more than a year ago, GM fired 15 employees for failing to act to resolve the switch problem. Last year, GM set up a fund to compensate victims. Lawyers administering it accepted 124 death claims and 275 injury claims. GM has set aside $625 million to compensate people who settled with the fund. The twin agreements bring to more than $5.3 billion the amount GM has spent on a problem authorities say could have been handled for less than a dollar per car.

Even with the settlements, GM cannot close the books on the scandal. It still faces more than 400 death and injury cases that have yet to be settled.

The deal with GM comes a year and a half after Toyota agreed to a $1.2 billion penalty from the Justice Department for withholding information about deadly unintended acceleration in its vehicles.

Evaluation and Audits

An effective way to guarantee quality in the organization is by conducting inspections and audits. This can be internal audits carried out by our own employees or external audits by certified bodies or by auditors of customers. In many sectors, such as in the automotive, aviation, healthcare and food sectors, conducting audits by external parties is very common. In some other sectors it hardly occurs, if at all. It is customary an auditor from a certifying body comes in once a year, but it is not customary customers come in to perform audits.

An external audit can be performed on a specific product or process. This is called a product audit and is performed, for example, when a company wants to release a new product for getting into production. An audit can also be performed on the entire organization and all underlying processes. This is the case, for example, if a certification body carries out an ISO9001 audit. An audit by an independent party is required in many sectors to obtain a recognized certificate. In both cases, these audits can take several days. During the audit, the inspector or auditor can request anything and, in principle, access must be granted to all systems and all information that has any influence on the quality, should be delivered.

An internal audit is usually carried out by the quality manager or an employee of the quality department. However, it can also be done by any other employee of the organization. During an internal audit, it is mainly checked whether the agreed procedures, work instructions and protocols are followed. Sometimes a specific audit is performed on a work instruction (SOP) or on the 5S status of a department.

In both internal and external audits, the intention is to offer the organization opportunities for improvement, which will enable it to develop further. It is therefore not the intention to get things right just before an audit and to warn everyone and to instruct them what they can or cannot say. However, this does occur. Too often an audit is seen as a test that must be passed and once the test has been passed, we can continue working in the old way. This is a missed opportunity to improve the organization.

CIMM assessment level I – Creating a solid foundation

Level I focuses on creating a solid foundation. Is your foundation solid enough to deploy the next level? Perform the assessment below by scoring each statement with a rating of 1 to 5. A score of '1' means that the statement does not reflect the situation within your organization; a score of '5' means that the statement fully reflects the situation within your organization.

As there are 15 statements, the maximum score is 75. If you score less than 50 points, we recommend not to start the deployment of the next level, but to continue to deploy the current level first.

Process level I – Creating a solid foundation (Structured)
1.1 – Professional work environment
All items and data of the organization are identified as being needed or unneeded.
Unneeded items and data are removed from the workplace.
Every item has a fixed location at the workplace.
Every item is back in its place at the end of the day (or shift).
There is an (audit) system in place to sustain and improve the organized work environment.
1.2 – Standardized work
Standard Operating Procedures are available, up-to-date and clearly composed.
All employees work according to the Standard Operating Procedures.
A process is in place to continuously improve and simplify Standard Operating Procedures.
Operating and inspection procedures are easily accessible and up dated when needed.
There is a program in place to train employees in standardized work.
1.3 – Quality management
Required and necessary quality certifications are in place.
Quality assurance documentation and procedures are regularly assessed.
A system is in place to ensure that only items that fulfill customer requirements are delivered.
Quality assurance documentation is updated by the process owner.
All employees understand the importance of safety and quality.

Each person in the organization has a certain role and responsibility at creating a solid foundation. The assessment distinguishes responsibilities and behaviors for top management, middle management and people working at the shop floor. There are again 15 statements with a maximum score of 75.

People level I – Creating a solid foundation (Awareness)
1.1 – Professional work environment
Top management stimulates and facilitates the conditions for a good work environment.
Management ensures a good work environment and that required resources are available.
Management creates conditions for employees to develop themselves continuously.
Employees actively contribute to the development of a professional work environment.
Employees keep themselves and colleagues to the agreements made about the work environment.
Top management endorse the importance of standardized work.
Management ensures that employees have sufficient knowledge of standardized work.
Management challenges employees to develop and improve standardized work.
Employees develop and improve standardized work.
Employees are critical in the absence of, or non-compliance with standardized work.
1.3 – Quality management
Top management ensures that quality is managed correctly.
Management actively ensures that the quality requirements are met.
Management translates customer requirements into an operational process.
Employees contribute to the collection of information about quality.
Employees understand customer requirements and act accordingly.

“The starting point for improvement is to recognize the need.”

— Masaaki Imai —

5 CIMM level II – Creating a Continuous Improvement environment (Managed)

The second level is about creating a culture of proactive problem solving and Continuous Improvement activities. At this level we adhere to the Kaizen philosophy of Masaaki Imai. This is about creating a bottom-up approach with the objective that many small improvements will be executed by employees at the 'Gemba'. The idea behind this is that by realizing a large number of small improvements, a major improvement is actually achieved.

Imai consciously advocates the bottom-up approach instead of the top-down approach to mobilize as many people as possible in the improvement process. We have already discussed the reversed organizational pyramid in paragraph [1.1.2], which is an important element in ' Creating a Continuous Improvement Culture'. In this way, managers, Green Belts and Black Belts will have time available to focus on the larger breakthrough projects.

A Continuous Improvement culture can be facilitated by organizing daily short stand-up meetings in which the progress of the operational process is reviewed and problems are identified that stand in the way of achieving the objectives for that day. Actions are then taken on these. The roadmap that is commonly used for Kaizen projects is the PDCA circle, which stands for Plan – Do – Check – Act.

In this chapter we will discuss how to facilitate stand-up meetings. We also discuss a number of basic quality techniques and brainstorming techniques that can be useful when carrying out Kaizen projects.

5.1 Visual management

A primary cause of mistakes and Waste is missing information or miscommunication. Employees simply lack the information they need, or communication between two persons is not clear. Employees may not fully understand priorities, deadlines or the proper way to perform tasks. This results in loss of time due to additional motion, searching, asking, waiting, retrieving, reworking and mistakes. An important building block of Lean is to organize the work environment in such a way that it becomes 'self-explanatory'. This is called visual workplace.

5.1.1 Visual work environment

The 'Visual work environment', or 'Visual workplace', is also known as 'Visual Factory', 'Visual Thinking' or 'Visual Management'. They all mean the same thing: making everything visible. Visualization helps organizations to reduce Waste and to sustain improvements. This is achieved by improving communication, by reducing complexity and by making deviations to the standard visible. Visualization is one of the most important building blocks in Lean environments. Visualization of data, by applying graphs, is also an important element within Six Sigma.

The purpose of creating a visual work environment is that everything is self-explanatory. It is intended that information about progress, priorities and standards is clear at a glance. This prevents ambiguity about the way of working and the status of the work. Lean also promotes an open communication. No problems are swept under the rug, even not for suppliers and customers visiting the shop floor. Everything is open and visible. This is something many organizations have to get used to when transforming themselves to a Lean organization.

Figure 77 – Visual work environment

Real-time information, clear work instructions, objectives, visual aids, warning signals, and other important information help employees to inform them what to do, when and how. The visual work environment plays an important role in the bottom-up approach by giving employees on the shop floor their own responsibility in managing their work. Because things are self-explanatory, supervisors and managers are not required for every action or decision. This is a critical step in any Kaizen or Lean transformation process. Some examples of visual workplace are listed below. Several examples are given in this book and many inspiring examples with pictures can be found on the internet.

- 5S programs and use of 5S red tags [paragraph 4.1.1]..
- White walls, white floors, white machines, white lab coats, etc.
- Color coding and labeling of tools.
- Standardized furniture and trays.
- Plasticized work instructions.
- Demarcation of cells or departments.
- Markings on the floor for machines, parts and walkways.
- Markings and labeling of work in process.
- Kanban racks and Kanban cards [see paragraph 6.7.1].
- Shadow boards for tooling [see paragraph 6.7.3].
- Clear communication boards.
- Photos of employees on the communication board.
- Andon lights (traffic lights) to visualize the working status of equipment [see paragraph 6.9.1].
- Use of Poka Yoke [see paragraph 6.9.1].

Within Lean organizations floor marking is a necessary element to create a visual work environment and a safe work environment. Because the idea is to create a self-explaining environment, it is necessary to define certain standards of floor marking and bins that is used. In Table 15 guidelines can be found for the colors to use.

Yellow	Aisles, walk-ways, traffic lanes, work cells
Orange	Temporary storage, materials for inspection
Red	On-hold location, defects, scrap, prohibited
Green	Materials, finished goods
Blue	Raw materials, components
Black	Work in progress
Black/Yellow	Warning, potential health risk
Black/White	Area to keep for operations (not safety related)
Red/White	Area to keep clear for safety (i.e. emergency exits)

Table 15 – Floor marking standard

5.2 Performance management

Regardless of the type of organization, it is important to have insight into whether the performance promised to the customer is actually being realized. And if something does not go as intended, action will have to be taken to achieve the correct result. This entire process of steering and accounting for results is referred to as performance management.

This can be achieved by agreeing on expectations at every level in the organization. This is expressed in measurable quantities (KPIs). For operational processes, you can think of logistical performance measures such as quantities, delivery times and processing times, or qualitative performance measures such as yield and rework. In Sections 6.2.1 and 6.2.2 we will discuss a number of measures in detail.

Lean organizations visualize performance measures on whiteboards. These signs are prominent in any self-respecting Lean organization. At periodic moments, employees gather around the boards and the results are discussed. In the event that a particular performance measure does not meet the agreed target, or if this threatens to happen, appropriate actions will be taken.

5.2.1 Daily stand-up meetings

Performance management in the workplace is often referred to as 'Lean Daily Management'. It is an organized work form to discuss performance and to feed the improvement process. 'Lean Daily Management' consists of daily stand-up meetings that are often held at the beginning of a day or mid-day to communicate results and issues. The intention is to keep these meetings short and to the point. Normally a meeting lasts around 10 to 15 minutes and is performed standing on the Gemba. That is more efficient than sitting down in a meeting room with a cup of coffee. The location of the meeting is a fixed location on the shopfloor or department that has been specially set up for this purpose with visual management boards. The place must also be quiet enough to be able to understand each other. Some companies have therefore set up special places with soundproof walls, high tables and improvement boards.

The boards only show the KPIs that are relevant to the team and that the team can influence. If the team has no influence on a certain KPI, it makes little sense to dwell on it for long. Typical data presented on the boards concerns the quality and quantity results of the production line or department. Examples are the output, the amount of work in progress, the average processing time, on-time delivery, status of urgent orders, safety, the number of rejects, etc. Another example are Srum-meetings, where the team discusses the progress of Scrum-items and activities. These are called 'Daily Scrum'. It is not the intention that all KPIs and Scrum items are discussed during every standup meeting. It is determined in advance which matters are discussed daily, weekly, monthly or doing a Sprint.

Deviating performance and incidents must lead to corrective actions during the Lean Daily Management, to ensure that the objectives are still achieved. If certain problems recur more often, this is a reason to start an improvement project. These projects are displayed on a separate whiteboard and discussed at a lower frequency (weekly or biweekly). In addition to looking back, we usually also look ahead to the performance to be delivered for the day and to see whether all people and resources are sufficiently available to make the day a success or to take action. Organizations that operate fully on CIMM level II are recognizable because performance management is applied at all levels, not just on the shop floor. The shop floor is working on smaller improvement projects, often following the Kaizen PDCA approach. Middle management works on the more complicated improvement projects, often using a Six Sigma DMAIC approach. Top management works on the organizational capability of solving and preventing problems.

Figure 78 – Stand-up meeting in front of KPI board

Figure 79 – Stand-up meeting in front of Scrum board

A fixed schedule is followed during the stand-up meetings:

Looking back – Review performance of the previous interval:

- Did we achieve the required quantity?
- Did we face any quality problems?
- Did we complete the actions that were defined in the prior interval?
- Were actions effective or are additional actions required?

Looking forward – Discuss the targets of the next interval:

- What are the required quantity and objectives?
- Do we have the necessary resources?
- Who will need help to meet their objectives?
- What specific actions are needed?

Discipline is a very important element to guarantee successful stand-up meetings. People must arrive on time and the meeting should not wait for latecomers. Managers should lead by example; employees should come prepared and data should be accurate. Problems will not be solved during the meeting, but actions will be defined and assigned to people who will work to solve the problem. Results will be discussed during the next stand-up meeting. The meeting is not intended for extensive story telling or detailed reviewing activities. To keep meetings short and effective, each one should focus on facts and results rather than on guesses and excuses.

'Short Interval Management' (SIM) is a bit more sophisticated. The SIM process engages team members to assess whether they are still on track to meet the established targets for the day. The term 'Short Interval' indicates that during the day at specified intervals the team's actual performance is compared to the planned performance for that interval. This action means that the team performance is checked regularly against the plan and reduces the response time if the team is underperforming and corrective actions are needed. The frequency of updates depends on the type of work and on the situation, but is about 2 to 4 times a day for about 5 to 15 minutes. Employees gather at a fixed time, following a fixed schedule:

Green and Black Belts are expected to not only participate in Stand-up meetings, but to also implement and support Short Interval Management and to drive Continuous Improvement initiatives.

Obeya room
Organizations that have a few years of experience in continuous improvement have often set up a so-called Obeya area. This is a Japanese term that means 'Big area'. This area is compared to the bridge of a ship or to a 'War room'. An Obeya room can be a place on the shop floor, but can also be a separate enclosed space where the noise from the factory cannot be heard. The Obeya room is fully equipped for the operational and continuous improvement process. The walls contains visual representations of performance measures and improvement projects. An organization normally consists of multiple departments and multiple levels of complexity. This also applies to the improvement boards in the Obeya room. Here, each department or product group can have its own improvement board.

Figure 80 – Obeya room

The Obeya room is the place where teams meet for their standup meetings. It is the place where employees come together to discuss the status and performance of processes and where improvement projects are discussed. Usually in the middle of the room there are one or more high tables where people can stand. Regular office desks with chairs were deliberately not chosen, with the aim of keeping meetings short and efficient. An Obeya room is not a meeting room. The signs themselves also undergo a process of continuous improvement. As an organization has more experience with the improvement process, the boards will also be more professional and structured in design, with pre-printed surfaces, insert sleeves, magnets, colored smileys, etc.

If the Obeya room is used by multiple departments and product groups, it is also necessary that there is a tight schedule for the meetings, so that the groups do not get in each other's way. Everyone must be present on time and be ready on time. Improvement projects often also take place on several organizational levels. When a problem arises and a new improvement initiative is formulated, it is important that it is started on the correct improvement board.

Although most Obeya spaces consist of physical signs, post-its and magnets, the Industry 4.0 era also introduces new techniques. Figure 81 shows an example of a digital variant. Such a digital sign is ideal for displaying operational performance such as numbers and quality, and also to fill out forms that belong to the improvement project. The advantage of a digital performance board is that the information is available real-time and is therefore continuously up-to-date. It also saves a lot of time to retrieve data from systems, print it and hang it on the boards. During the COVID-19 pandemic and the lockdowns, it was difficult to organize physical standup meetings at the shopfloor. Most employees outside the actual production were forced to work from their home offices. Adopting digital aids, like the Active Cockpit, have the benefit that people can login remotely and participate from different locations.

Figure 81 – Digital performance cockpit (Rexroth Active Cockpit)

5.2.2 Kaizen events and problem solving

As discussed, an improvement project is started if a certain metric repeatedly deviates from the target during the daily stand-up meetings. These improvement projects are displayed on the improvement board. Simple improvement projects are tackled on the shop floor, often following the Kaizen or PDCA approach. The meaning of ‘Kai’ is change and the meaning of ‘Zen’ is meditation or contemplation. An explanation of the Japanese word Kaizen is: ‘Taking it apart and putting it back together in a better way.’ The object that has been taken apart is usually a system, a product or a process. Masaaki Imai has published a number of books on this method, including ‘Kaizen’ and ‘Gemba Kaizen’ [13.], meaning ‘Improvement from the shop floor’. Examples of Kaizen events are:

- Improving equipment set up and tooling change.
- Improving ergonomics and safety.
- Improving quality.
- Reduction of cost.
- Designing bins and racks for storage of raw components and finished goods.
- Designing forms, templates and inspection criteria.
- Waste identification and elimination.
- Problem-solving activities to prevent quality issues.

Kaizen events are coupled very often to Standardized Work. If an abnormality occurs, always ask yourself the following: ‘Was there no standard?’, ‘Was the standard followed?’, ‘Was the standard insufficient?’

The customer should always be the starting point of an improvement project. This not only concerns the external customer, but also the internal customer (e.g. colleagues and departments). Each step in the process has a customer who receives the outcome of its process step. At the same time each process step is a customer itself, as it receives products from the prior process step. Therefore, it is important that each process step is treated like a customer. Each process step should not accept errors from prior steps; it should not make errors and it should not forward errors to consecutive process steps. If everybody follows this principle, the quality of the entire process will be better and at the end of the process the customer will receive a good product or service.

A Kaizen event is about getting things done immediately, not about making weeks of analysis and then taking a few more weeks to implement the solution. The solution will not always be perfect after the first event, but a big improvement will be made. Later on, we can start another event and make another step.

“Better to be 80% right today
than 100% right in six months!”

Masaaki Imai

A typical Kaizen event is the Kaizen Blitz. It is the most well known and most effective way of achieving immediate and obvious gains within any environment (service or manufacturing). The Kaizen Blitz event takes from a few days up to a week and is led by a facilitator (e.g. Lean facilitator, supervisor or external consultant). The team focuses on one specific area. Typically, a Kaizen Blitz concentrates on the removal of the eight types of ‘Waste’. We will discuss these types in section [6.5]. The first Kaizen Blitz can be very much like an initial 5S implementation, looking at work cell design, layout and safety. The strength of any Kaizen approach is gaining the result within a short period of time.

Genchi Genbutsu

In the Toyota Production System 'Genchi Genbutsu' is one of the key principles. It is also explained as *"Go and See"*. It means that in order to truly understand a situation one needs to go to Gemba or Genba, as the Japanese call it. 'Gen' means actuality or reality. When we look at the word Gen-Ba, it means the actual place or the place where the work is done.

Taiichi Ohno, creator of the Toyota Production System, had a special way of teaching managers the power of Genchi Genbutsu. He drew a circle on the shop floor with a piece of chalk. The manager would be told to stand in the circle, observe and note what he saw. Several hours later, Ohno would return and ask the manager *"What did you see?"*. Usually Ohno had spotted an irregularity, and wanted the manager to see the same. So, if the manager's reply was something else than what Ohno had already seen, his response would be *"Watch some more"*. The chalk circle is therefore also called the 'Ohno Circle'.

Ohno's statement was that the only way to truly understand what happens on the shop floor was to go there and observe. He truly believed that value is created at the shop floor only, and also problems should be solved on the shop floor. Therefore, the shop floor is where managers should spend their time.

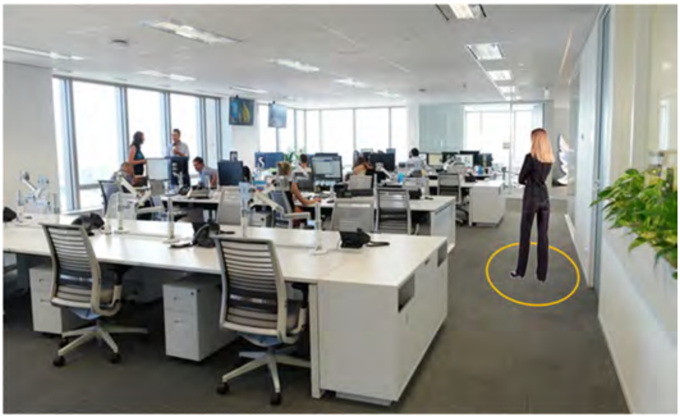


Figure 82 – Genchi Genbutsu (Ohno circle)

Problem solving

Problem solving or 'Root Cause Analysis' (RCA) is a method that tries to identify the root causes of faults or problems. RCA arose in the 1950s as a formal study following the introduction of Kepner-Tregoe Analysis. There are many different approaches for performing RCA though, containing different techniques such as 5-Whys, Is-Is Not and the Cause & Effect diagram. RCA is typically applied after an event has occurred as a reactive method of identifying and eliminating root causes. Using the correct terminology is necessary within RCA to prevent confusion.

Figure 83 – Symptom versus Root Cause

The following list of definitions will help to ensure clarity. A number of examples are listed in Table 16.

- Symptom: A characteristic or complaint belonging to a specific problem.
- Effect: A deviation of expectation (Problem) or unexpected effect with unknown cause(s).
- Failure: The way in which a component fails functionally, causing a problem.
- Cause: The contributing factors that led to the failure.
- Root Cause: The deepest underlying reason for the cause to originate.

Symptom	Effect	Failure mode	Cause	Root Cause
Poor readability document	Copier gives vague print	Not enough toner	Empty toner	No procedure to replace toner in time
Room is dark	No light in the room	Defect bulb	Broken tungsten wire	Tungsten wire worn out over time
Not able to drive car	Engine won't start	No battery	Empty battery	Battery not replaced during maintenance
High absenteeism	Sick employee	Overworked employee	High workload	No proper resource planning

Table 16 – Examples of Root Cause analysis

5.3 Basic Quality tools

Kaizen en Root Cause Analysis use a number of graphical tools and brainstorming tools. These tools are called the ‘Basic Quality tools’. They are called ‘Basic’ because they are suitable for people with little formal training in statistics and because they can be used to solve many quality issues. These tools and techniques stand in contrast to more advanced statistical methods and Six Sigma tools that will be discussed in sequel chapters.

5.3.1 Brainstorm techniques

In this paragraph, we will discuss a number of techniques that are very effective in solving problems. These techniques are used in brainstorming sessions. Thinking out-of-the-box is important to get as many ideas about the problem and the solution together. Causes or ideas do not necessarily have to be supported by data or facts. Brainstorming is a process for developing ideas. Verification will take place later. An important rule in the brainstorming process is that it is not allowed to criticize the ideas of others.

Brainstorm techniques are creative processes used by teams to produce lots of possible ideas (the trivial many) in response to a single question or statement prior to then prioritizing the most likely results (the vital few). Brainstorming can be used at many different stages in the process improvement project: to develop ideas for CTQs; to identify helpful measures; to record all the potential causes or to generate lots of possible solutions.

It is advisable to facilitate the brainstorming in two phases: an opening phase of silent individual brainstorming reduces the likelihood of a dominant or senior member of the team inadvertently leading the team down a single train of thought (group think); a summarizing stage that involves the whole team can then be used to share, capture and group the ideas and simultaneously encourage the synergetic process that produces innovative spin off ideas. ‘Multivoting’ can be used when multiple people are involved in the decision-making process. It helps whittle down a large list of options to one decision.

Four common brainstorm techniques are:

1. Affinity diagram
2. 5-Whys method
3. Ishikawa diagram
4. Cause & Effect matrix

1 – Affinity diagram

The Affinity diagram is a brainstorm tool used to organize causes or ideas. It is one of the Basic Management and Planning Tools. The 'Affinity diagram' technique, was devised by Kawakita in the 1960s.

The technique is often used within problem-solving projects to create an overview after a brainstorm session about possible root causes or improvement suggestions. This is done by clustering items that are similar or can be combined in a certain way. The best results will be achieved when the session is performed by a cross-functional team.

In a problem-solving session, the Affinity diagram follows these steps:

1. Each team member receives a bundle of post-Its.
2. Each team member writes suspected causes on post-Its.
3. The causes will be pasted on the wall.
4. Post-Its will be sorted into clusters when they are related or similar.
5. Common headlines will be defined for each cluster.

Sometimes headlines will be defined before the brainstorm session starts (step 5 will be put after step 1).

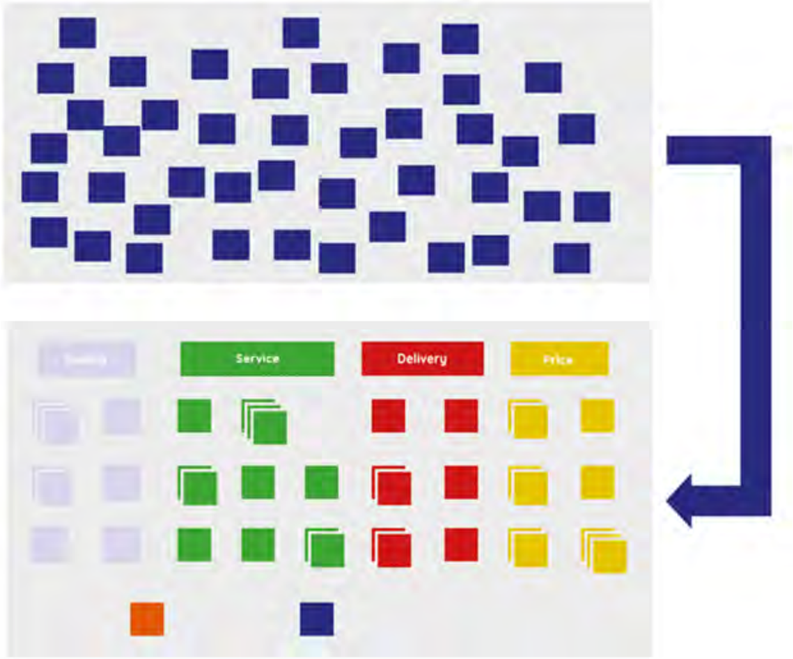


Figure 84 – Affinity diagram

2 – 5-Whys method

The 5-Whys is an iterative question-asking technique used to explore the Cause-and-Effect relationships underlying a particular problem. The primary goal of the technique is to determine the root cause of a defect or problem. The technique was originally developed by Sakichi Toyoda and incorporated in the Toyota Production System. Today the 5-Whys has seen widespread use beyond Toyota. It is used within Kaizen, 8D problem solving (step D4), Lean manufacturing and Six Sigma improvement programs. The 5-Whys has to answer three questions which are visualized in a 'Tree diagram' (Figure 85).

A. Why did the problem occur?
B. Why was the problem not detected earlier?
C. Why did the 'System' not function?

It is not strictly necessary to answer all three questions. For instance, there is no need to move on to B and C if the problem was caught by the operator due to the correct functioning of the Quality System! It is also not strictly necessary to ask exactly five times 'Why?' to each question. Each answer to the question 'Why?' needs to be relevant, controllable and significant. The root cause can be recognized when the answer is a process or policy or person. If the 5-Whys ends with a person then great care needs to be taken NOT to apportion blame. People do make mistakes but there are many ways to reduce how many mistakes a person might make. So the next line of questioning should be to find a solution that aids the person: Is new training needed? Can the mistake be prevented with Poka Yoke?

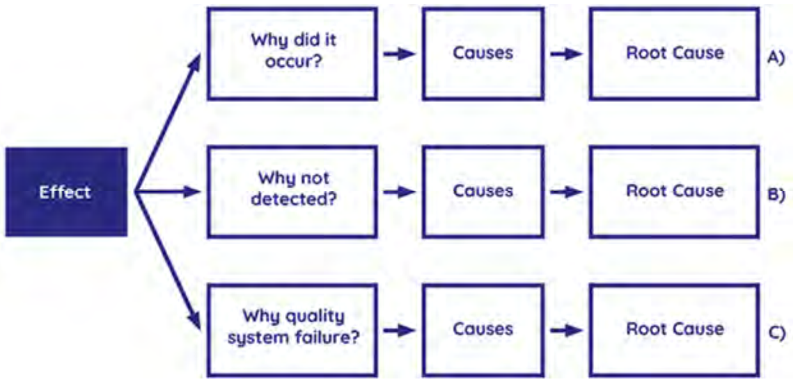


Figure 85 – 5-Whys Tree diagram

An example of a 5-Whys is given below:

1. Why did the machine stop during production?
   → The drive chain is broken.
2. Why is the drive chain broken?
   → The bearings have been broken.
3. Why are the bearings broken?
   → The bearings have run dry.
4. Why are the bearings run dry?
   → The lubricating oil pipe to the bearings is broken.
5. Why is the lubricating oil pipe broken?
   → A pallet truck has hit the lubricating oil pipe.
6. Why did the pallet truck hit the lubricating oil pipe?
   → The oil pipeline runs unprotected outside the machine.

Solution: Move the lubricating oil pipe or place a guardrail.

3 – Ishikawa diagram

The purpose of the Ishikawa diagram is to collect possible Causes for a certain Effect by conducting a brainstorm session. In most cases the Effect is a failure mode or problem statement. Kaoru Ishikawa (1968) created this type of graphical visualization. The Ishikawa diagram is also known as the Fishbone or Cause & Effect diagram. Fishbone refers to the graphical shape of the diagram, because it looks like a fish.

Causes can be derived by performing a brainstorming session with a group of people. The outcome of this brainstorm session is often enlightening but also depends very much on the people who participate in the session. To facilitate the thinking process of the attendees, six major groups of causes have been determined. These are called the 6 Ms. The group should focus on one M at a time to identify as many as possible potential causes within that group.

1. Machine: Technology or equipment related causes.
2. Method: Process related causes.
3. Material: Raw Material or information
4. Man: Causes related to people or employees.
5. Measurement: Causes related to measurement tools or inspection methods.
6. Mother Nature: Environmental causes.

In the first phase of the brainstorm session, as many potential causes as possible per major group will be collected. Of course, not all these potential causes will be the actual or significant cause of the effect. Therefore, a second round is needed to group causes and to highlight the causes that are highly suspected. At the end of this second round the result should be a limited number of potential causes that need further investigation.

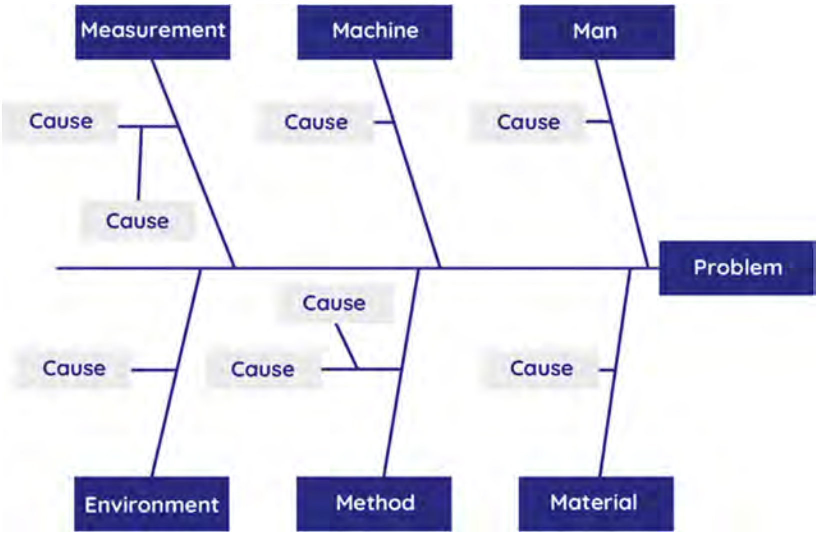


Figure 86 – Ishikawa diagram

4 – Cause & Effect matrix

When working on process improvement projects, making the right decisions can lead to success, while making the wrong decisions can result to failure. Therefore, it is important that thoughtful consideration is put into each decision that needs to be made. Visualization of data and brainstorm techniques, as reviewed in the previous paragraphs, support the decision-making process. The steps to be followed are about identifying the decision to be made, gathering relevant information, weighting evidence and finally choosing the best alternative.

The most commonly used technique is the 'Cause & Effect matrix' (C&E matrix) or 'Decision matrix'. It is a funnel tool that is used to focus on the most important factors of influence. It shows the strength and relationship between the factors of influence (Causes) and Responses (Results or Effects). It connects the process input variables to the process output variables.

- Step 1: Enter the output variables or effects (Key Process Output variables – KPOV).
- Step 2: Enter the specifications of the outputs or requirements (from the CTQ-Tree).
- Step 3: Indicate the importance of each output for the customer or for the organization (1 to 10).
- Step 4: Enter the factors of influence or causes (Key Process Input variables – KPIV).
- Step 5: Define the correlation between the Inputs and the Outputs.
- Step 6: Calculate the total score for each KPIV.

		Rating Customer Importance:	9	7	10	3	3	3	
			1	2	3	4	5		
Rating: 0 - no effect 1 - weak effect 3 - moderate effect 9 - strong effect		KPOV: Key Process Output Variables (Customer requirements)	Availibility	Pricing	Promise Date	Order confirm.	Order Number	1	Total
	Process Step	KPIV: Key Process Input Variables							
1	Answer Phone	Info from customer	3	3	3	1			81
2	Answer Phone	Greeting script	1	1	1	3			35
3	Internal Info	Cross ref for P/N	3	3	1	1			61
4	Internal Info	Corder Info	9	9	9	1	3		246
5	Internal Info	Pricing algorithm		9				5	63
6	Order Entry	Order worksheet	9	9	9		9		261
7	Order Confirm.	Printed confirmation sheet	1	1	3	3	3		64
8	Order Confirm.	Production schedule	1		3	1			42
9	Order Confirm.	Production contact info	9		9	9			198
10	Order Confirm.	Confirmation procedure			1	9	3		46
Total:			234	245	390	84	54		
		Low Spec							
		Target						2	
		Upper spec							

Figure 87 – Cause & Effect matrix

Remote Team Collaboration

During the COVID-19 pandemic, everyone was asked to work from their home office as much as possible. And if we were allowed to be present at the office, we had to keep a distance of 1.5 meters. This of course has a huge impact on the brainstorming techniques we described here. The strength of such sessions is that the team gathers together around a whiteboard or brown paper. The sticky notes that are put on the wall by one person, are supplemented by another and moved by a third person. This interactive collaboration is the power of brainstorming. During the COVID-19 pandemic this interactive way of working was no longer possible.

Fortunately, there are a number of digital solutions to work together remotely. We call this 'Remote Team Collaboration'. Figure 88 shows an example of Miro and Figure 89 shows an example of Mural.

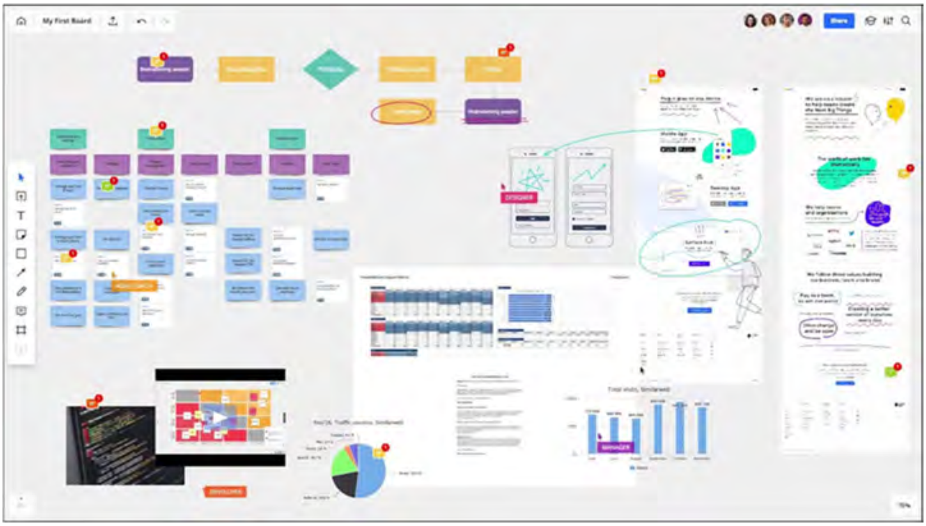


Figure 88 – Remote Team Collaboration (Miro)

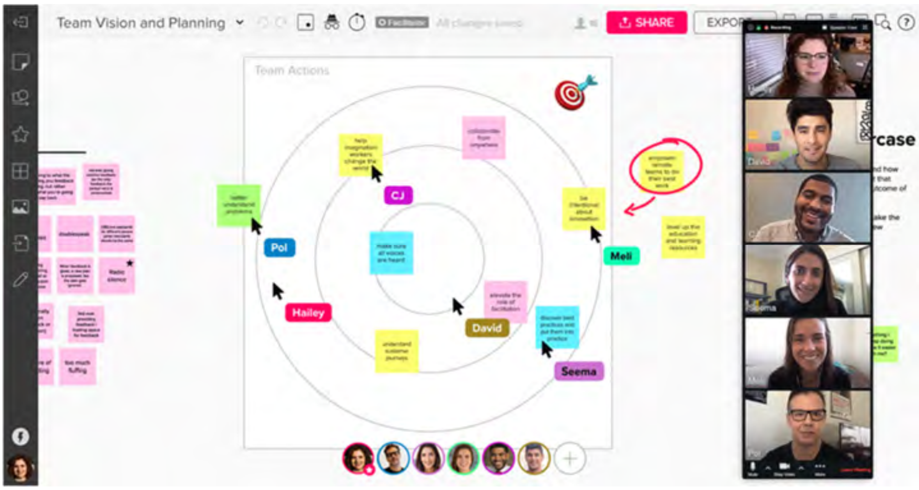


Figure 89 – Remote Team Collaboration (Mural)

5.3.2 Visualization of data

The human brain is unable to analyze a set of numbers. A spreadsheet full of numbers often doesn't tell us anything. When the same data is then converted into a graph, things suddenly become clear. Our brain is very capable of interpreting a visual image of the same dataset. One picture says more than a thousand words. In this way we can visualize trends over time, show the relationships between different situations and set priorities. Visualization includes the following elements:

- display the data visually over time;
- show many numbers in a single picture;
- visualize the current performance in relation to the target;
- distinguish main issues from side issues;
- prevent the data from being misinterpreted;
- make the relationship between multiple datasets visible;
- make the difference between two or more datasets visible;
- make different levels of detail visible;
- make statistical conclusions visible and interpretable.

Visualizing data makes it easier to formulate hypotheses about possible causes of problems. It therefore helps us to analyze data and determine the solution direction. Visualization also helps to communicate the statistical conclusion more easily to persons who do not have the knowledge of the statistical techniques. We will discuss several examples of this in this chapter and in Chapter 7.

In this paragraph we will review commonly used visualizations. Most of these tools are part of the so-called 'Basic Quality tools'. These tools can be very useful in Kaizen initiatives. Some of the graphical tools will be demonstrated using Minitab, a software program used for statistics. However, most of these tools can also be applied using Excel or even pen and paper. In the next paragraphs we will discuss the following Quality tools:

1. Scatter plot
2. Pareto chart
3. Bar chart
4. Pie chart
5. Time Series plot
6. Histogram
7. Box plot

1 – Scatter plot
(Minitab: Graph > Scatter Plot)

The Scatter plot is used to study the potential relationship between two continuous variables. This is done by drawing each variable on a different axis. Using the graph, we can see the relation between the water usage and electric charges of homes. As you can see there seems to be a relation that shows that families who use more water, also have higher charges for electricity. If the measurements on the graph were to look like a cloud of points, there is no relation. Scatter plots are also useful for plotting a variable over time. Unlike a Time Series plot, you must provide a time variable from the worksheet yourself. This is especially useful for data that are not entered in chronological order or were collected at irregular intervals.

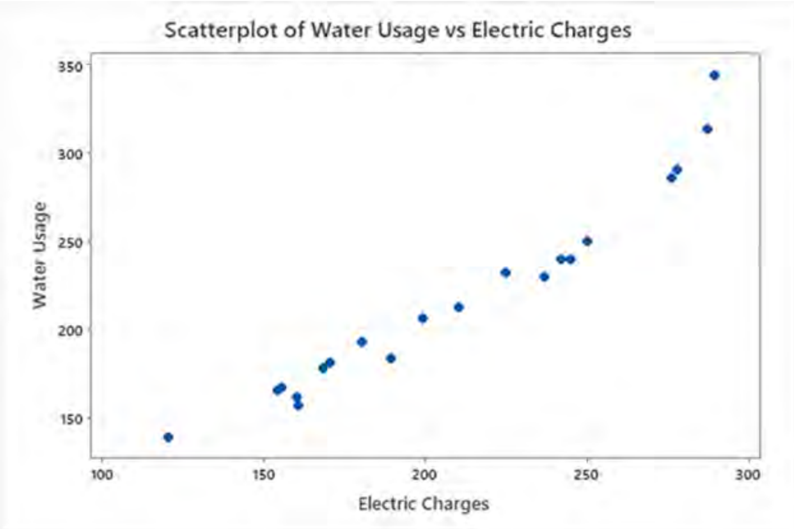


Figure 90 – Scatter plot

2 – Pareto chart
(Minitab: Stat > Quality tools > Pareto Chart)

The Pareto chart is a type of chart that contains both bars and a line graph. Individual values are represented by bars. The chart is named after Vilfredo Pareto. The purpose of the Pareto chart is to highlight the single most important factor among a (typically large) set of factors. In quality control, it often represents the most common sources of defects, the highest occurring type of defect, or the most frequent reasons for customers to complain and so on. The Pareto chart is the graphical representation of the well-known 80%-20% rule. Figure 91 demonstrates the number of COVID-19 infections per country.

The difference between a normal Bar chart and a Pareto chart is that the bars are presented in descending order. The left vertical axis is the frequency of occurrence, but it can alternatively represent cost or another important unit of measure. The second difference is that it shows a second vertical axis on the right. This axis is the cumulative percentage of the total number of occurrences or total of the particular unit of measure. This always counts up to 100%. Because the bars are in a decreasing height order, the cumulative function is a concave function.

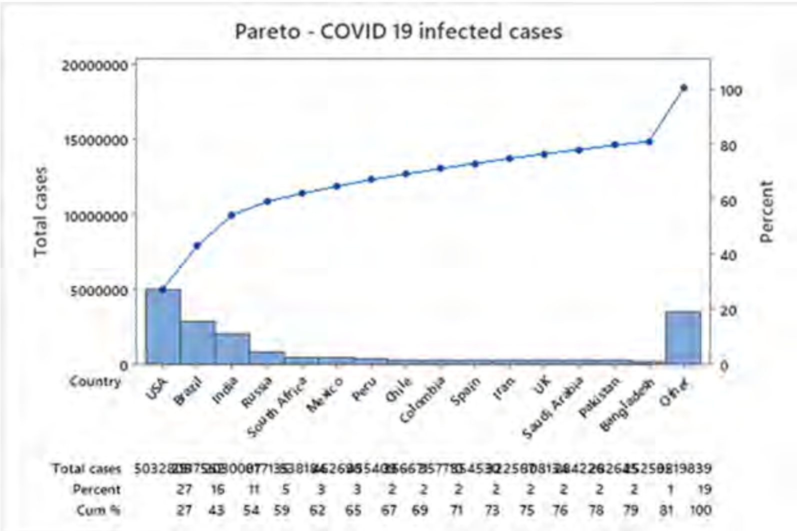


Figure 91 – Pareto chart – Number of COVID-19 infections per country (July, 2020)

3 – Bar chart
(Minitab: Graph > Bar Chart)

Bar charts are used to visually compare category measures like quantities or frequencies for two or more groups. There are several different variants of charts. Different types of Bar charts can be made with software like Excel or Minitab. A few possible variants of Bar charts are shown below:

Counts of unique values:
Use this Bar chart if you have one or more columns of categorical data and you want to chart the frequency of each category.

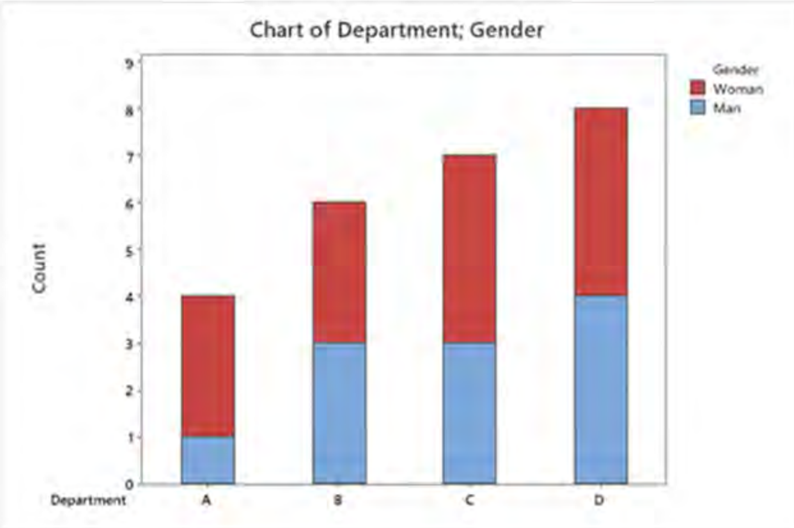


Figure 92 – Bar chart

A function of a variable:
Use this Bar chart if you have one or more columns of quantitative data and you want to chart a function of the measurement data, such as gender.

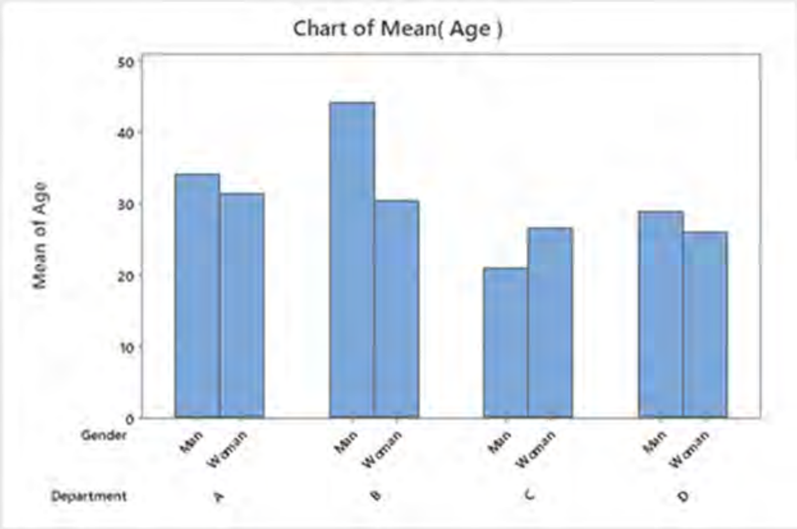


Figure 93 – Bar chart

Values from a table:
Use this Bar chart if you have one or more columns of summary data and you want to chart the summary value for each category.

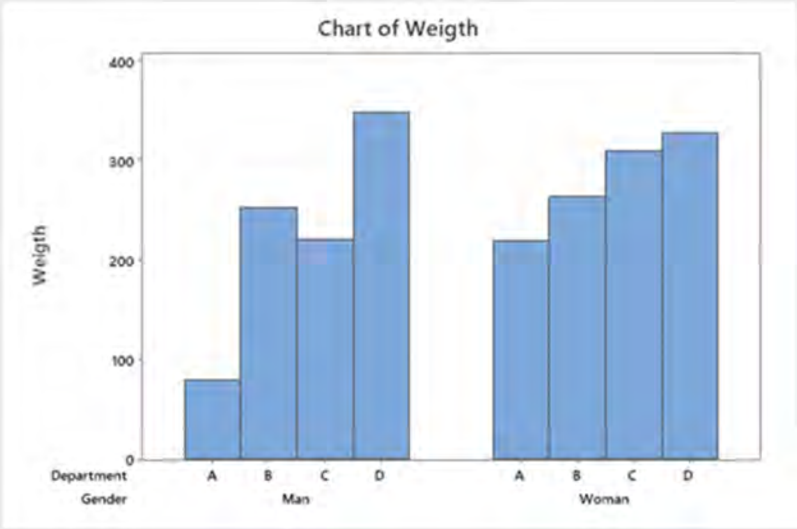


Figure 94 – Bar chart

4 – Pie chart

(Minitab: Graph > Pie Chart)

A Pie chart visually represents the proportion of different categories. The pie is divided into slices, with each slice representing a category. By comparing and contrasting the size of the slices, you can evaluate the relative magnitude of each category.

For example, a hospital collects data from patients to find the most common causes of no-shows for appointments. A Pie chart with five slices is presented. Each slice displays a common cause of 'No Show' and the frequency of the data.

	Quantity
Forgot appointment	65
Got sick	3
No more complaints	45
Too busy	25
No reason	32

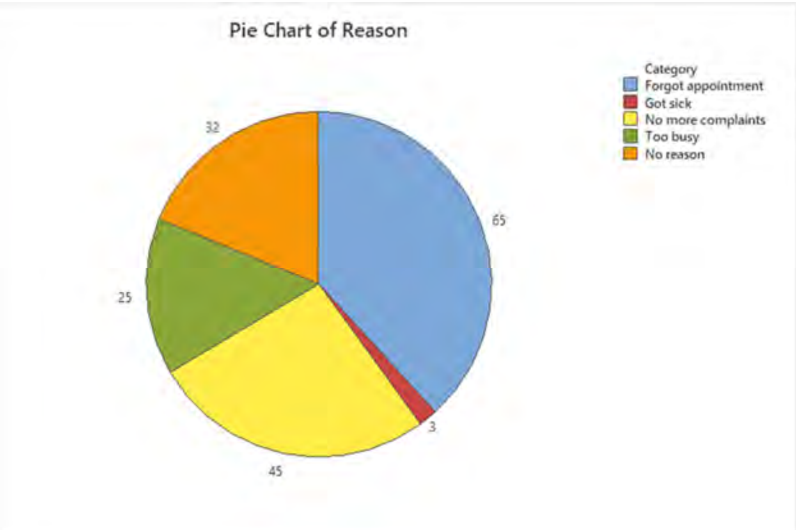


Figure 95 – Pie chart

5 – Time Series plot
(Minitab: Graph > Time Series Plot)

The Time Series plot is a very simple tool. Yet, together with the Histogram, it is one of the most powerful tools of Six Sigma. Time Series plots can help you to observe (sudden) changes and trends over time that cannot be observed by Histograms.

On the horizontal axis the time is plotted, while on the vertical axis a performance measure is plotted. This measure is very often the measure that is related to the problem focus of the project (e.g. dimension, temperature, number of defects, Lead Time). As soon as the first data are collected this is often one of the first graphs that is plotted after the start of a new project. It gives the team an indication of the extent of the problem over a certain period of time.

Examples of behavior that can be observed within Time Series plot are:

- Upwards or downwards trends (fig. A).
- Amount of variation and changes in variation (fig. B).
- Structural bad performance or defects caused by outliers (fig. C).
- Sudden changes in measurement or performance (fig. D).
- Difference between short time performance and long-time performance.
- Patterns or cycles in performance.

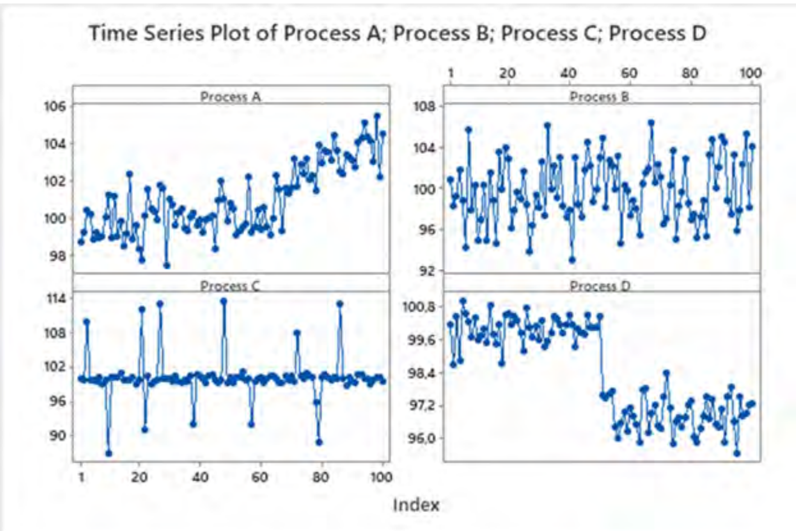


Figure 96 – Time Series plots

6 – Histogram

(Minitab: Graph > Histogram)

Histograms are used to divide sample values into a certain number of intervals. These intervals are called 'bins' and are represented by bars. Each bar represents the number (or frequency) of observations falling within one bin. Histograms are used to examine the shape and spread of data. The histogram in Figure 97 demonstrates 8 bins on the *x*-axis. Each bin represents a certain amount of water usage. On the *Y*-axis the number of families for a certain water usage is represented for each bin.

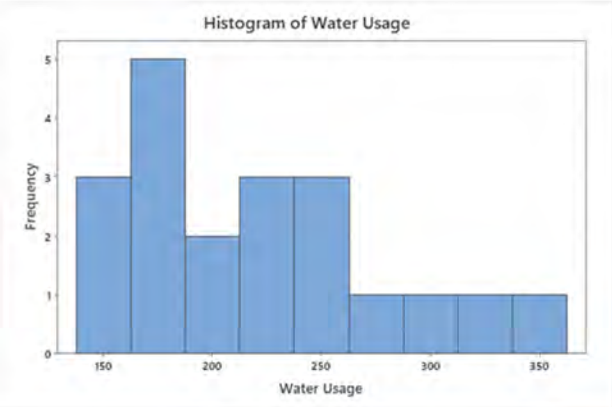


Figure 97 – Histogram

When more data are available, it may make sense to draw a probability density function over the histogram in order to make a visual evaluation of the shape of the distribution of the data. Figure 98 depicts a histogram with a normal probability density function drawn over it. Green and Black Belts are expected to perform several types of calculation on histograms, while Yellow and Orange Belts are expected to understand and interpret the graphical representation of a histogram.

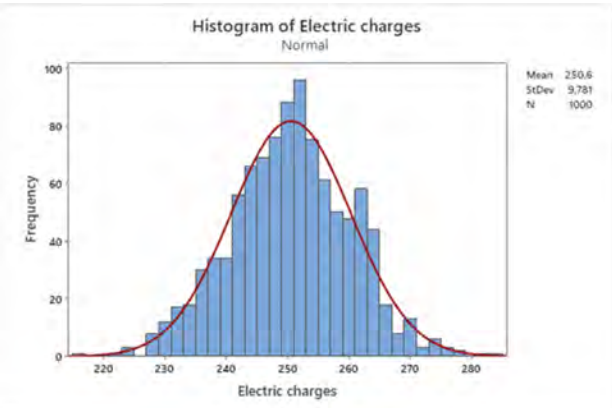


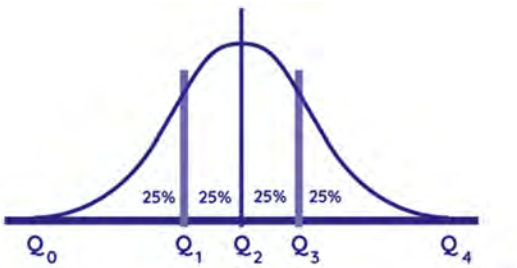
Figure 98 – Histogram

7 – Box plot

(Minitab: Graph > Boxplot)

A Box plot (also called 'Box-and-whisker plot') gives a graphical summary of the distribution of a sample that shows its shape, central tendency and variability. The Box plot consists of the following elements:

- Q_0 = Lowest value of the data
- Q_1 = Lower Quartile
- Q_2 = Median
- Q_3 = Upper Quartile
- Q_4 = Highest value



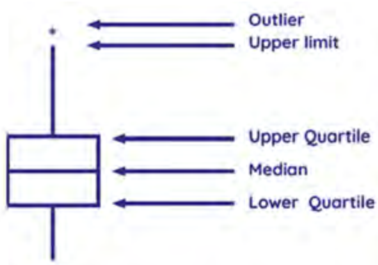


Figure 99 – Box plot versus normal distribution

Median calculation:
The Median can be found by arranging the data in ascending order and choosing the middle value. So for data {5,9,1,7,4} arranged in ascending order {1,4,5,7,9}, the middle value is 5 and so is the Median. If there is an even number of values then we take the arithmetic Mean of the two middle values. So for data {2,9,1,7,6,8} arranged in ascending order {1,2,6,7,8,9}, the middle values are 6 and 7 and the Median is 6.5.

Quartile calculation:
There are various methods of finding the value of the Quartiles. For Box plots we use the method that excludes the Median, which gives the same results as the excel function QUARTILE.EXC.

Q1: 'First Quartile' or 'Lower Quartile': 25% of the data are less than or equal to this value.
Q2: 'Second Quartile' or 'Median': 50% of the data are less than or equal to this value.
Q3: 'Third Quartile' or 'Upper Quartile': 75% of the data are less than or equal to this value.

So for data {1,9,7,3,4,6,1,8,6} arranged into order {1,1,3,4,6,6,7,8,9}, the Median of all the data is the first 6 which splits the data set into a lower half {1,1,3,4} and an upper half {6,7,8,9}. The Lower Quartile Q1 is the median of the lower half data {1,1,3,4} and is 2. The Upper Quartile Q3 is the median of the upper half data {6,7,8,9} and is 7.5. In the event that there are an even number of values in the main dataset then simply split them into the upper half and lower half for the quartile calculation.

Often, the quartiles are not values that are present in your data. This is because it is sometimes necessary to interpolate between two observations to calculate a Quartile accurately.

Inter Quartile calculation:
The 'Inter Quartile Range' (IQR) is equivalent to 50% of the data collection and is shown by the 'Box'. This box is drawn from the Lower Quartile Q1 '2' to the Upper Quartile Q3 '7.5'. A horizontal line is drawn to mark the Median '6'. The 'Inter Quartile Range' is calculated, by IQR = $Q_3 - Q_1 = 7.5 - 2 = 5.5$.

Whisker and Asterisks calculation:
The data below Q1 and above Q3 are represented by a 'Whisker'. We will first calculate the inner fences, which are 1.5 x IQR below the Lower Quartile Q1 and 1.5 x IQR above the Upper Quartile Q3.

Lower Inner Fence: LIF = 2 – 1.5 x 5.5 = -6.25

Upper Inner Fence: UIF = 7.5 + 1.5 x 5.5 = 15.75

The lower whisker can be found by the first value above (to the right of) the Lower Inner Fence, which is '1'. The upper whisker can be found by the first value below (to the left of) the Upper Inner Fence, which is '9'. 'Outliers' are represented by individual points (Asterisks) that are below the LIF or above the UIF. In our example there are no Outliers.

Box plots are particularly useful for comparing distributions between several groups or sets of data, because it is very easy to plot several Box plots in one graph (Figure 100). Using histograms this is not possible, because it would look confusing. For example, Figure 100 demonstrates that process C has many outliers, and process D has the lowest Median.

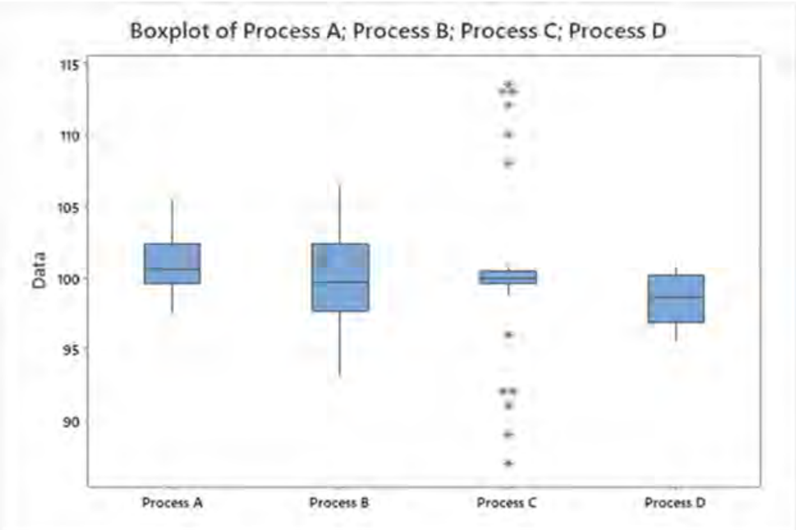


Figure 100 – Box plot

CIMM assessment level II – Creating a Continuous Improvement culture

Level II focuses on creating a Continuous Improvement culture. Is the culture in your organization strong and flexible enough to deploy the next level? Perform the assessment below by scoring each statement with a rating of 1 to 5. A score of '1' means that the statement does not reflect the situation within your organization. A score of '5' means that the statement fully reflects the situation within your organization.

As there are 15 statements, the maximum score is 75. If you score less than 50 points, we recommend not to start the deployment of the next level, but to continue to deploy the current level first.

Process level II – Creating a Continuous Improvement culture (Managed)
2.1 – Visual management
Areas are self-explaining (e.g. floor marking, labeling, shadow boards).
The daily schedule with activities is self-explaining (minimum involvement of supervisors).
Every person in the organization is supportive to the operational process.
There is a process in place to deal with occurring problems and deviations from the standard.
All employees see incidents as an opportunity for improvement rather than a problem.
2.2 – Performance management
KPIs for the workplace have been defined to monitor delivery and quality performance.
KPIs are made clear by using visual management boards or communication boards.
Stand-up meetings take place on the work floor regularly.
Information about progress, priorities and quality is followed by appropriate actions.
Necessary changes are implemented quickly and flawlessly.
2.3 – Kaizen and Problem Solving
Problems are discussed and solved in a short-cycle interval.
Continuous improvement events involving employees are organized regularly.
An improvement cycle is used in case of deviations (for example PDCA).
Techniques are applied in the Root Cause Analysis process (e.g. Pareto, 5-Whys, Ishikawa).
The organization is receptive to new ideas and suggestions for improvement.

Each person in the organization has a certain role and responsibility at creating a Continuous Improvement culture. The assessment distinguishes responsibilities and behaviors for top management, middle management and people working at the shop floor. There are again 15 statements with a maximum score of 75.

People level II – Creating a Continuous Improvement culture (Foundation)
2.1 – Visual management
Top management is regularly present at the workplace (observing, listening and supporting).
Management ensures that employees have sufficient time and resources available.
Management challenges employees to suggest continuous improvement opportunities.
Employees continuously contribute in the development of standardized work.
Employees actively contribute to the further professionalization of the work environment.
2.2 – Performance management
Top management is regularly present at stand-up meetings and show genuine interest.
Management ensures that stand-up meetings are structured and according to agreement.
Management facilitates continuous improvement by translating goals into concrete actions.
Employees are open minded and proactive in communication during stand-up meetings.
Employees understand that many small improvement steps lead to big steps ahead.
2.3 – Kaizen and Problem Solving
Top management shows appreciation for results achieved and celebrates results.
Management coaches employees in the continuous improvement process.
Management facilitates Kaizen events and is open to new ideas.
Employees are involved in problem solving and root cause analyses.
Employees are actively involved in continuous improvement projects and Kaizen projects.

“The most dangerous kind of Waste is the Waste we do not recognize.”

— Shigeo Shingo —

6 CIMM level III – Creating stable and efficient processes (Predictable)

During the first two Continuous Improvement maturity levels the workplace has been organized, standards have been determined and a system has been put in place to solve problems and to continuously work on improving the operation. The third maturity level focuses on improving the logistical flow and making it stable, efficient and predictable. The main objective of creating stable processes is intended to avoid incidents, stress, fire-fighting, downtime, unsafe situations, quality spills, mistakes etc. In other words, the creation of an environment where you can predict what will happen and what can be promised to the client.

In this chapter we will review tools to visualize and analyze the process flow. We will review how to identify Waste and opportunities for improvement. Also, we will review a number of tools and techniques that are very powerful for improving efficiency, effectiveness, productivity and agility. We will review the five principles of Lean and Value Stream Mapping, which are amongst the most powerful tools for this level. Finally, we will review how to eliminate Muda (Waste), Muri (Overburden) and Mura (Unevenness).

A number of tools that can be used at this CIMM-level are demonstrated in Figure 101. It is important to realize that it is not necessary to use each of these tools in your project. The table only demonstrates tools that are commonly used. Other tools can be used as well. Although the origin of this roadmap is from Six Sigma, it can be followed in Lean projects as well. The tools listed in Figure 101 are placed in one of the DMAIC phases. However, many tools can be used in other phases as well.

Figure 101 – Lean DMAIC roadmap and tools

Define

6.1 Process Mapping

A process is a systematic series of activities that are required to achieve a goal. The series of activities uses one or more types of input and creates outputs with added value for the customer. Charting the process in a visual representation will work like a map to guide the team. Discussions about scope, objectives and causes will be visualized by pointing out places on the map and by drawing lines and by making notes on the map. There are different ways of mapping a process. In this paragraph we will discuss different tools that are often used in Lean projects.

6.1.1 High level process description and SIPOC

Physical versus Transactional processes
Processes can be divided into two groups. The first group is 'Physical processes'. The second group is 'Transactional processes'. Most companies tend to have both types of processes, but have a focus on one of these groups. Table 17 demonstrates a number of processes for both groups.

Although Lean Six Sigma finds its origin in manufacturing, it can be applied within service organizations as well. However, before you can apply Lean Six Sigma in transactional environments successfully, you should realize the inherent similarities and differences between physical processes and transactional processes:

- Transactional environments tend to have a stronger need for fast adaptability as customers' requirements change more frequently.
- Inventory is less visible in transactional environments, as most Work in Process has the form of electronic data and correspondence rather than physical items.
- Transactions within one process take place on computer systems that are connected across multiple locations, sometimes around the world, while manufacturing processes are more centralized in one location. At the same time the connection of different manufacturing processes is much more complicated as parts are produced around the world by different companies, making it a logistical challenge to get all parts together at the right moment without huge piles of inventories.
- Maintenance has a different meaning within transactional environments, as computer software and algorithms do not wear out like equipment and tooling. Although computer systems can break down, like equipment.
- Transactional processes tend to have more waiting time than manufacturing. In most cases this is the consequence of several approval steps in the process and the lack of control of 'Work in Process and FIFO' (First In First Out).
- Transactional processes are less (analytical) data-driven. Data is recorded but fractional hidden in multiple systems. People are unaware or do not have access to all data or do not look for data to support decisions. As a consequence, decisions are often based on opinions rather than facts.
- Transactional processes evaluate quality by subjective metrics, like customer satisfaction and complaints. Physical processes use more objective metrics that are collected during processing.
- Within transactional processes, defects are relatively invisible and not evident until experienced by the customer. The quality of the final product is often good or bad (within or without 'Service Level Agreement' (SLA), while in manufacturing products vary more between good and bad.
- Data within transactional processes is very often discrete (e.g. number of defects) while data in manufacturing processes is much more continuous (e.g. mean and standard deviation of a dimension). As a consequence, some tools, like 'Measurement System Analysis' (MSA) and 'Design of Experiments' (DOE), are more difficult to apply.

Besides the difference in the processes itself, there is also a difference between the people working with transactional processes and people working with physical processes. People in service organizations tend to have less affinity with statistical analysis, whereas this is an important element within Six Sigma. Furthermore, improvement programs are associated with change. Generally, changes tend to generate more resistance within transactional environments than they would in manufacturing environments.

If you read all the above, you might think that Lean Six Sigma is difficult to apply in service organizations. This is not the case, although it requires a different approach. On the other hand, transactional processes have great opportunities for improvement, as there is more low-hanging fruit and more waiting time. If you are able to describe processes, standardize activities, visualize performances, gather data and have people accepting changes, you can achieve major breakthroughs.

At the same time Black Belts working in manufacturing environments should keep in mind that this type of organizations also has many transactional processes like sales, order intake, planning and customer service. The focus on process improvement should be extended from the workplace to the offices.

	Process type
Physical processes (Manufacturing)	Assembling, connecting
	Forming, machining
	Chemical processing
	Joining, finishing
	Testing (e.g. inspection, electrical, laboratories)
	Groceries, shops, restaurants, etc.
	Distribution, transportation & logistics
	Construction
Transactional processes (Service)	Strategic planning process
	New product development & IT development
	Financial transactions (e.g. billing, banking, insurance)
	Request for quotation
	Customer service
	Complaint management
	Planning process & order entry process
	Human resource management

Table 17 – Physical versus Transactional processes

Spaghetti diagram

An organized environment can still mean 'Chaos' in operation. A Spaghetti diagram can be helpful to track the routing on the shop floor. Spaghetti diagrams visualize movement and transportation of a product or document. Analyzing flows through systems can determine where time and energy is Wasted and identify where streamlining would be beneficial.

The tool is not only used for physical products, but also for more abstract products like a passport or a request for car insurance. If you visualize for the first time all the movements of a product before it is finished, you will probably be amazed. Analyzing the movements and transportations will determine the amount of time that is Wasted and identifies where streamlining would be valuable.

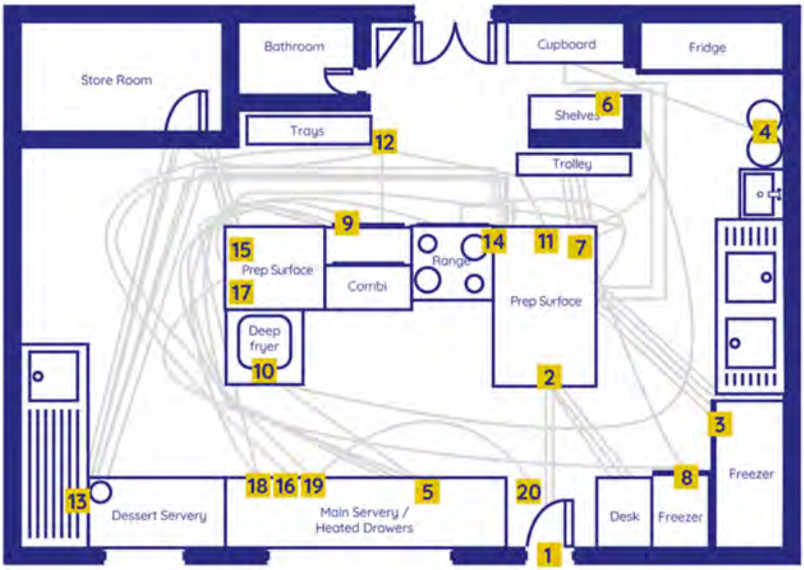


Figure 102 – Spaghetti diagram

KPIV versus KPOV

If we review process performance, we can distinguish between variables that have influence on the performance of the process and variables that are used to measure the output of the process. The first group of variables are called 'Key Process Input Variables' (KPIV) or 'X's. Some KIPV's can be influenced by us, while others cannot. Examples of KIPV's are time, temperature, employee, machine, components, etc. The process output or result can be measured by 'Key Process Output Variables' (KPOV) or 'Y's.

Figure 103 – Process model

SIPOC

A SIPOC analysis is one of the first steps in a Lean Six Sigma project. The acronym SIPOC stands for Suppliers, Inputs, Process, Outputs and Customers. It is a high-level process description that defines the scope of the process, the main inputs, outputs, customers and suppliers. Creating a SIPOC can be done in the Define phase or Measure phase. Detailed process mapping however should be avoided in this phase of the project. This will be done later in the Analyze phase. SIPOC is also very helpful before performing a full and detailed Value Stream Map.

SIPOC helps with:

- A high-level Process description P
- Identification of Suppliers and Customers S/C
- Identification of Inputs and Outputs I/O

The entire process from supplier to customer can be very long and focus is needed to be effective in finding the root cause and solving the problem. The SIPOC helps you to determine which phase of the process needs analysis and improvement effort. It also helps to make a rough distinction between the dependent and independent factors of influence and to compose a list of input and output variables to investigate.

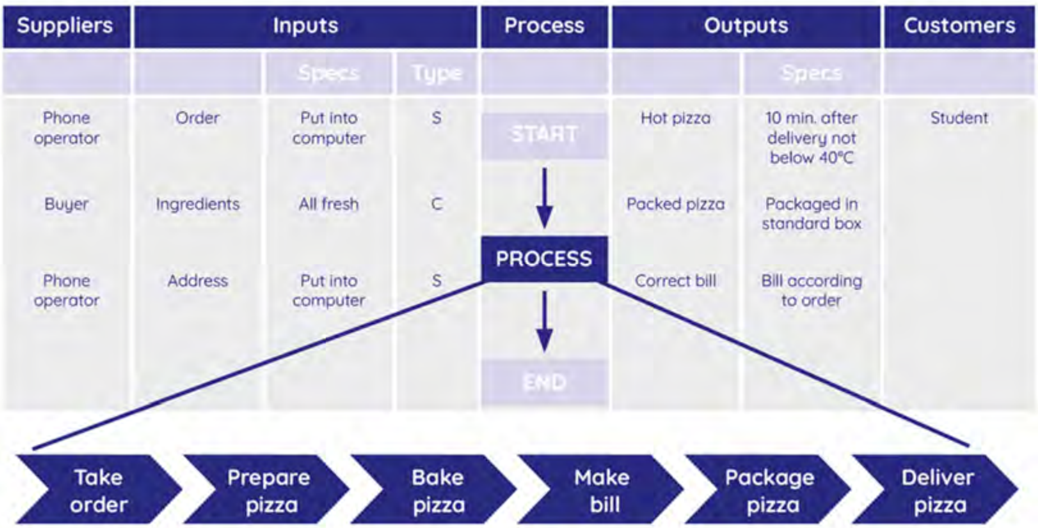


Figure 104 – SIPOC

SIPOC is a team effort. The team composition should be such that it contains people with different functions related to the process to assure that all suppliers, customers, activities, inputs and outputs are included. It regularly involves people from the Yellow Belt to Black Belt level. Creating a SIPOC is an iterative process. You can start with the complaint of the client, with the fall-out in the process itself or with the supplier who is causing the problem.

The result of creating a SIPOC with the team is to compose a visual map of all elements that are related to the complaint or problem. In the end the team will better understand the relations between the elements and will be able to highlight elements that need further analysis or investigation in the next phase.
Steps for creating a SIPOC:

- Customers:
  List the client who is experiencing the problem. Also enter a list of clients who have obtained the same product or service, but did not encounter the problem or did not complain. Instead of external clients, we can also start here with an internal process that has a low yield.

- Outputs:
  Enter a list of outputs. These are measures of the process (CTQ_{int}). Clients can be coupled to process outputs, requirements or specifications. It is not necessary to determine a client for each output.

- Process:
  Compose a high-level overview of the process (vertical), mentioning the start and the end of the process. The key process step(s) that are linked to the problem, are expanded at the bottom of the SIPOC (horizontal) in 4 to max. 7 steps. It is not the intention to apply more detail at this stage.

- Inputs:
  Enter a list of inputs that are needed for the process. If specifications have been defined for a certain input, it should be listed in the 'Specs' column. Optionally you can list the Input type (<u>C</u>ontrollable, <u>N</u>oise or <u>S</u>tandard Operating Procedure).

- Suppliers:
  Enter a list of suppliers to the process. Suppliers can be coupled to an Input description or a requirement. It is not necessary to determine a supplier for each Input.

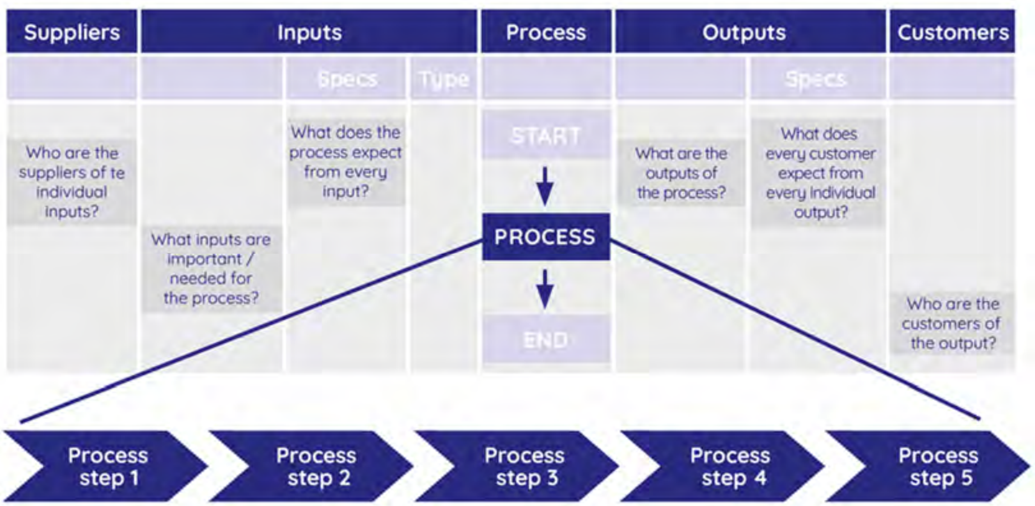


Figure 105 – SIPOC

6.1.2 Process Flow diagram

A Process Map or Flow Chart or 'Process Flow Diagram' (PFD) is a diagram commonly used to indicate the general flow of activities carried out on the product and of decisions to be made. A process flow is also a graphical representation of the routing of the product. In 'Process thinking' it is important to understand what happens in the organization and to understand how the work is done. Mapping the process is a way to instruct employees of what to do in a graphical way rather than a written description. It is also a way to identify and reduce Waste in the process. Process Maps can be used:

- to communicate the processes;
- to define the scope of a project;
- to describe and understand the processes;
- to document and standardize the processes;
- to define responsibilities and competencies;
- to analyze the processes / problems;
- to identify improvement opportunities.

There are different ways to map a process. A schematic representation of a Pizzeria process is demonstrated in Figure 106. This example is from the perspective of the Pizza Chef. It has a clear start (Take order) and end (Deliver); it has a number of process steps (Activities) and a decision point (Inspection).

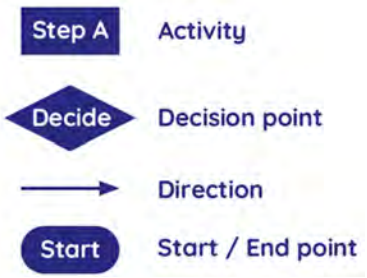


Figure 106 – Most common symbols

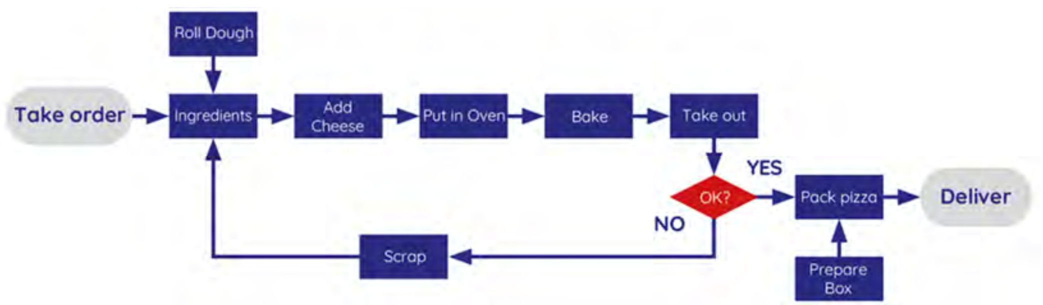


Figure 107 – Process Flow Diagram

Swimlane

A Swimlane flowchart is a visual representation of the process with the purpose to distinguish responsibilities for sub-processes within the overall process. Very often activities within a department or under the responsibility of a person are distinguished by the use of horizontal or vertical 'Lanes'. In Figure 108 an example is given of a student who submits a registration and ultimately gets either an acceptance letter or a rejection letter. (source: www.swimlaneflowcharts.com).

By drawing this business process in a Swimlane flowchart, the opportunity for improvement becomes obvious. Two different groups, represented by two lanes in the flowchart, are writing rejection letters. The efficiency and effectiveness of the process can be improved by having only one group write the rejection letter. The improved process is represented in the second Swimlane flowchart (Figure 109).

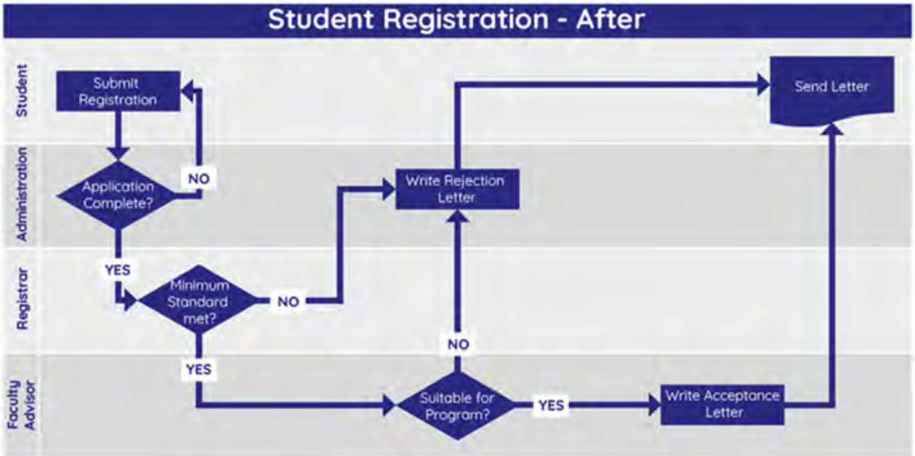


Figure 108 – Swimlane flowchart (before)

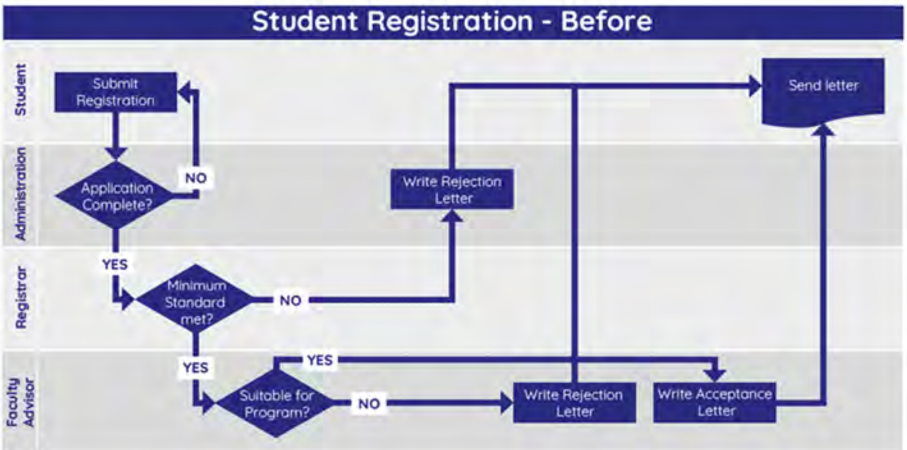


Figure 109 – Swimlane flowchart (after)

Measure

6.2 Performance metrics

Operations Management is concerned with managing the process that converts inputs (e.g. raw materials, resources) into outputs (goods or services). According to the United States Department of Education, operations management is the field concerned with managing and directing the physical and/or technical functions of a firm or organization, particularly those relating to development, production, and manufacturing. Operations management programs typically include instruction in principles of general management, manufacturing and production systems, factory management, equipment maintenance management, production control, industrial labor relations and skilled trades supervision, strategic manufacturing policy, systems analysis, productivity analysis and cost control, and materials planning.

For this data is needed. Most organizations have an ERP-system (Enterprise Resource Planning) that is used to support business processes, such as sales, inventory, logistics and finance. In addition to the ERP-system, most producing organizations also have a MES-system and a SCADA-system. A ‘Manufacturing Execution System’ (MES) ensures the exchange of data between the ERP-system and the production floor. On the one hand, the MES-system receives orders from the ERP-system and, on the other hand, produced output and use of raw materials are passed on to the ERP-system.

The MES-system is again linked to a SCADA-system. SCADA stands for ‘Supervisory Control And Data Acquisition’. This involves the collection, transmission, processing and visualization of measuring and control signals from machines. With a SCADA-system, data from the production processes can be collected and displayed clearly. This provides insight into the course of the processes, and adjustments can be made if necessary. The MES and SCADA links mean that operators are less busy with administrative tasks and can fully concentrate on the production process. To ensure a structured exchange of data between the various systems, a number of integration standards have been issued by the ISA.

In this section we will review two types of performance metrics. The first set is related to time, while the second set is related to quality.

6.2.1 Performance metrics (Time)

One of the core principles of process improvement is that management should be based on facts. Hence, reliable and accurate data are required. Like with all other processes the collection of data is also a process, which should be managed appropriately. In practice it has been proven to be difficult to explain to a person what data are needed and how it should be collected. The team should make sure that the measurement system and data are valid and reliable before it continues with analyzing it. It is therefore important to spend sufficient time in order to agree on the definitions of the project objective and the associated measurable target. This includes good definitions and identification of the sources and systems to extract the data from.

Process performance measures are important to sustain and improve performance. Performance metrics need to be measured over time to ensure that performance will not deteriorate. ‘Key Performance Indicators’ (KPIs) are used to classify the performance against a maximum (e.g. 96% of the products are ok) or against a certain goal (e.g. 92% of the deliveries arrived within 48 hours). Typical KPIs in Lean projects are ‘On Time Delivery’ (OTD); ‘Net Promoter Score’ (NPS); ‘Overall Equipment Effectiveness‘ (OEE); ‘Costs of Poor-Quality‘ (COPQ) and number of defects. Typical Six Sigma measures are related to quality e.g. ‘parts per million’ (ppm), ‘Defects Per Million Opportunities’ (DPMO), ‘Defects Per Unit’ (DPU), ‘Process Capability’ (Cpk) and ‘Rolled Throughput Yield ‘(RTY). In this paragraph we will review the metrics that are related to Time. In the next paragraph we will review the metrics that are related to Quality.

The most commonly used performance metrics related to time are:

- Takt Time:
  The rhythm at which products are requested by the customer (or market).
- Cycle Time:
  The (average) time between the completions of two successive products or the time it takes an employee to go through all of the work elements before repeating them.
- Lead Time:
  The time for a product or service to travel the entire process from start to finish.
- Processing time:
  The Lead Time of an individual process step.
- Queue time:
  The waiting time between two process steps.
- Work in Process (WIP):
  The number of products or amount of Work in Process or waiting.
- Completion rate:
  The amount of work that is completed within a certain time period.
- Overall Equipment Effectiveness (OEE):
  The measure that represents the effectiveness of a line, machine or plant.

There are many different types of data and information. When we listen to the radio, read the newspaper or find information on the internet, we acquire data. How do we know that what we acquire is correct? When sales tell us that a certain customer has a serious complaint, does this mean the product did not meet the requirements? When we perform a database query about delivery times, how do we know if we are looking in the correct records or fields?

Agreement on the operational definition is important before we continue the process of collecting and evaluating the data. The operational definition is a description of how the product or service's characteristic is to be quantified. There may be several ways of quantifying a given characteristic. Example: How would you define the measure 'Repair time for broken phone'? Improving the performance of 'Repair time' starts with a clear operational definition and agreement about the source for data that represents the operational definition.

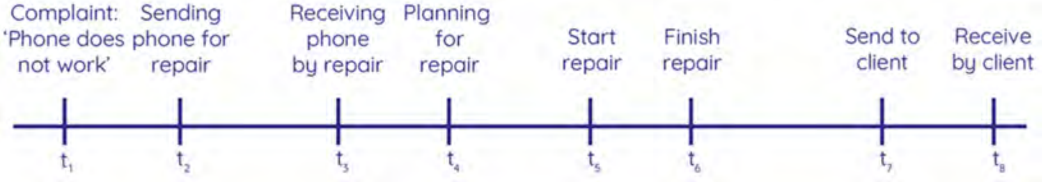


Figure 110 – Operational definition

Finally, it is important to realize that when we talk about a measure, we are not only addressing the measurement instrument. We must take into account the measurement system as a whole. So, every measure contains everything involved from collecting data to assigning a value to a characteristic (e.g. databases, collection method, definitions, opinions, observations, instruments, devices, software, people performing the measurement etc.).

Takt Time

The rhythm at which products are requested by the customer (or market) is called the 'Takt Time'. It is defined by the customer and not by the process or by the planning department. It can be calculated by dividing the 'Available work time' by the 'Customer demand'. In 'Theory of Constraints' (TOC) this measure is called the 'Drumbeat of the process'.

$$Takt\ Time = \frac{Available\ Work\ Time}{Customer\ Demand}$$

Figure 111 – Takt Time

Cycle Time

This is the average time between completion of two consecutive products. It is also one divided by the completion rate. Cycle time should not be confused with processing time of a particular process step. For example, if three people perform a specific process step in parallel, the Cycle time is one-third of the processing time.

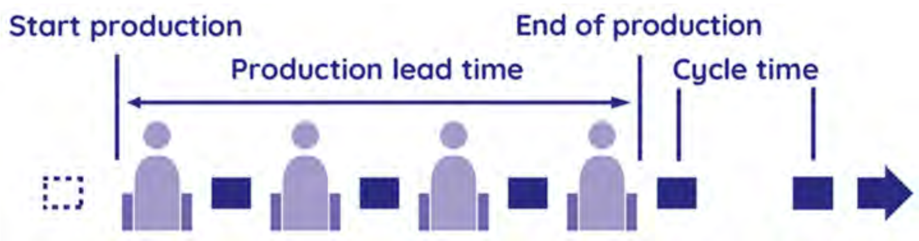


Figure 112 – Cycle Time

Lead Time
The Lead time is the sum of all processing times and waiting times. For the organization itself, the Lead time is the average time between the start of the production of a new product and the completion of the same product. However, from the customer's perspective, the Lead time starts with submitting a sales order, or request, and ends at the time the order is delivered or service is completed.

Figure 113 – Lead Time

The total Lead time for the customer, also called delivery time, can be both longer and shorter than the Lead time within production itself. This is because the customer Lead time depends on the location of the so-called 'Push-Pull point' in the process, also called the 'Decoupling point'. This is the point that indicates how far upstream in a supply chain a customer order penetrates into the production or distribution process of the supplier of a product or service. The process steps prior to the Decoupling point are general and not customer specific, while the process steps after the Decoupling point are for a specific customer. For the customer the Lead time starts at this point. The further upstream the Decoupling point the longer the customer Lead time.

Little's Law
A measure that represents the efficiency of a process is the average Lead Time. This is the average time of one product or service passing through the entire process. Average Lead Time can be calculated by using the equation developed by Little (1954), also called 'Little's Law':

$$Average\ Lead\ Time = \frac{Work\ in\ Process}{Completion\ Rate}$$

The WIP level is the amount of work (e.g. orders, products) that is waiting on the shop floor or in the process. The Completion rate is the number of products or services that are completed in a specific time period (e.g. per minute, hour or day). This is also called the 'Output' of the process. The equation, developed by Little, shows that the average Lead Time is constant if the WIP-level is constant. A constant Lead Time will make an operation predictable, which is more important than being fast. It also shows that WIP is a major cause of long Lead Times and that reducing WIP is one of the best ways of achieving a faster process.

Example: If you have 100 requests for a new passport waiting on your desk and you can complete 5 requests per hour, the average Lead Time is 20 hours.

$$Average\ Lead\ Time = \frac{Work\ in\ Process}{Completion\ Rate} = \frac{100\ requests}{5\ requests\ per\ hour} = 20\ hours$$

However, if the number of requests in the stack is only 20, the average turnaround time is only 4 hours. A new application is therefore already processed within 4 hours. This also shows that a large amount of work in progress is the main cause of long lead times and that reducing the amount of work in progress is one of the best ways to reduce waiting times and shorten delivery times.

6.2.2 Performance metrics (Quality)

In the former paragraph we discussed the performance of a process with regard to 'Time'. In this section we will discuss the performance related to 'Quality'. First, we will explain the difference between Defects and Defectives. 'Defective' indicates that something is wrong with the product. It does not work as it is supposed to, or it does not look like it is supposed to. The product does not meet the specifications or expectations of the customer. Second, the defective product can have one or multiple 'Defects'. In this case a single product has more than one dimension or features that are out of specification or expectation. Examples are several typing mistakes in one document, multiple dimensions out of specification for one component, several scratches on one product, etc.

In summary, it only takes one 'Defect' to create one 'Defective' product. However, one 'Defective' product can have several 'Defects'. The difference is important for yield calculations as explained in the following sections. To quantify the quality level of a process the following metrics are used:

1. ppm:
   Parts per Million.
2. DPU:
   Defects per Unit.
3. DPMO:
   Defects per Million Opportunities.
4. Yield:
   Percentage of good products.
5. Rolled throughput Yield (RTY):
   Probability a unit will pass a number of sequential process steps without any defect.

It is also important to understand the difference between a 'Defect' and a 'Nonconformity':

- Defect:
  A departure of a quality characteristic from its intended level or state that occurs with a severity sufficient to cause an associated product or service not to satisfy intended normal, or foreseeable, usage requirements.
- Nonconformity:
  A departure of a quality characteristic from its intended level or state that occurs with severity sufficient to cause an associated product or service not to meet a specification requirement.

1 – ppm (Parts per Million):
In high volume operations with high demand for quality, the ppm measure is used to indicate the quality performance of a production process. The abbreviation stands for defective parts per million. Example: 50 ppm performance indicates that within a production volume of one million parts, it is expected to find 50 products that do not meet specifications. If 100,000 parts are produced, a 50 ppm performance means that it is expected that 5 parts do not meet the specification. For many operations 50 ppm is already a pretty high-quality standard to meet, but a Six Sigma performance is expecting an even higher quality performance of 3.4 ppm [see section 7.7.3].

2 – DPU (Defects per Unit):
The abbreviation DPU stands for the amount of defects in one unit. A defect is defined as a feature that does not meet the stated specification. DPU can be greater than 1 because one unit can have several defects (e.g. a hood of a car can contain multiple dents or scratches and a document can contain more than one typing mistake).

Example: Defects on a hood

- Number of Units = 30 number of inspected hoods
- Number of Defects = 53 number of dents + number of scratches

$$DPU = \frac{Number\ of\ Defects}{Number\ of\ Units} = \frac{53}{30} = 1.77$$

So, on average there are 1.77 defects per hood.

3 – DPMO (Defects per Million Opportunities):
The abbreviation DPMO stands for Defects Per Million Opportunities or nonconformities per million opportunities. DPMO is similar to ppm and is used as a quality performance measure. However, DPMO differs from ppm in that it comprehends the possibility that one unit under inspection may be found to have multiple defects of the same type or may have multiple types of defects.

Example: DPMO for a toaster

- Opportunities = 80 possible defects on one toaster (missing screws, broken springs, etc.)
- Number of Units = 2,500 toasters produced
- Number of Defects = 53 different defects were found during inspection of the toasters

$$DPMO = \frac{Number\ of\ Defects \times 1{,}000{,}000}{Opportunities\ \times Number\ of\ Units} = \frac{53 \times 10^6}{80 \times 2{,}500} = 265$$

If we produce 2,500 toasters, we expect to find 53 mistakes (defects).

If we produce 100,000 toasters, we expect to find 2,120 defects:

$$Number\ of\ Defects = \frac{DPMO \times Opport. \times Number\ of\ Units}{1{,}000{,}000} = \frac{265 \times 80 \times 100{,}000}{10^6} = 2{,}120$$

The measure DPMO can also be used to compare the quality performance of different products. Using the DPMO measure, we can, for instance, compare the quality performance of a computer with a toaster. The computer has much more opportunities to fail than the toaster because the computer is more complex and it consists of more components than the toaster.

4 – Process Yield (%):
Yield is the percentage of good products that are passed to the next operation. This can best be explained by an example. Assume we are producing a part of a toaster in four consecutive process steps (A, B, C and D). Each process step delivers a number of good parts and a number of bad parts (Scrap). Any part that contains a fault that can be successfully reworked is counted as a good part. Any part that contains a fault that cannot be successfully reworked clearly is counted as a bad part.

$$Process\,Yield\,[\%] = \frac{Total\,number\,of\,products\,without\,defects}{Total\,number\,of\,products}$$

You can find the process Yield [%] of each of the four process steps in Table 18.

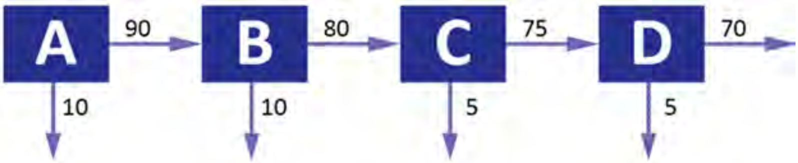


Figure 114 – Process yield

Process	Scrap	Out					Yield-%
A	10	90	90 / (90+10)	=	90 /100	=	90%
B	10	80	80 / (80+10)	=	80 / 90	=	89%
C	5	75	75 / (75+5)	=	75 / 80	=	94%
D	5	70	70 / (70+5)	=	70 / 75	=	93%
Total Process Yield							70%

Table 18 – Total Process Yield

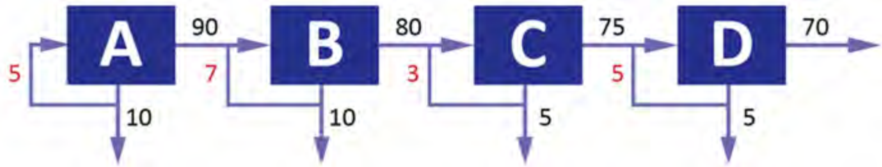
$$Total\,Process\,Yield = 0.90 \times 0.89 \times 0.94 \times 0.93 = 70\%$$

5 – Rolled Throughput Yield (RTY%):
In many cases the Rolled Throughput Yield (RTY%) or First Time Right Yield (FTR%) is used rather than the Process Yield. The 'Rolled Throughput Yield' is defined as the probability that a unit will pass a number of sequential process steps without any defect. The main difference between RTY and normal Process Yield is that products that are not 100% OK, but could be reworked or corrected, are now considered incorrect in the RTY-calculation because the products were not 'Right the First Time'.

Rolled Throughput Yield helps us measure the cumulative effects of inefficiencies found throughout the process. It can be calculated by the product of First Time Yields for each process step of the entire process:

$$Rolled\ Throughput\ Yield\ [\%] = \frac{Total\ number\ of\ products\ right\ first\ time}{Total\ number\ of\ products}$$

We will explain this once again with an example:



Process	Scrap	Rework	Out					FTR-%
A	10	5	90	(90-5) / (90+10)	=	85 /100	=	85%
B	10	7	80	(80-7) / (80+10)	=	73 / 90	=	81%
C	5	3	75	(75-3) / (75+5)	=	72 / 80	=	90%
D	5	5	70	(70-5) / (70+5)	=	65 / 75	=	87%
RTY-%								54%

Table 19 – 'First Time Right Yield' and 'Rolled Throughput Yield'

$$RTY\% = 0.85 \times 0.81 \times 0.90 \times 0.87 = 54\%$$

Each of the process steps has a number of OK parts that are passed on to the next operation, but some of these products have been reworked, repaired or corrected. Taking into account that some of the products were not OK the first time, the Rolled Throughput Yield of this process is 54%.

When the number of defects is recorded instead, another way of calculating yield and rolled throughput yield should be used. These calculations are a bit more complicated and are listed below:

The number of defects k per unit is Poisson distributed with λ =DPU: $$P(k) = \frac{e^{-\lambda} \cdot \lambda^k}{k!}$$

So, the probability to produce a unit without defects is: $$P(0) = \frac{e^{-DPU} \cdot DPU^0}{0!} = e^{-DPU}$$

The Yield of a process step is: $$Y = e^{-DPU}$$

The RTY of several process steps is: $$Y = e^{-\sum DPU}$$

We will explain this with an example. Imagine a product that is made in five consecutive process steps. Each process step delivers a number of units with a certain number of defects. The total DPU can be calculated by the sum of the five DPUs of each step (0.0049 + 0.0494 + 0.0098 + 0.0318 + 0.0743 = 0.1703). The total RTY-% can be calculated by multiplying the 'First Time Right'-percentage (FTR-%) from the five steps (99.51 x 95.18 x 99.02 x 96.87 x 92.84 = 84.34%) or by calculating e to the power of -0.1703. This is demonstrated in Table 20.

Step	Defects	Units	DPU		DPU				FTR-%
1	4	812	4 / 812	=	0.0049	=	$e^{-0.0049}$	=	99.51%
2	33	668	33 / 668	=	0.0494	=	$e^{-0.0494}$	=	95.18%
3	13	1322	13 / 1322	=	0.0098	=	$e^{-0.0098}$	=	99.02%
4	7	220	7 / 220	=	0.0318	=	$e^{-0.0318}$	=	96.87%
5	74	996	74 / 996	=	0.0743	=	$e^{-0.0743}$	=	92.84%
RTY-%					0.1703		RTY = $e^{-0.1703}$	=	84.34%

Table 20 – Rolled Throughput Yield

Please note that the RTY (84.34%) is higher than 1 – DPU (1 – 0.1703 = 83.97%). This is caused by the chance of having more than one defect in one single product. This means that fewer products will be defective as one might expect if all the defects were spread out evenly over all products.

6.3 Basic statistics

Statistics is the study of the collection, organization, analysis, interpretation and presentation of data. Statistics deals with all aspects of data including the planning and execution of experiments, the collection of data and the analysis of the data. In this section we will review data types, measurements scales and descriptive statistics as how to calculate the center and dispersion of a set of data.

6.3.1 Data types and Measurement scales

Data types

Before you gather information about the properties of a process or service, you must realize that there are different types of data. Data can be divided into two groups: Qualitative or Quantitative. Qualitative data are descriptive information and describe properties. Quantitative data are numerical information and can be measured or counted. Applying statistical methods is more valuable for quantitative measures than for qualitative measures.

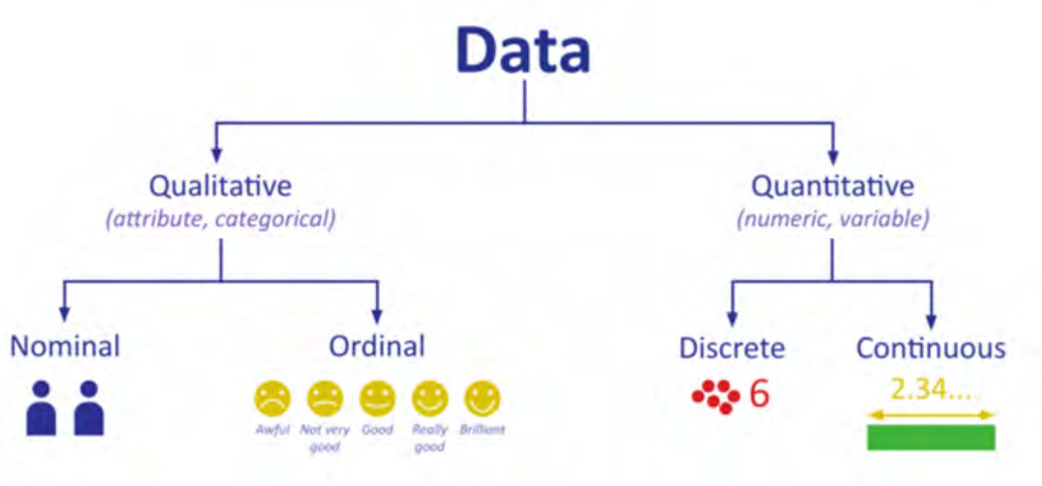


Figure 115 – Qualitative data versus Quantitative data

1 – Qualitative data:
Qualitative data cannot actually be measured. As you know, 'There is no arguing about matters of taste'. It is not possible to measure 'taste' like the length of a bar can be measured for instance. You can qualify this type of data by assigning a characteristic or property to the object. These properties of an object are called attributes. For example, 'taste' can be qualified as 'it tasted good', or 'it tasted bad'. Other examples are the attributes of a 'person' such as gender, birthplace and education. Attribute data is categorical in nature and can be measured on either a nominal or an ordinal scale, as explained on the next page.

2 – Quantitative data:
Quantitative data are data that can be counted or measured using measuring equipment like a tape measure, voltmeter or balance. Quantitative data can be divided into discrete and continuous data.

Discrete data can only be discrete values, for example the number of defects or the number of attributes. Measuring data on a discrete scale is like counting. Often in order to make comparisons of qualitative data, we will count the number of measurements falling into each nominal or ordinal category. This creates a quantitative comparison of attribute measurements and is often called discrete or attribute data.

Continuous data are measured on a continuously variable scale, i.e. one that is infinitely divisible and are sometimes called 'variable data'. Examples of continuous data are: dimensions, time, currency, weight and resistance and are expressed as any real number. Quantitative data is numerical in nature and can be measured on either an interval or a ratio scale, as explained on the next page. Sometimes, in order to simplify its reporting or visual representation, we will count the number of continuous data measurements that falls into pre-determined ranges or 'buckets'. This creates discrete or discretized versions of continuous data.

Measurement scales
In order for any measurements to be valid, we need to employ well-defined rules of measurement that depend upon the item to be measured. There are four basic measurement scales that should be distinguished between: Nominal, Ordinal, Interval and Ratio.

1 – Nominal scale:
A nominal measurement scale is used to differentiate between items that can be placed into distinct categories but there is no logical and natural order between the categories. The value of an observation belongs in one of the categories and when it is in one category it cannot be in another. For example, measuring 'someone's Blood type: (A+, A-, B+, B-, AB+, AB-, O+)'. There is no order in blood types and a person has just one blood type. Another example of categorical data measured on a nominal scale is 'gender (male or female)'.

2 – Ordinal scale:
An ordinal measurement scale is used to differentiate between items that can be placed in distinct categories and where the categories have an inherent order or relationship. The value of an observation belongs in one of the categories and when it is in one category it cannot be in another, however the differences between the different categories cannot be quantified e.g. measuring 'someone's ranking in a race: (1st, 2nd, 3rd, etc.)'. There is a natural order to the ranking but there is no information about whether it was a close race or whether someone won easily. Another example of categorical data measured on an ordinal scale is 'a company's service level based on a recent transaction (excellent, good, average, poor, very bad)'.

3 – Interval scale:
An interval measurement scale is used to quantify items that have a natural order. The size of differences can be quantified and compared. However, crucially there is an arbitrary zero. In this case it is not possible to say that one interval measurement is some multiple bigger or smaller in size than another interval measurement, only that there is a measurable interval between them. This could be for example the 'temperature in an oven: 100°C'. This is hotter than 'temperature in a room: 20°C', but you cannot say the oven is five times hotter than the room. This is because 0°C is actually an arbitrary point on the scale.

4 – Ratio scale:
A ratio measurement scale is used to quantify items that have a natural order. The size of differences can be quantified and compared. Additionally, a meaningful zero exists on a ratio scale, which means that it is possible to say that one ratio measurement is a multiple bigger or smaller than another ratio measurement. An example is the height of the Eiffel tower. This can be compared to another building, like the church in your own city center. A height of zero means the ground level of the tower. Another example of a ratio measurement scale would be waiting time at the dentist. Temperature can also be measured on the ratio scale of degrees Kelvin, because 0 Kelvin is defined as absolute zero temperature.

An overview with examples of data types and measurement scales is demonstrated in Table 21.

Data type	Scale type	Natural order	Quantifiable differences	Meaningful zero exists	Example
Qualitative	Nominal	-	-	-	Blood type: (A+, A-, B+, B-, AB+, AB-, O+)
	Ordinal	X	-	-	Performance rating (scale 1 to 5)
Quantitative	Interval	X	X	-	Temp. in an oven is higher than room temperature
	Ratio	X	X	X	Height of tower; number of inhabitants

Table 21 – Data types and Measurement scales

The Likert scale or Rating scale is commonly involved in research that employs questionnaires to convert ordinal data in quantitative data. The Likert scale is named after its inventor, psychologist Rensis Likert. An example is the 'Pain rating scale' used in hospitals to convert the question 'How bad is the pain today?' into a measurement that is more tangible so that it can be used to define a concrete action (Figure 116). Another example of the Likert scale is a range of pictures with scratches that are used in manufacturing for defining actions for visual inspection.

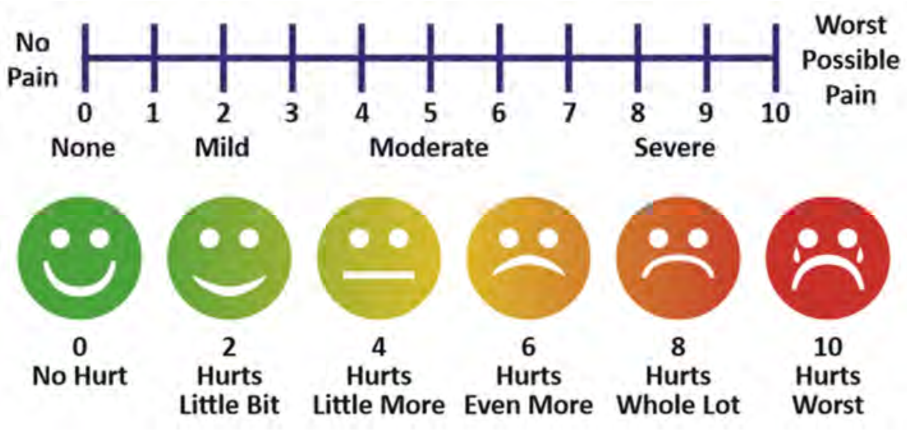


Figure 116 – Pain rating scale using Likert

6.3.2 Data collection tools

Green and Black Belts apply various techniques to attain representative samples and develop sheets for collecting data. After it is decided what to measure and how to record it, a data collection plan will be composed that specifies how much data should be collected (sample size) and how often data should be collected (frequency). Often, people outside the process will collect the data (i.e. someone other than the person who has determined what data needs to be collected in order to perform the analysis, or the person who subsequently analyzes the problem).

In this section we will review the following five data collection instruments:

1. Data sheet
2. Check sheet
3. Frequency plot Check sheet
4. Concentration diagram
5. Questionnaire or Survey
6. Heatmaps

1 – Data sheet
A data sheet is used to capture numerical readings, measures or counts. There is usually some unique identifier in the left-hand column with all required measurements recorded to the right.

Figure 117 demonstrates a simple data collection sheet containing 10 samples of a bar. There are three different input variables: Material (*x*1) and two equipment settings Force (*x*2) and Speed (*x*3). The employee has been asked to perform the test on the 10 samples, using the setup values listed in the sheet and to measure and record two dimensions of the sample after performing the test. These dimensions are the responses of the process. The first response is the Length of the bar (*y*1) and the second is the Diameter of the bar (*y*2).

Worksheet 3 ***

↓	C1	C2-T	C3	C4	C5	C6
	Nr	Material	Force	Speed	Length	Diameter
1	1	A	100	1,0		
2	2	B	100	1,0		
3	3	A	150	1,0		
4	4	B	150	1,0		
5	5	A	100	2,0		
6	6	B	100	2,0		
7	7	A	150	2,0		
8	8	B	150	2,0		
9	9	A	125	1,5		
10	10	B	125	1,5		

Figure 117 – Example: Data collection sheet

Within transactional environments most data are available in the ERP system or any other software system. Reports or SQL queries can be used to extract this data from the system. In most cases it will has the form of a data sheet.

2 – Check sheet

Check sheets are often used to collect data about defects or causes of defects. Possible causes are listed on a sheet and a tick is made for every occurrence. After a set period of time, the checks can be counted to provide a summary. An example of a Check Sheet is given in section [5.2.2].

	Tally sheet				
Lamp defect	III				
Illegible code	𝍸	𝍸	II		
Empty battery	𝍸	𝍸	𝍸	I	
Scratch on lens	II				
Broken ring	𝍸	II			
Missing cord	𝍸				

Figure 118 – Check sheet

3 – Frequency plot Check sheet

The Frequency plot Check sheet is a special type of Check sheet. It is used to record numerical data. When plotting the data, you are actually creating a visualization of how often different values appear.

Age	Tally	Frequency
0 - 9	𝍸 III	8
10 - 19	𝍸 𝍸 II	12
20 - 29	𝍸 𝍸 𝍸 𝍸 IIII	24
30 - 39	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 III	43
40 - 49	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 I	41
50 - 59	𝍸 𝍸 𝍸 𝍸 𝍸 II	27
60 - 69	𝍸 𝍸 𝍸 𝍸 III	23
70 - 79	𝍸 𝍸 𝍸 III	18
80 - 89	III	3
90 - 99	I	1

Figure 119 – Example: Frequency plot Check sheet

4 – Concentration diagram
A concentration diagram uses a picture or diagram of the product or document on which the location of defects/problems/damage are then marked by the observer. Examples of concentration diagrams are registering data on rental car damage, plastic molding defects and errors on forms.

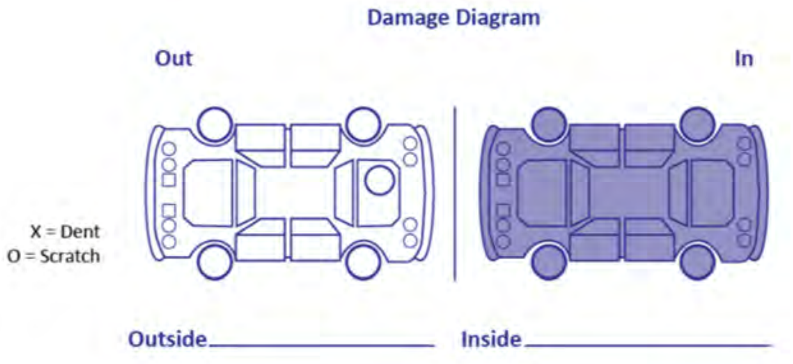
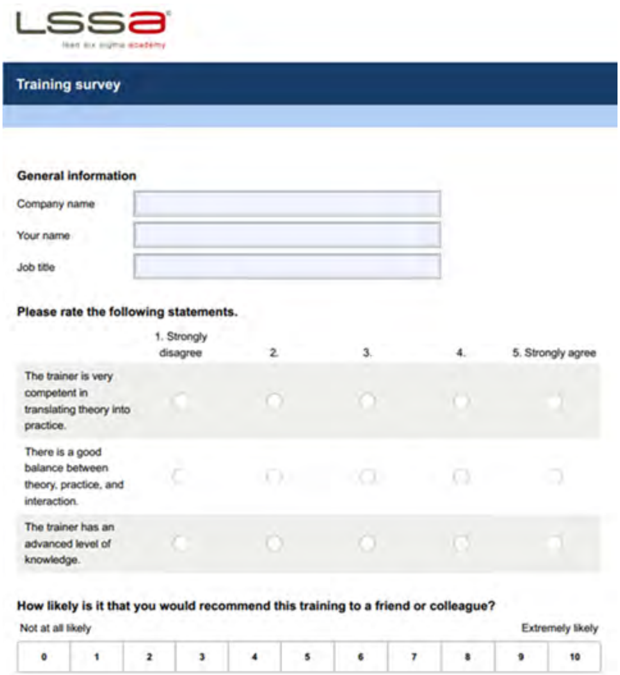


Figure 120 – Example: Concentration Diagram

5 – Questionnaire or Survey
Questionnaires or surveys use carefully scripted questions with a discrete set of responses for respondents to choose from.


Training survey

General information

Company name

Your name

Job title

Please rate the following statements.

	1. Strongly disagree	2.	3.	4.	5. Strongly agree
The trainer is very competent in translating theory into practice.					
There is a good balance between theory, practice, and interaction.					
The trainer has an advanced level of knowledge.					

How likely is it that you would recommend this training to a friend or colleague?

Not at all likely — Extremely likely

0	1	2	3	4	5	6	7	8	9	10

Figure 121 – Example: Questionnaire

6 – Heatmaps

'Automated Business Process Discovery' (ABPD) is an area that analyzes business processes based on the electronic footprints that users leave when using the IT-systems or webpages. There are tools that, for example, record the actions that employees perform when they are processing their mail or are visiting on the internet or webpage. ABPD can automatically track, analyze and visualize all this. If this had to be done by hand, it is very time consuming. Generating a heatmap for mouse clicks is one possibility.

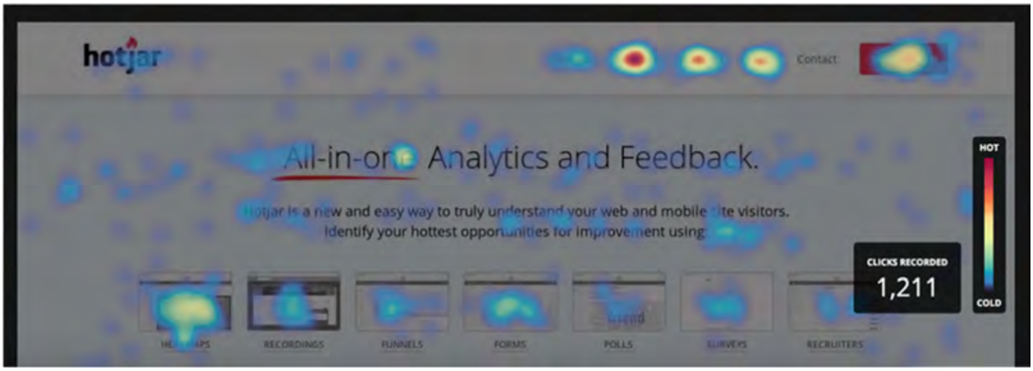


Figure 122 – Webpagina Heatmap (Hotjar)

6.3.3 Descriptive statistics

Descriptive statistics is a set of measures (statistics) that characterizes a given set of data, which can either be a representation of the entire population or a sample. Based on the sample we can calculate statistics to estimate parameters of the whole population. These statistics of the sample are always estimated with quantifiable confidence.

(Minitab: Stat>Basic Statistics>Basic Descriptive Statistics).

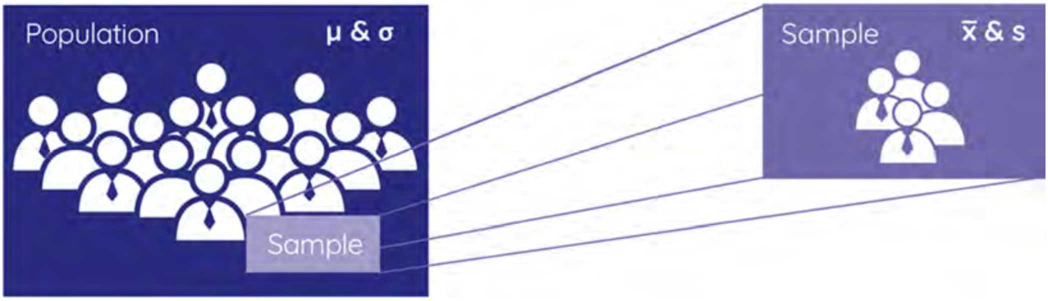


Figure 123 – Population and Sample

Process data have several components:

- Center — Is the process on target?
- Dispersion — How much variation is in the data?
- Shape — What does the shape of the distribution look like?
- Stability — Does the process drift in time?

Measures of central tendency

The center of the process is called central tendency. There are different measures for central tendency. Which measure to use depends on the objective of the analysis and the shape of the population. Usually, especially for the Normal distribution and other symmetrical distributed populations, the 'Mean' is used. Below, three measures of central tendency are listed based on a simple set of data: {3, 5, 4, 7, 5}.

Mean:

For the commonly used normal distribution, but also for other symmetrical distributions, the sample Mean is often used. This is the most important and most used center size. It is also called the center of gravity of a dataset. The symbol 'µ' (mu) represents the arithmetic Mean of a population, while '$\bar{x}$' (Xbar) represents the Mean of a sample. This center size is sensitive to outliers (flyers or outliers). If a dataset contains extremely high or extremely low values, it is often better to use the median.

$$\bar{x} = \frac{(3 + 5 + 4 + 7 + 5)}{5} = 4.8$$

Median:

The Median (or mean value) is often used for non-symmetrical distributions. The Median divides the ordered outcomes into two equally large groups. For the Median of a distribution, 50% of the outcomes have a value that is smaller than that of the Median and at the same time 50% of all outcomes have a value greater than that of the Median. If the number of values is even, the Median is the average of the middle two values. In order to determine the Median, it is necessary that the results can be ranked. The Median can therefore only be calculated for variables measured at an ordinal measurement scale, because classification is not possible at a nominal measurement scale.

The advantage of the Median relative to the average is that outliers have little influence on the value of the Median. The Median is therefore a robust measure for the center of an asymmetric or skewed distribution. Graphical use is often made by a box plot, where the asterisk in the middle of the box indicates the value of the Median.

$$Median\ (3; 4; 5; 5; 7) = 5$$

Mode:

In some cases, the Mode is applied to identify the central tendency of the process. This is the result that occurs most often in a dataset, or the value with the highest frequency. In the case of a discrete variable we speak of the Mode, while in a classified continuous variable we speak of the Modal class.

$$Mode\ (3; 4; 5; 5; 7) = 5$$

Measures of dispersion

There are different measures to describe the amount of variation within a sample. Which measure is used depends again on the objective of the analysis and the data? The symbol 'σ' (sigma) represents the Standard Deviation of a population, while 's' represents the Standard Deviation of a sample.

Range (R):

The Range or variation width is the difference between the highest and the lowest value in a dataset. The Range quickly gives a first impression of the spread in a dataset, but is very sensitive to outliers.

$$R = x_{max} - x_{min}$$

Interquartile Range (IQR):

The Interquartile Range is the difference between the first and the third quartile in a dataset. In a horizontal box plot the interquartile is represented as the difference between the values of the right side of the box (the third quartile) and that of the left side of the box (the first quartile). The Interquartile Range only uses the first and the third quartile, which means that outliers have no influence on the outcome. The Interquartile Range is a robust measure for the spread of a distribution and is therefore preferable to skewed distributions above the standard deviation or the variation width.

$$IQR = x_{75\%} - x_{25\%}$$

Variance:

The variance σ^2 (sigma squared) of a population is the mean of the squares of the deviations (distance relative to the mean μ) of those outcomes. The symbol σ^2 represents the variance of the population, while s^2 represents the variance of the sample. If we calculate the variance of the entire population σ, we have to divide by n, but if we calculate the variance of a sample, we have to divide by n-1 to obtain an unbiased estimator.

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

Standard Deviation (SD):

The Standard Deviation is the square root of the Variance. The symbol σ represents the standard deviation of the population, while s represents the Standard Deviation of the sample. The Standard Deviation is the most important and widely used measure for dispersion. The greater the spread, the greater the deviations and the greater the Standard Deviation.

$$s = \sqrt{s^2}$$

Standard Error:

Another measure is de 'Standard Error of the Mean' ($SE_{\bar{x}}$). This is de standard deviation of the sample Mean $\bar{x}$ and tells how much the Mean varies. SE Mean helps to quantify how precisely you estimate the true Mean of the population. It takes into account both the samples standard deviation and the sample size n. The SE Mean gets smaller for larger sample sizes, which makes sense because the Mean of a large sample is likely to vary less than the Mean of a small sample.

$$SE_{\bar{x}} = \frac{s}{\sqrt{n}}$$

The SE Mean is an important measure as it is used to calculate Confidence Intervals for the population Mean. In section 7.4 we will show how this is done.

Example: assume we have a sample with the following five measurements: 250, 300, 275, 310 and 295. For these data we would like to define the descriptive statistics. The Mean $\bar{x}$ can be calculated as follows:

$$\bar{x} = \frac{250 + 300 + 275 + 310 + 295}{5} = 286$$

The Variance s^2 is defined as the average of the squared differences from the Mean $\bar{x}$. We divide by n-1 because we are evaluating a sample:

$$s^2 = \frac{(250-286)^2 + (300-286)^2 + (275-286)^2 + (210-286)^2 + (295-286)^2}{(5-1)} =$$

$$= \frac{(-36)^2 + (14)^2 + (-11)^2 + (24)^2 + (9)^2}{(4)} = \frac{2270}{4} = 567.5$$

Then we calculate the standard deviation (SD):

$$s = \sqrt{s^2} = \sqrt{567.5} = 23.8$$

Finally we will calculate the Standard Error of the Mean (SE Mean):

$$SE_{\bar{x}} = \frac{s}{\sqrt{n}} = \frac{23,8}{\sqrt{5}} = 10,7$$

Measures for both central tendency, standard deviation and variance can be generated respectively in Excel by using the functions '=AVERAGE', '=STDEV' and '=VAR' on the set of data. Within Minitab we can also calculate descriptive statistic.

(Minitab: Stat > Basic Statistics > Display Descriptive Statistics > Statistics)

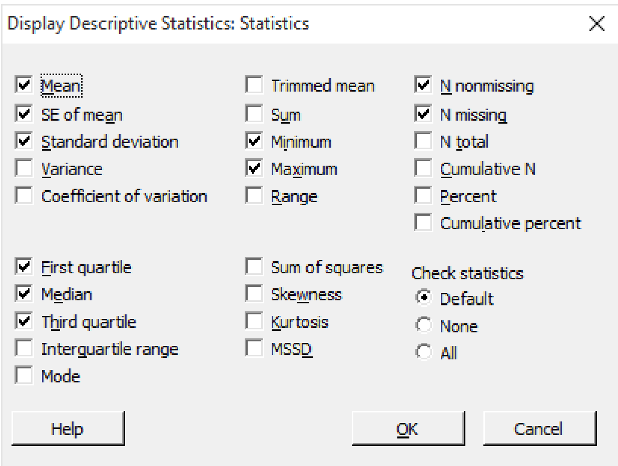


Figure 124 – Descriptive Statistics (Minitab)

Ratios, Proportions, Percentages, Rates

A ratio shows the relative sizes of two or more values. For example, if a group of people consists of 1 man and 3 women you could write the ratio as 1:3 (for every one man there are 3 women), 1/4 is man and 3/4 is women or 0.25 is man (dividing 1 by 4). Within ratios there is no defined way to determine which value is the numerator and which value is the denominator. So, instead of writing 1:3, you can also choose to write 3:1.

A proportion is a ratio where the denominator is the total, while the numerator is the subpart of the total. When we are interested in which part of a population possesses a specific value of an attribute, the measure of interest is a percentage or a proportion. Both measures refer to the fraction of the total that possesses a specific value of the attribute.

For example, you might want to know what proportion of students in a lecture is younger than 20 years. So, the attribute is age and the value is 'younger than 20'. Since 8 students of a group of 32 are younger than 20, the proportion $p = 8 / 32 = 0.25$. The percentage is equal to the proportion times 100. In this case the percentage of students younger than 20 is 0.25 x 100 = 25%. The proportion descriptive statistics are: (Note that $q = 1 – p$ which is the proportion of the students that has an age of at least 20 years):

- Proportion of elements that has the specific attribute value: p
- Proportion of elements that doesn't has the specific value: q
- Variance of the proportion: $s^2 = p \cdot q$
- Standard deviation proportion: $s = \surd\, s^2 = \surd\, (p \cdot q)$

A rate is a statistic that is measured against another quality or measure. Often a rate is the number of events divided by a measure, e.g. time period, area or volume. The rate per standard units can be calculated by dividing the total number of events by the total number of standard units in the observations. The rate of occurrence is defined as:

$$\hat{\lambda} = \frac{Total\ number\ of\ events}{Total\ size\ of\ observations}$$

Example: An operator has recorded the number of defects in 7 separate periods of a week, that contains 5 working days. The operator recorded respectively 3, 5, 6, 7, 2, 8 and 4 defects. Then, the average rate per week is:

$$\hat{\lambda} = \frac{3+5+6+7+2+8+4}{7} = \frac{35}{7} = 5$$

When the standard unit is equal to one day, the rate per standard unit is:

$$\frac{5}{5} = 1$$

Analyze

6.4 Value Stream analysis

The objective of ‘Value Stream Mapping’ (VSM) is to reduce Lead Time and to eliminate Waste. Value Stream Mapping is a technique that is used to analyze the series of activities to manufacture a product or to complete a service. It can be applied to nearly any value chain. Very often it is the first step of each Lean initiative or improvement initiative. Value Stream Mapping is one the most powerful Lean tools. It links all activities together in one visual representation. As such it provides the bigger picture by illustrating the complete flow and all its connections, which is not only limited to the operational process but also includes material flows, information processes and business processes. Within the visual representation it is possible to distinguish Value adding activities from Non-value adding activities and to identify Waste.

Value Stream Mapping was pioneered in the 1980s by Toyota chief engineer Taiichi Ohno and Sensei (teacher) Shigeo Shingo, with the intention to gain competitive advantage. Value Stream Mapping is a Lean tool and, in principle, not a quality tool. However, Ohno and Shingo proved that reducing Lead Time and Waste also result in better product quality. A value stream is defined as the series of all activities required to deliver a product or service. Examples for a Value stream are:

- From raw material to customer delivery.
- From product concept to product launch.
- From customer demand to delivered service.

6.4.1 Value adding versus Non-value adding

Like many other quality programs, Lean places the customer in the center of its activities. The first Lean principle is ‘Value’. The definition of value is ‘What is of value to the customer’. Even more specifically, value means ‘The activities the customer is willing to pay for’. Furthermore, the activity must be done correctly the first time (First Time Right) and the activity must change the product or service in some way. If one of these criteria is not met, the activity is classified as a ‘Non-value adding activity’ and therefore as ‘Waste’ or ‘Muda’, which should be eliminated. Necessary Activities are needed to keep the process running. These activities cannot be taken out of the process easily, but should be limited as much as possible. An example of a ‘Necessary activity’ is an inspection required by the customer or by the government.

1. Value adding Activities (VA) — Customer is willing to pay for.
2. Non-Value adding Activities (NVA) — Customer is not willing to pay for.
3. Necessary Activities (NA) — Necessary for the process.

It is obvious not all activities in most processes add value to the customer. So, why do it then? What is the point of doing things nobody wants to pay for? The purpose of Value Stream Mapping is to visualize the process and distinguish the value adding activities from the non-value adding activities.

6.4.2 Value Stream Mapping (Current State)

Makigami

Makigami is the Japanese word for 'roll of paper'. It is a technique for visualizing Value-Adding activities and Waste quickly and clearly. A Makigami is especially useful in organizations where the process is not immediately visible, like in transactional or administrative processes. When creating a Makigami, fewer symbols and less calculations are used than when applying Value Stream Mapping. This means that this technique is easier to apply than creating a full Value Stream Map.

Within Makigami, four steps are distinguished:

1. Workflow; the visualization of all process steps and activities.
2. Documents and systems used in the process.
3. Cycle time or processing time for each process step.
4. Bottlenecks and Waste in or between process steps.

The preparation of a Makigami helps a team to understand each other's role in the process better. It is also gaining insight into which process steps and transfer moments are most relevant, and to identify Waste and Bottlenecks. An effective way of working as a group is to cover a wall with paper and provide adhesive notes. Different colors can be used to represent different purposes. Each team member writes their tasks on individual notes and applies them to the paper in sequence. Notes with tasks can easily be moved around as other steps come to mind.

Figure 125 – Makigami 'Brown' paper session

Value Stream Mapping (VSM)

When the product in the process is visible or can be counted, it is more useful to construct a 'Value Stream Map'. A VSM examines the bigger picture and accounts for the connections between all processes. To construct a so-called 'door-to-door' Value Stream Map, it is necessary to perform a walk along the whole process starting at the end of the value stream and moving upstream. Use a simple paper and pencil to construct the process along the walk. The mapping process is simple, real-time and iterative, as this method allows for simple corrections.

The amount of 'Work in Process' (WIP) between each process step is counted. Lines are drawn between the steps to indicate the workflow. Also, lines are drawn to represent the information flows. This part is similar to the Makigami.

The steps to perform Value Stream Mapping are listed below:

1. Define Product Family:
   Group of products with similar process steps that make use of common equipment in the value stream to the customer.
2. Construct Current State Map:
   Identify Waste in the process by mapping the current situation of material flows, work in process and information flows.
3. Construct Future State Map:
   Map the future situation and determine improvements to eliminate Waste.
4. Define Work Plan & Implementation:
   Implement future state map.

VSM Current State – Example:
In this section we will construct a Current State Value Stream Map, step by step. This example is based on the fictitious factory 'PEN N.V.' that is assembling pens for its client 'Walmart'.

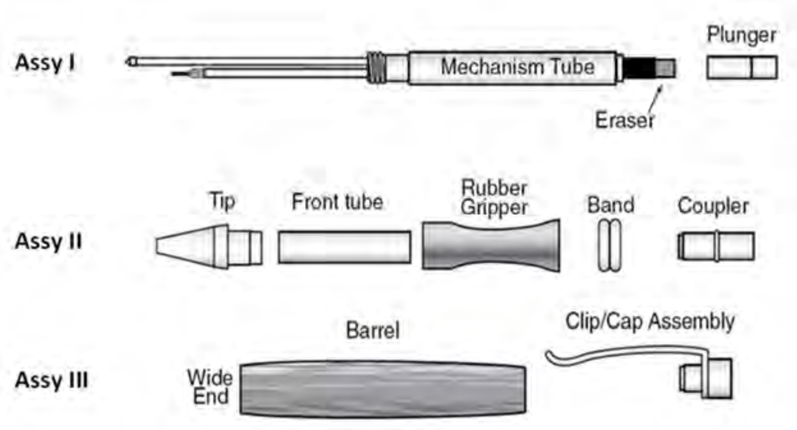


Figure 126 – Pen assembly overview

On the opposite page we will visualize the end-result of the Current State Value Stream Map, following the next steps:

- Step 1 – Map customer demand.
- Step 2 – Map available (production) time.
- Step 3 – Map process flow and Work in process.
- Step 4 – Add work flows between processes (Push & Pull).
- Step 5 – Add data boxes with current state information.
- Step 6 – Add information flows.
- Step 7 – Add flows for incoming requests and completed work.
- Step 8 – Add timeline with queue time and Cycle Time.
- Step 9 – Determine Value Adding percentage.

Although constructing a Value Stream Map is a 'Pencil-and-paper'-tool, we will use a software program called 'Minitab Work Space' to visualize and analyze the Value Stream Map. This tool is explained using the pen assembly process example, but Value Stream Mapping can also be applied in many other sectors, such as Transactional environments, Logistics and Healthcare.

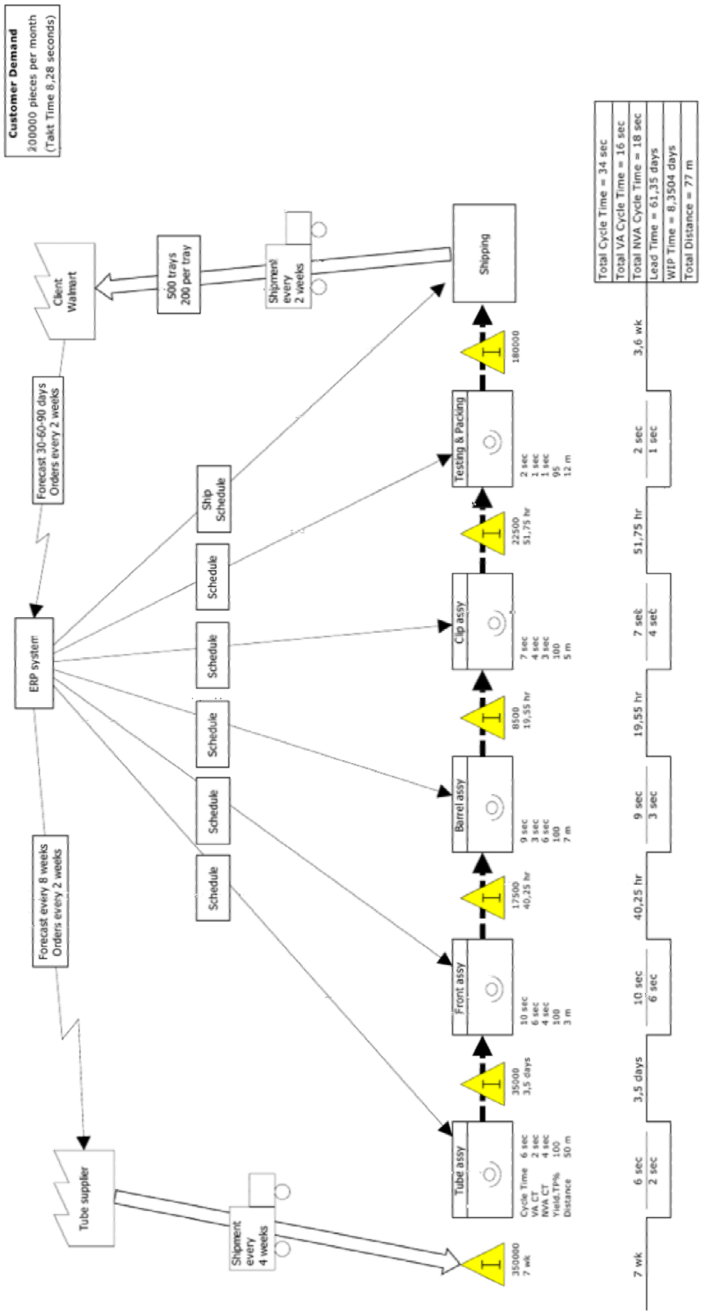


Figure 127 – Value Stream Map Current State

Step 1 – Map customer demand:
Our client Walmart is ordering 200,000 pens per month.

- Customer: 'Walmart'
- 200,000 pens per month
- 500 trays per pallet / 200 pens per tray

Step 2 – Map available (production) time:
The factory plant is producing in three shifts, with an average of 20 days per month.

- 3 shifts per day
- 8 hours per shift
- 20 minutes break per shift
- 20 days/month (avg.)

Taking into account the customer demand of 200,000 pens per month, this results in a Takt Time of 8.28 seconds.

$$Takt\ Time = \frac{Available\ Work\ Time}{Customer\ Demand} = \frac{3\ \times (8 - \frac{1}{3}) \times 20 \times 3{,}600}{(200{,}000)} = 8.28\,sec\ per\ part$$

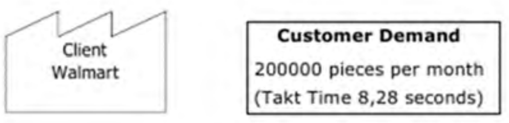


Figure 128 – Customer Takt Time

Step 3 – Map process flow and Work in process:
We will map the process from 'door-to-door', starting at the end of the line and taking the most expensive part (the Mechanism Tube) into account. This results in the following illustration. Triangles represent the inventory levels or Work in Process level (WIP), between two process steps.

The production process consists of the following five steps:

1. Assembly I: Tube Assembly (Tube, eraser, plunger).
2. Assembly II: Front Assembly (Tube assembly, tip, front tube, gripper, band, coupler).
3. Assembly III: Barrel Assembly (Front assembly, barrel).
4. Assembly IV: Clip Assembly (Barrel assembly, clip/cap assembly).
5. Testing & Packing.

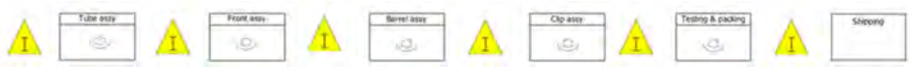


Figure 129 – Process Flow Map

Step 4 – Add work flows between processes (Push & Pull):
In this step we will add the material flows between processes. Depending on the way materials are delivered to each process step, we will use different symbols. In our case we only use the Push-arrow.

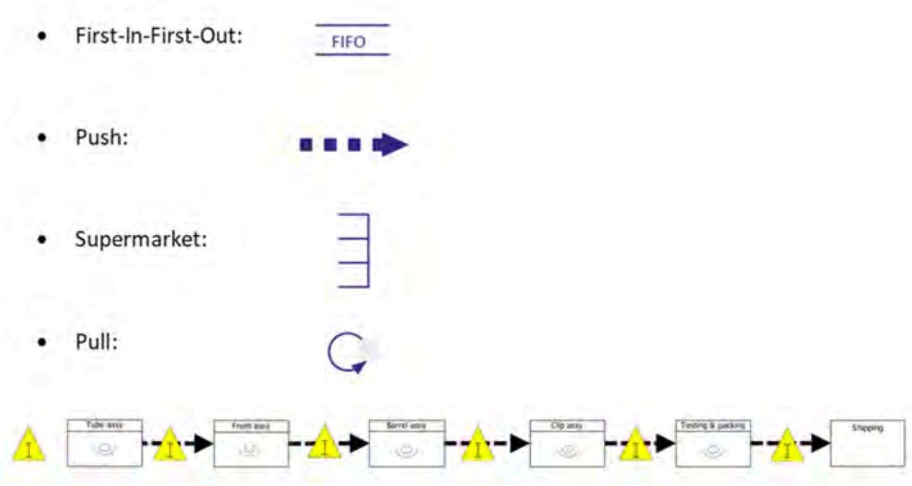


Figure 130 – Material flow

Step 5 – Add data boxes with current state information:
For each operation step we will collect Current State information by observing the operation with a stopwatch for 15 minutes. The Total Cycle Time is calculated by dividing the operating time (15 x 60 sec.) by the number of pens assembled during this time. The Total Cycle Time consists of Value-Added Cycle Time and Non-Value-Added Cycle Time. The difference can be calculated by comparing the number of pens assembled during the 15 minutes with the number of pens assembled during the entire operating time of one shift. The difference is caused by activities like walking, searching, waiting etc. These activities are called 'Waste'. We will review examples of Waste in the next sections. The time that is not used to assemble pens will be represented in the Value Stream Map by 'Non-Value-Added Cycle Time'.

Current State information:

- One employee at each process step.
- Total Cycle Time (measured during 15 minutes).
- Yield-% at assembly processes is 100%.
- Yield-% at the testing station is 95%.
- The amount of sub-assemblies in front of each process step is counted.
- All distances between the operation steps are measured.

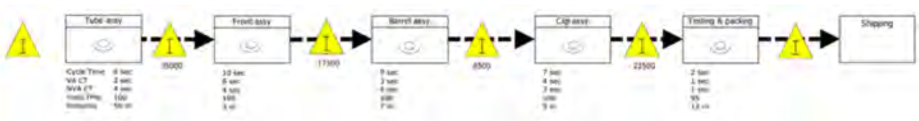


Figure 131 – Data boxes

Step 6 – Add information flows:
We will now map the existing information flows and scheduling.

- Volume of each process step is scheduled by the business system.
- We receive a 30, 60 and 90 days forecast from our client Walmart.
- Orders by the client are given every 2 weeks.
- A forecast to the supplier of the Tubes is given once every 8 weeks.
- Orders for Tubes are given to the supplier every 2 weeks.

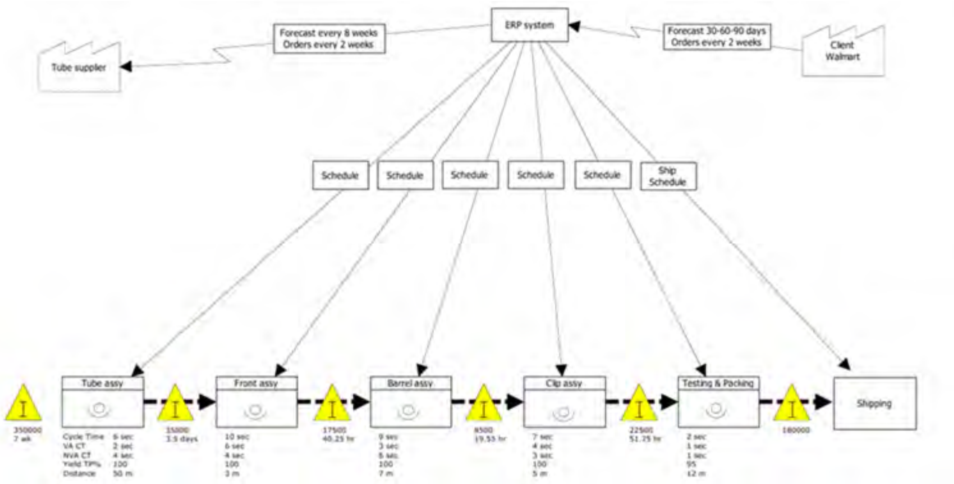


Figure 132 – Information flows

Step 7 – Add flows for incoming requests and completed work:

We will now add the logistic information of incoming requests or raw components deliveries to the line and the delivery of completed work or finished goods to the customer.

- Shipment of finished goods to client by truck every two weeks.
- Delivery of Tubes is done once every four weeks by supplier.

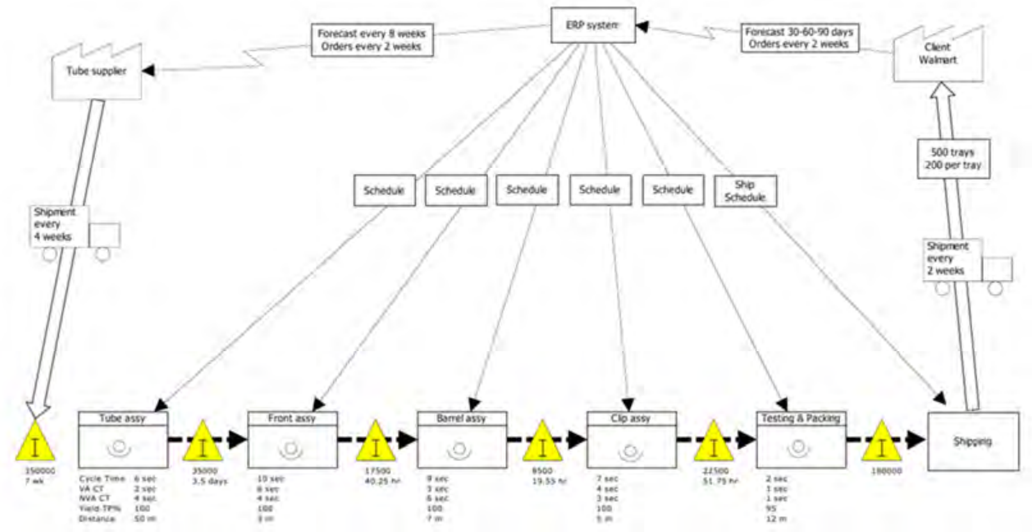


Figure 133 – Raw components & Finished goods

Step 8 – Add timeline with inventory times and Cycle Times:
In this step we will construct a timeline along the process. This is sometimes called the 'Lead Time Ladder'. For each process step we will note the 'Cycle Time' (at the bottom of the timeline), which is the Cycle Time that was collected in step 5. For each inventory location we will calculate the 'WIP time', based on the Customer demand. We will place this time at the top of the timeline.

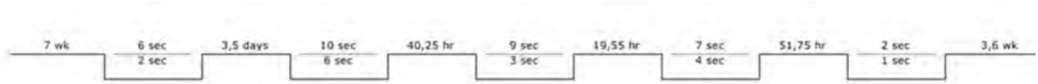


Figure 134 – Lead Time Ladder

Step 9 – Determine Value Adding percentage:
In this step we will determine the so called 'Value Adding percentage'. This is the percentage of the total Lead time in which customer value is added. For this we can use the following formula:

$$Value\ Adding\ \% = \frac{VA\ Cycle\ Time}{Lead\ Time} \times 100\%$$

Here, the VA Cycle time is the sum of all processing times in which value is added. In our example, that is 16 seconds. The Lead time can be determined by calculating the cumulated waiting time for each process step, related to the Takt time. The Lead time for the 'Front assy' for example is 35,000 x 8.28 = 289,800 seconds. The total Lead time is 61.35 days or 5,079,780 seconds, as shown in the following table. In our example, the processing times are so short compared to the waiting times that they actually do not affect the VA%, but in some processes this may be the case. Based on these values we can calculate the Value Adding percentage:

$$Value\ Adding\ \%. = \frac{VA\ Cycle\ Time}{Lead\ Time} \times 100\% = \frac{16}{(5{,}079{,}780)} \times 100\% = 0.00031\%$$

Takt time	8,28
Working hours per day	23
Working days per week	5

		Tube assy		Front assy		Barrel assy		Clip assy		Testing		Total
Total Cycle Time (sec)		6		10		9		7		2		34
Total VA Cycle Time (sec)		2		6		3		4		1		16
Total NVA Cycle Time (sec)		4		4		6		3		1		18
Total Distance (m)		50		3		7		5		12		77
Inventory	350.000		35.000		17.500		8.500		22.500		180.000	
Waiting time (weeks)	7		0,7		0,35		0,17		0,45		3,6	12,3
Waiting time (days)	35		3,5		1,75		0,85		2,25		18	61,35
WIP Time (days)	-		3,5		1,75		0,85		2,25		-	8,35
Waiting time (hours)	805,00		80,50		40,25		19,55		51,75		414,00	1.411
Waiting time (sec)	2.898.000		289.800		144.900		70.380		186.300		1.490.400	5.079.780

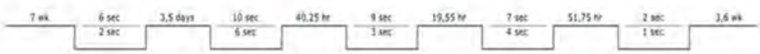


Figure 135 – Lead Time ladder calculations

The conclusion is that only 0.00031% of the time components value is added to the Tube. The rest of the time subassemblies are sitting idle and no Value is added. This sounds extreme, but these numbers are not strange. Try it at your own organization for a certain product group. On the up-side, it means that there is huge opportunity for improvement. We will discuss this in the following sections where we will review a number of tools and techniques to reduce the Non-Value Adding times, waiting times and inventory times. At the Improve-phase we will compose a Future state of the Value stream [6.8.1].

6.4.3 Process Mining

In the previous paragraphs we have discussed several classical business process management techniques, like SIPOC, Swimlane and VSM. None of these require software tools to analyze the process. Process mining however is a data driven way to visualize, understand and optimize your processes and to create a process model. It is one of the process management techniques that become more popular nowadays.

For performing process mining event logs are needed with data that can be analyzed. Constructing an event log is often the most difficult task in process mining. Building the event log might take you 80% of the total project time. Having the necessary programming skills and expertise in the field of data is often indispensable for expertly compiling a proper event log. For example, the event log can consist of a uniquely identifiable document or product-ID, employee-ID, machine-ID, task or activity description (also called ‘the Event’) and a timestamp (like start time or completion time). In addition, multiple other characteristics can be recorded in the event log or database as well.

By utilizing software able to track event logs, the company can automatically generate processes and process maps of pretty much the whole organization. You can also see where bottlenecks occur or where inefficiencies lie within the process.

Figure 136 – Process mining software (Disco)

For organizations that already have defined its processes or work instruction, process mining is used to describe the real as-is situation, with all of its possible paths including exceptions and escalations. In general process mining pulls in data from a range of sources and then looks at how processes function in real life. It then allows you to set up how the process should look so that you can see where conformance has occurred and where variants are appearing. This is referred to as ‘Conformance checking’. Data of the activities of each person are recorded in an event log. The data of the event log can be analyzed to check if actions line up with the described process. For example, a work instruction describes that people should follow steps 1, 2, 3, 4, 5 and 6. But the event log shows that some people perform steps 3, 4 and 5 in a different order. Now that we know that we can act on it. It can mean that training is required, but it can also mean that the standard operating procedure is adapted to the way people actually work.

Another application of process mining is performance analysis. For example, from the event log the average time to perform a specific task can be determined. We can also see if there is a big difference in time between different (groups of) persons or related to certain product types. We can then ask ourselves “How well is the process constructed; How well are people using that process; What can be done to improve the process”, etc. This can really help you crack down on problems and boost your process standardization.

There are several software tools that support process mining. Some are paid tools while others are open sourced free tools: Disco, Process Street, QPR Process Analyzer, Kofax Insight, ARIS Process Mining, Celonis, Icaro Tech EverFlow, ProM Tools, Apromore to name a few.

Disco is quick and relatively easy to use for someone with previous experience of analysis software. The Disco Process Mining technology comes straight from the leading group of Professor Wil van der Aalst, who invented process mining at the Eindhoven University of Technology.

Process Street offers a special feature that increases process adherence. It imposes people to follow certain predefined process templates including checklists, form fields, conditional logic and file uploads. You will be able to verify if people worked through the process as intended or not.

QPR Process Analyzer can take data from products like Salesforce, Epicor, Oracle, Microsoft Dynamics and more. It then be used for Automatic process visualization, Root cause analysis, KPI analysis, Lead time analysis and Conformance analysis.

Kofax is a player in the area of ‘Robotic Process Automation’ (RPA) and financial process automation. Robotic Automation or Robotization refers to the automation of processes, mostly transactional processes in serviced organizations like banking and insurances. With RPA processes can be streamlined quickly, easily and with low costs without the need of complex adjustments in your ICT infrastructure. With RPA you can build a 'virtual robot' that carries out repetitive tasks automatically. This varies from automatically answering an email to complex analysis and processing a credit request. Kofax claims to provide RPA within some of the major banks, insurance firms and logistics companies.

Improve

6.5 Reducing Muda (Waste)

Within the Toyota Production System, the following three types of variation can be distinguished:

- Muda:
  Waste, uselessness, non-value added or idleness.
- Muri:
  Overburden, impossible, beyond one's power or excessiveness.
- Mura:
  Unevenness, irregularity or lack of uniformity.

These are also called the 3 Ms of Lean. The reduction of these three types of Waste is fundamental within the Toyota Production System to increase effectiveness and profitability. For each of the three types we will review a number of principles and techniques to reduce the types of variation.

6.5.1 Waste identification and elimination

Reducing Muda can be achieved by assuring that a process will not consume more resources than are necessary to produce the goods or provide the service that the customer actually wants. Reducing Muda can be achieved by avoiding activities that do not add value to the product, meaning producing 'First Time Right', without loss of materials, loss of resources, rework, repair and waiting. In most Lean programs this is the first variation that will be addressed because it is more easily distinguished than the other types. Also redesigning processes or products (Innovation) can result in using fewer resources.

A Value Adding Activity must meet the following criteria: The customer is willing to pay for the activity; it must be done correctly the first time; and the action must change the product or service in some way. If one of these criteria is not met, the activity is classified as a 'Non-Value Adding Activity' and therefore as 'Waste' or 'Muda', which should be eliminated. Initially there were 7 types of Waste, but many also acknowledged 'Unused expertise' as the 8th type of Waste.

1.	Over-production	Producing more than asked by market
2.	Waiting	Waiting, idling or defect equipment
3.	Transport	Transporting materials or products
4.	Over-processing	Taking unneeded steps to process parts
5.	Inventory	Unnecessary supplies or stock
6.	Movement	Searching and unnecessary movements
7.	Defects	Faults, scrap or bad quality
8.	Unused expertise	Not using existing expertise or knowledge

Figure 137 – Muda: 8 types of Waste

1 – Overproduction:
Overproduction occurs when more products are produced than are required at a certain time by the internal or external customer. One common practice that leads to this Muda is the production of large batches.

Overproduction is considered the worst Muda because it hides and/or generates all the others. Overproduction leads to excess inventory, which then requires the expenditure of resources on storage space and preservation – activities that do not benefit the customer. There is also the possibility that customer demand or customer requirements change. As a consequence, goods might become obsolete or services will be provided while there is no customer request (anymore).

2 – Waiting:
Whenever goods or documents are not being processed, these are waiting. Waiting is not about people who are waiting, but goods or documents that are waiting to be processed. In traditional processes this is mostly the largest type of Waste. Waiting for information or approval in order to continue the process is also classified as 'Waiting'.

3 – Transport:
Each time a product is moved between process steps we qualify it as Waste. Transportation between operation steps does not make any transformation to the product that the consumer is willing to pay for. Transport therefore adds to costs without adding value. There is also a risk of the product or service being damaged, lost, delayed, etc.

4 – Over-processing:
Over-processing occurs any time that work is done to the product for which the customer is not willing to pay. Examples are the use of components that are more precise, complex, expensive, or higher quality than absolutely required. In service organizations it means unnecessary inspections, verifications and stamps. It also means unnecessary, redundant or superfluous information.

Measuring quality or inspection is also classified as 'Over-processing' as long as the measurement is used for verification only and not used to adjust or improve the quality of the product. Unfortunately, many companies cannot do without inspection in order to deliver good products or services. This is due to a low performance capability and low reliability of the process.

5 – Inventory:
Inventory is the excessive quantity of raw materials or excessive semi-finished products (Work-in-Process) between operations and finished goods. Inventory represents a capital outlay that has not yet produced an income either by the producer or for the consumer. In service organizations inventory refers to documents (complaints, requests, orders etc.) waiting between operations in the process.

A certain amount of inventory is needed in order to assure 'Flow' in the process, but it should be limited as much as possible. In a situation where activities within the process are perfectly balanced, there is almost no inventory between operations. Slowly reducing the amount of inventory is the best way to realize the opportunities for improvement.

6 – Movement:
Movement refers to the movement (walking) of operators and employees from one activity to the other activity. Searching for information (not walking) is also classified as ‘Movement’, because during the searching process no value is added to the product.

7 – Defects:
Products with defects cannot be delivered to the consumer. Documents that are not complete and perfectly clear to the customer are also classified as ‘Defects’. Not producing ‘First Time Right’ (FTR) is classified as ’Defects’ as well.

In the event that the product can be repaired or reworked, it requires resources to do so. If it cannot be repaired or reworked, it should be scrapped. In both cases extra costs are incurred for reworking, new components, rescheduling etc.

8 – Unused expertise:
Initially there were only 7 types of Waste. The 8th type of Waste has been added later. Not using the available knowledge, skills or expertise that is present in the organization is also Waste. Young people can learn from older people. Management can learn from the expertise at the shop floor etc.

6.6 Reducing Muri (Overburden)

Reducing Muri can be achieved by producing according Takt Time and implementing 'Flow' and Standardized Work. Flow should be observable and every process step must be reduced to its simplest elements or components. The number of different components and specialized steps throughout the organization should be limited. Limiting the number of different screws for instance will result in fewer tools, less training, less stock, fewer mistakes etc. A World Class example of this is the truck producer Scania. This principle is also known as 'Smart customization' or 'Modularization' [8.2.1]. Muri can also be avoided by not pushing equipment or employees to the edge of what they are capable of. Working overtime for a longer period, bad ergonomics and postponing preventive maintenance will increase the risk of Muri.

6.6.1 Flow

One of the Lean principles is 'Flow'. Taking a walk on the shop floor with an experienced Belt or Lean Sensei, the first question to be answered is 'Where is the Flow?' Flow should be visible at the shop floor. This should not be compared with people being busy. Everybody can look very busy, without having a Flow. Lean is focused on getting the right things to the right place at the right time in the right quantity to achieve perfect Flow. If operation flows perfectly without interruptions, there is no inventory or only a limited amount of inventory between process steps. This results in a lower risk off confusion and mistakes. Flow will create a continuous process to identify problems. Each problem becomes an opportunity for improvement.

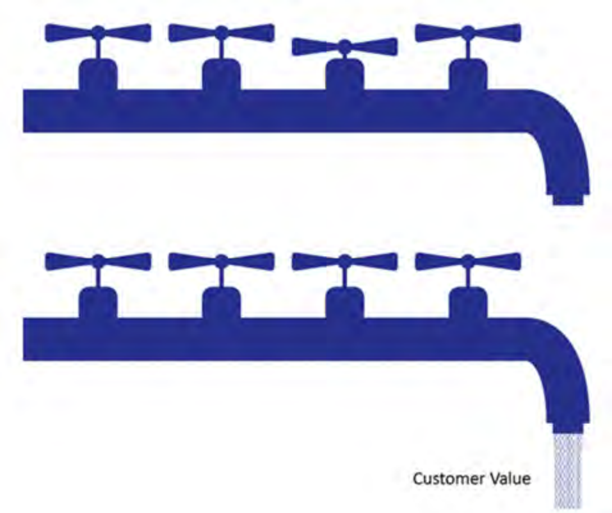


Figure 138 – Flow

If you experience no Flow, there is no Lean. The easiest way to observe flow is to take a look at both 'doors' of the shop floor. At one door you should see orders coming in (e.g. parts, components, sick patients, clients, bins, trucks, requests, etc.). At the other door you see finished goods and completed products going out (e.g. subassemblies, healthy patients, happy clients, products, passports, answers, etc.). Between these two 'doors' you should see people busy and equipment running, but more important is that you observe Flow at each work location or machine. At one side of the work location you should see work being done and on the other side of the location you should see work that is completed and moved to the next operation step. The amount of work waiting should be limited, organized and clear.

A steady and continuous Flow can be observed easily because the time for work to move between stations is constant. The amount of time depends on the type of organization, but will typically vary between a few seconds and a few minutes. It should not take hours, days or even longer. Even for very complex processes it should be possible to observe Flow. A good example is the production of trucks or treating a patient in a hospital.

Sometimes it is not possible to move the product between stations. Examples are building a house or a ship. This is very often experienced in 'Engineering-to-Order' (ETO) organizations where each product is designed and built to customer specification. When it is not possible to move the product, Flow can be experienced by bringing pieces of work to the location. It is possible to apply the Flow principle in the preparation of work packages and in the scheduling process of the people working at the product. When you see the product standing alone, without a person working on it, there is no Flow. No value is added to the product when no person is making a change to the product, even if other people have done preparatory work. If you see a group of people standing around the equipment, discussing what to do but not performing changes to the product there is no Flow.

As soon as the first added value activity on a certain product starts, it should be moved through the process in such a way that the total Lead Time is limited as much as possible. The equipment, the people or the departments are not leading in a Lean program, but customer value and eliminating Waste should be leading. You can compare this with a trauma patient arriving in the hospital. Every part of the organization is focused on getting the patient through the process as quick as possible, eliminating Waste in the process.

It is important that the Cycle Time of the process will match the Takt Time of the customer as much as possible. If the Cycle Time of the slowest operation step is longer than the Takt Time, it will not be possible to deliver the product or service on time. If the Cycle Time of the slowest operation step is less than the Takt Time, there is a risk of overproduction.

Ideally the Cycle Time should be equal to the Takt Time. However, the reality is that demand is dynamic and process disruptions can occur (e.g. unplanned downtime, employee sickness etc.). Therefore, it is recommended to organize the Cycle Time in such way that the time of the operation steps will be slightly less than the Takt Time of the customer. It is even better to make the Cycle Time flexible by enabling variation of workload in the production cells by simply varying the number of employees/machines.

In the VSM example, the Takt Time can be calculated as follows:

$$Takt\ Time = \frac{Available\ Work\ Time}{Customer\ Demand} = \frac{3 \times (8 - \frac{1}{3}) \times 20 \times 3{,}600}{(200{,}000)} = 8.28\, sec\ per\ part$$

Conclusion: the optimal speed of the slowest process should be producing a part every 8.28 seconds.

6.6.2 Work balancing

In processes, often one employee or machine has a high workload while at the same time other employees or machines are underutilized. The workload between the activities should be balanced as much as possible to avoid unevenness in the process

Let's review the process of handling requests for getting an internet connection. Time studies are performed for the four employees involved in the process. This shows that the average Cycle Time of the first stage (A) appears to be 6 minutes. The following three process steps take respectively 10, 3 and 4 minutes. The speed of the entire process follows the speed of the slowest process step, which is a Cycle time of 10 minutes. The process cannot deliver any faster than one request each 10 minutes.

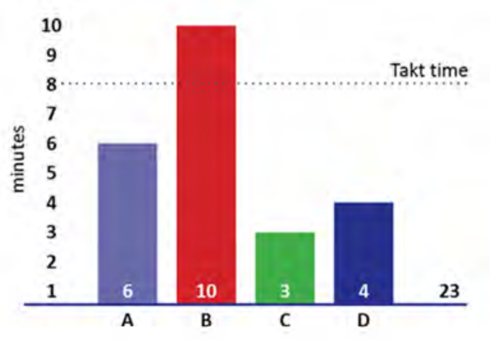


Figure 139 – Before Work balancing

It appears that the actual Takt time is 8 minutes, meaning the process is not fast enough to handle customer requests in time. The team is asked to redesign the process in such a way that it is able to meet this Takt time. Together they evaluate whether activities can be arranged in a different way between the operation steps. It appears that activities from the slowest process step B can be moved to process steps C and D, as is represented in Figure 140.

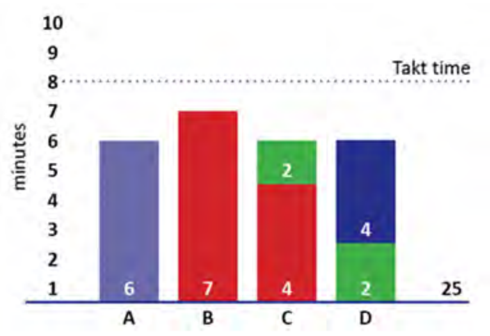


Figure 140 – After Work balancing

Although the sum of activities now takes 25 minutes instead of 23 minutes, the process is now able to handle customer requests within a Cycle time of 7 minutes which is faster than the Takt time of 8 minutes.

6.6.3 Resource management

The leveling of workload between operations will reduce unevenness and Muri. However, in some cases the inefficient distribution of competencies of employees across the different operation steps is a roadblock for workload leveling. For some operation steps you may have an adequate number of people who can perform the operation step, while simultaneously you may have a limited number of people who have the skills for performing another operation step. This will limit the flexibility of the organization to move people around operations if needed. Try to identify which competencies are a roadblock for work leveling and which activities can only be executed by one person. What will happen if this person is on holiday, gets sick or finds a different job?

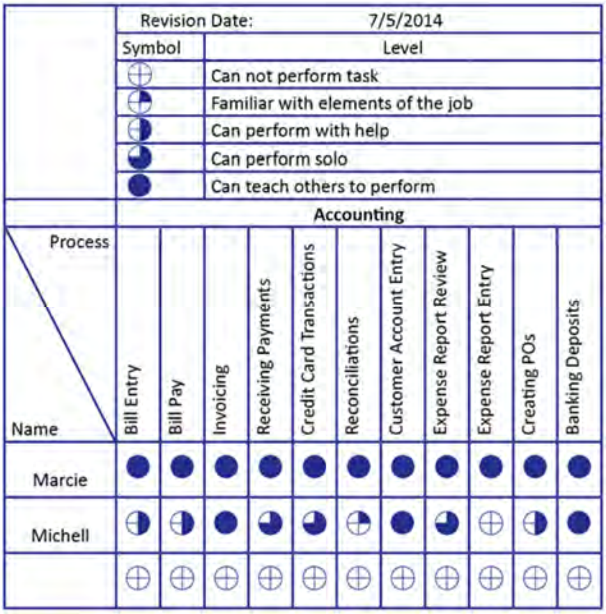


Figure 141 – Competence matrix or Skill matrix

At the same time, many organizations make no distinction in the level of expertise that employees need to execute an operation. Figure 141 distinguishes five different levels of expertise from 'Cannot perform task' to 'Can teach others to perform'. This approach will give the department manager or team leader a tool to define what competencies should be developed and what competencies are available sufficiently within the department. It can also help clarify the need to train employees and gives clarity in the difference between a very experienced employee and a less experienced employee. A program to increase the competencies in a structured way will improve the flexibility of a department. Combining this with standardization across the different departments will also increase the flexibility of the entire organization because it will be easier to shift an employee from one department to another. It will also avoid Muri by assigning employees on tasks that they are not capable of.

When striving for sufficient competencies within the organization, we should first focus on the operational steps that only have one qualified person for the job. Examples are approval steps by the manager and a professional who is the only one who has mastered a particular expertise. Subsequently, we should focus on bottleneck operations, because problems at the bottleneck operation will have an impact on the entire value stream. The '1:3/3:1 rule' indicates that each person should be able to perform three tasks and each operation should be mastered by three people. This is one of the conditions for a stable process.

6.7 Reducing Mura (Unevenness)

A common misunderstanding is that improving productivity is working faster. Lean however does not have the intention to treat every job as a sprint and to complete every task as soon as possible. Lean is not about increasing speed, but about reducing unevenness in speed in order to increase predictability. This will create a smooth and regular basis for further improvement initiatives.

“The slower but consistent tortoise causes less Waste and is much more desirable than the speedy hare that races ahead and then stops occasionally to doze. The Toyota Production System can be realized only when all workers become tortoise.”

Taiichi Ohno

Unevenness in production is called Mura. Reducing Mura can be achieved by production leveling, by product leveling and through following the ‘Just In Time’ (JIT) principle. Reducing Mura will result in a minimum of inventory on the shop floor. In order to avoid shortages and late deliveries of parts, it is necessary to develop a forecasting system to predict demand for process steps and suppliers for long Lead Times or changeover time.

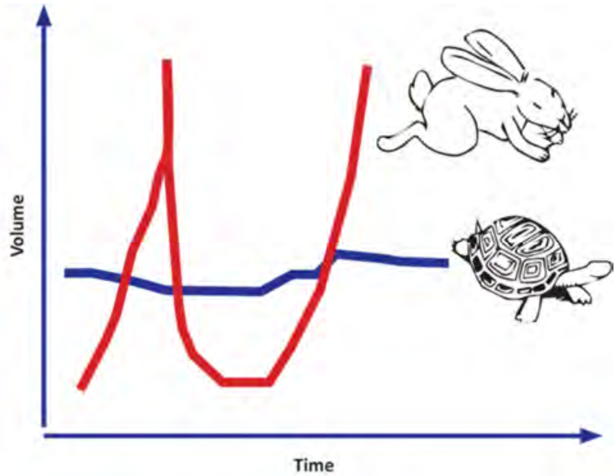


Figure 142 – Rather ‘Slow but steady’

6.7.1 Pull

Imagine what would happen if every operation in the process produced the amount of parts that it was capable of without alignment of the amounts needed by the other processes. This will result in chaos with huge piles of parts around the respective machines. These piles are pushed to the next process step in the operation in order to create space. Increasing the efficiency of only a single machine or process step will increase the logistical chaos even more. It will result in excessive quantities of raw materials and excessive semi-finished products. Observing many different products on the shop floor and many people being very busy is a signal that the organization is not Lean. As mentioned earlier: excessive Inventory means Waste. Lean organizations are organized, have oversight and demonstrate no stress.

Nevertheless, many operations apply Push. Sometimes even without realizing it. Operation managers are focusing on optimizing individual process steps or equipment especially when it concerns expensive equipment. Also, a backlog in the delivery process will result in Push-behavior when managers and logistical planners are pushing new orders into the operational process. Push will result in overproduction of finished products waiting for a customer that might never come. Overproduction is called the worst type of Waste, because all resources have been used and you cannot be sure if the product will be sold.

To avoid Waste, it is necessary to work according the 'Just In Time' principle. This can be achieved by supplying each operation step in the process with the right part, at the right time, in the right amount. This can be achieved by implementing Pull, which is the fourth Lean principle. Working according Pull instead of Push will avoid inventory and overproduction, as illustrated in Figure 143 and Figure 144. This starts with the demand of the customer, who pulls first! Pull means that the subsequent process determines the number of items that needs to be delivered by the downstream process.

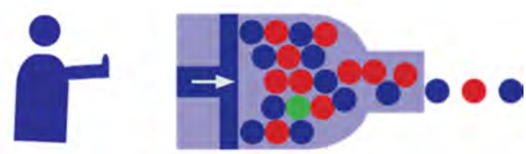


Figure 143 – Push:
Output: 1 part per minute
Inventory: 24 parts

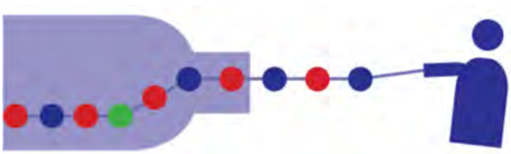


Figure 144 – Pull:
Output: 1 part per minute
Inventory: 10 parts

Pull can be applied in the process before the so-called 'De-coupling point'. This is the point where products will turn from generic parts to customer specific parts. The de-coupling point is the point where the forecast-driven elements (Push) meet the demand-driven elements (Pull). An inventory buffer will always be needed just before the de-coupling point to cater for the discrepancy between the sales forecast and the actual demand (i.e. the forecast error). Pull can be achieved by using Kanban and One-Piece Flow, which will be explained in the following sections.

Kanban

Kanban is one of the tools through which 'Just In Time' and Pull are achieved. It was developed at Toyota by Taiichi Ohno. Kanban systems control the logistical chain between operation steps by aligning inventory levels with actual consumption. It is not an inventory control system though. Kanban systems allow each sub-process to withdraw only the parts needed in the amount that is needed from the downstream sub-processes. The Kanban itself is a physical card or a digital signal that is sent to the preceding process step to indicate that certain parts are needed. Such a Kanban is called a withdrawal Kanban. It contains information about the parts that are needed, like the amount and specification. The earlier process delivers exactly the number of items that is indicated by the Kanban. The process will not produce parts when there is no production Kanban (no demand).

A Kanban is sometimes called a 'Supermarket', as the development of Kanban is based on the way supermarkets schedule demand. In a supermarket, customers obtain the required quantity at the required time, no more and no less. The supermarket only puts products on the shelves that are expected to be sold within a certain timeframe. Customers take only what they need for the next couple of days, no more. Lean organizations should treat each process step both as an internal client to upstream processes and as an internal supplier for downstream processes. As a client it should request no more than is needed for the timeframe and as a supplier it should prepare or produce no more than what is requested by its customer.

Figure 145 – Kanban card in office

Figure 146 – Kanban card in hospital

Example: Assume a process requires 100 parts per day. The parts are packaged in boxes of 20 pieces and each Kanban card represents one box. We want to calculate the required number of Kanban cards to create a 2-day supermarket of the part. We first need to calculate the consumption over two days, which is 200 parts. This process then requires 10 Kanban cards.

$$Number\ of\ Kanban\ cards = \frac{2 \times 100}{20} = \frac{200}{20} = 10$$

Two-bin system

A Two-bin system is a special Kanban system that is often applied for standard parts and small items. At a certain work location, a rack is placed with a number of positions. Each position can contain two boxes (bins) for a certain item. When the box is empty, it will be placed behind the filled box or at the bottom of the rack as is shown in Figure 147. There is no Kanban card since the empty box itself is the Kanban. In some cases there might be a flag available at the back of the rack that indicates that an empty box needs to be replaced by a full one. When the box contains standard (inexpensive) parts like screws or bolts, the amount in the box is not counted but is weighted or just filled. For inexpensive articles, a two-bin system is cheaper than controlling the stock by an ERP (Enterprise Resource Planning) system.

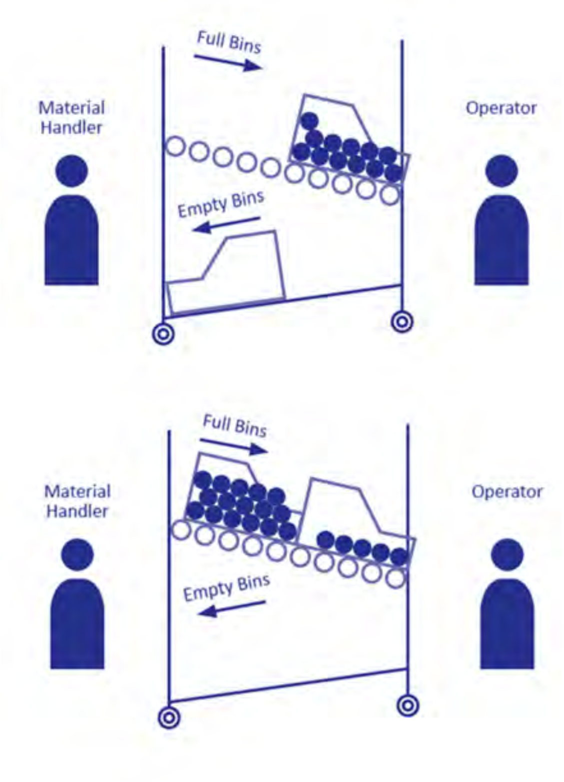


Figure 147 – Two-bin system

In office environments, this system can be used in many situations for small items like pens, paper or other office supplies. The empty box is delivered to the department's secretary who will order new pens. The system is also applied a lot in hospitals for small items like bandages or needles.

First-In-First-Out (FIFO)

Applying Type leveling and One-Piece Flow in production can be achieved by applying FIFO lanes that can hold only a certain amount of parts or products. FIFO stands for 'First-In-First-Out'. The purpose of this system is to reduce and control inventory between process steps. It is the responsibility of the planning department to place customer orders in the right sequence according to demand and certain priority rules. It is the responsibility of the operation department to complete the requested orders in the right sequence, without changing priorities again.

While Kanban systems are applied before the de-coupling point, FIFO lanes can be applied after the de-coupling point at the location in the process where products become customer specific or model specific. Let's consider a mass producer of four different types of headphones. The company receives customer orders from their clients for one of the models; A, B, C or D. The de-coupling point in the process is the point where it is determined if a headphone will be model A, B, C or D. The planning department sends the order to the de-coupling point of the production line. After this point orders will follow the First-In-First-Out concept until the headphones are completed. Also, there should be minimum inventory levels from the de-coupling point to the end of the line.

A FIFO lane can be a belt or trolley that is used to move products between stations. The products will remain in the same order and cannot overtake each other. If the FIFO lane is full, no Kanban is released to the upstream process until inventory is used up. In some cases, employees can sit next to each other and move the parts to each other. One-Piece Flow is the most optimum way of moving parts.

Scheduling the Pacemaker

In a Lean organization, the scheduling instructions are introduced only at one point in the 'door-to-door value stream'. Controlling the so-called pacemaker process sets the pace for all downstream processes. Upstream the pacemaker process we have to apply Pull, using supermarkets and Kanban cards. At the same time FIFO lanes will be applied after the pacemaker to assure Flow.

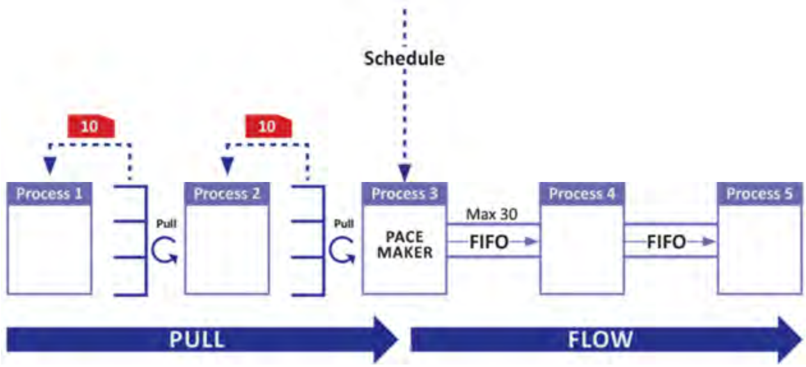


Figure 148 – Scheduling the Pacemaker

Theory of Constraints (TOC)
TOC is also called Bottleneck management or Constraint management. The concept of Theory of Constraints was introduced in the mid-80s by Eliyahu Goldratt (1947-2011). A wide awareness and understanding of the TOC methodology was first accomplished through people reading the book, 'The Goal'. (Goldratt & Cox, 1984) [11.]. This is a novel that continues to be enjoyed by managers and not only criticizes the assumptions and decisions of managers, but also provides a sensible alternative.

The basic concept of Theory of Constraints (TOC) is often introduced through the chain analogy. A chain is only as strong as its weakest link. Not operating the bottleneck (weakest link) for one hour should be considered a loss of output for the entire organization because the bottleneck will never be able to catch up the backlog. Activities that do not improve the performance of the bottleneck most likely do not improve the total system and therefore it is considered to be Waste. Although you might think this approach is common sense, it is surely not common practice.

One of the TOC basic concepts is about finding and speeding up the bottleneck, which will reduce Muri (Overburden). In the book 'The Goal', this bottleneck is called 'The Herbie'. After solving the first Herbie, you look for the next Herbie and the next, etc. Every process has a Herbie. This bottleneck (or constraint) is the limiting factor in the capacity of the entire system.

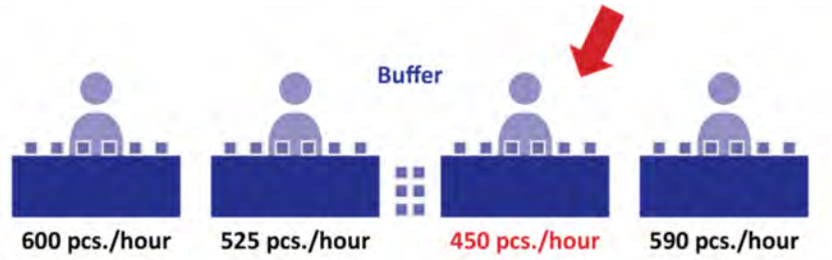


Figure 149 – Theory of Constraints

Although solving Herbies is very powerful, the full concept of Theory of Constraints incorporates more than this. TOC is about managing the total system, which includes all system constraints (e.g. money, equipment, competencies). This comprises interdependencies and variability to ensure maximum bottom line results for the organization. First, TOC is about focusing on the system's leverage points and then on how all products of the system impact the operation of the leverage points. This is the way to achieve total system improvement, not just localized improvements. TOC contains a number of special elements such as the Money-making machine, Focusing steps, the Drum-Buffer-Rope planning model and Value-added thinking. However, these elements are outside the scope of this book.

Strictly TOC is not part of Lean, but it fits perfectly into Lean principles like Value, Flow, Pull and Just In Time. As mentioned, one of the Lean techniques is to schedule the pacemaker in a Value stream, which is similar to the Drum-Buffer-Rope principle of TOC.

6.7.2 Volume and Type leveling

Mura relates to variations in production. These are on the one hand caused by variations in the requested volume, and on the other hand by a variation in type. An organization should focus on reducing variation and also to cope with variations better. This will lead to a more flexible production with less stress and fewer errors. In Japanese this principle to reduce unevenness is called Heijunka, which means production leveling or production smoothing. In this section we will discuss two elements volume leveling and type leveling.

Volume leveling
Volume leveling means that organizations operate at levels of long-term average demand. Inventory buffers need to be kept proportional to the variability in demand, stability of production process and shipping speed. Heijunka also indicates whether production is ahead of schedule or behind schedule.

Organizations can apply certain tools and scheduling rules to ensure that the process has as little encumbrance as possible due to fluctuations in customer demand. Most organizations will have little influence on fluctuations in customer demand though. You simply cannot tell the customer when to order a product or service. One way to cope with this fact is to try to improve the predictability of demand. Most organizations will have some kind of prediction model and sales forecasts, which will help them to anticipate on fluctuations in demand. For some organizations it is easier to develop such models than for others as all business are different. Some organizations have seasonal demands; some have an extensive variety of different products, while others have a very regular and stable demand of one single product. However, it appears that even the emergency department of a hospital is able to predict the number of patients that will arrive at certain days of the week and at certain times by analyzing historical data. A good prediction of demand can be used to define the number of resources that will be needed. Techniques that support production leveling are Heijunka boxes, Kanban and CONWIP scheduling.

Figure 150 demonstrates the order schedules for two departments A and B. Both schedules have a loading of 280 products in a week. Department A demonstrates an enormous fluctuation in loading, as it is not leveled. Department B demonstrates a loading of 40 pieces every day. Once every month a forecast is made to verify if a loading of '40 pieces per day' is still in line with the Takt Time of the clients.

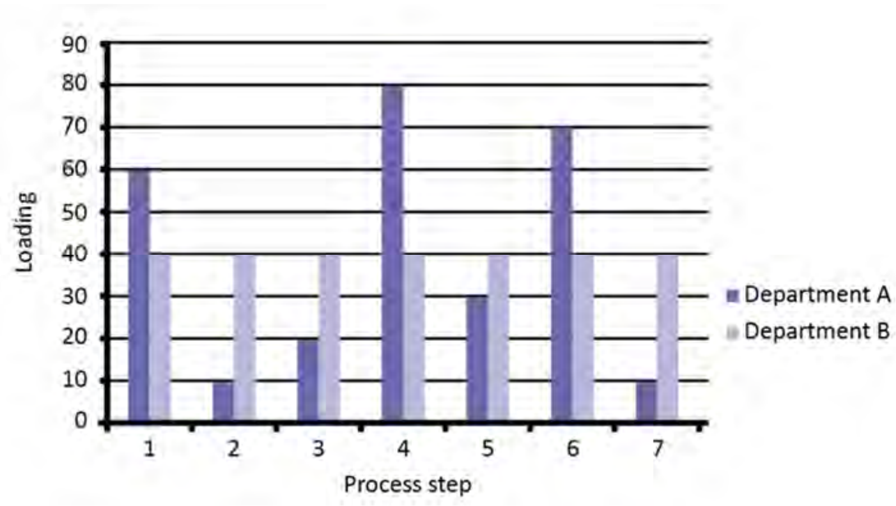


Figure 150 – Work leveling (department B)

Type leveling

The essence of Type leveling is to make every part every day. Type leveling in a transactional environment involves, for instance, scheduling meetings at a fixed time of the day, week or month. Another example is to categorize performance measures in groups that will be reviewed each day, each week or each month. As such type leveling improves predictability, everybody knows what to do and when.

Let's consider the mass production of kid's bikes. The manufacturer receives orders from department stores for one of the models: A, B or C. Since the company is trying to minimize Waste around equipment changeovers, the production schedule as represented in Figure 151 (left): 15 times model A, 10 times model B and 5 times model C.

However, it might happen that at the last minute a client decides that volumes of model A need to be model B instead and that volumes for model C suddenly increase. These kinds of changes put an enormous amount of pressure on the manufacturer. For example, imagine that a large batch of model C is already in production, causing an increased Lead Time for model A that is produced on the same production line. The planning department might now choose to stop the order that is already in production. Another option might be to increase resources, capacity and inventory when the change in demand is encountered. The customer services department will have to work overtime to discuss the resultant late deliveries with clients and redefine priorities together with sales and planning. This example might look exaggerated, but it is pretty common in many organizations. Running your organization as a mass producer will increase Waste. To avoid such Waste, the principle of 'Type leveling' should be applied as represented in Figure 151 (right).

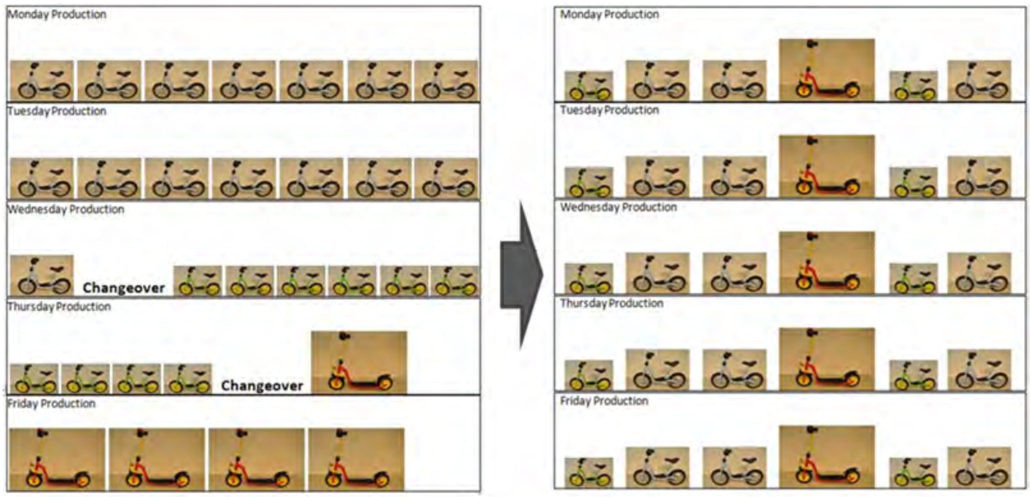


Figure 151 – Type leveling (before and after)

One-Piece Flow
A term that is related to Type leveling is 'One-Piece Flow', which demonstrates that the ultimate goal of an organization should be the ability to produce one single product at any moment. It might sound strange, but One-Piece Flow does not necessarily mean 'One-Piece'. It can also refer to a very small batch size.

An advantage of One-Piece Flow is that quality problems will be discovered earlier. Imagine that bike model A has a problem with the brakes. In the traditional situation we would have produced 15 bikes of model A before the mistake was discovered at the downstream process. In the new situation we would have produced only one bike of model A when the problem was discovered. Since the operation is now more flexible, we will be able to postpone the production of model A for a while so that the problem can be solved. Once that is done, the production of model A can be resumed.

Batch production:

- Every process step has its own inventory.
- Production is moved in batches.

Figure 152 – Batch production

One-Piece Flow:

- No inventory between process steps.
- Production is moved by single piece.

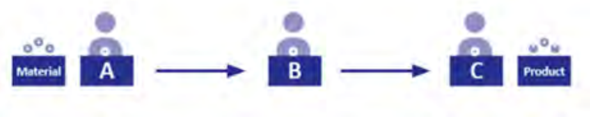


Figure 153 – One-Piece Flow

Service organizations should try to reduce batches and aim for One-Piece Flow as well. Although you might feel that working in batches is more effective, it is not. The best way to convince people is to show them a few videos that can easily be found on YouTube. This will explain the concept far better than a verbal explanation would. Challenges that service organizations experience in changing-over are very often related to limitations in IT-systems and limitations in employees' competencies. The limitations in the IT-system are related to logging in and out to different systems and systems not being integrated. Improving transactional processes is therefore very often related to improvements in IT-systems.

Implementing Type leveling or One-Piece Flow will increase the number of changeovers. This seems illogical but the reduction of Waste, the need for less capacity and an increased flexibility is in favor of Type leveling and One-Piece Flow. It does emphasize the need for efficient changeover times and smart inventory buffers. Type leveling therefore cannot be implemented without Quick Changeover initiatives. This can be achieved by Skill development of employees, by improving IT-systems in transactional processes or by SMED projects.

CONWIP

One tool that can be used to manage Work in Process and to avoid unevenness in customer demand is the 'CONWIP', which is an abbreviation for 'CONstant Work in Process'. An example is shown in the picture below. Each column on the board represents a different operation on the shop floor (equipment or process step). The left part of the column is the line of orders that are waiting to be operated, while the right part of the column contains the orders that are currently being worked. When the employee has completed a specific order, the system will show him what the next operation step of the order is. The employee will then move the tag on the board to the respective column and place it at the bottom of the waiting list. Then the employee will pick the upper tag in the column of his own operation and move it to the right part of the column. When the last operation step of an order has been completed, the tag will be removed from the board and placed in a bin for 'completed orders'. The planning department can take the tags, complete the logistic information in the system and use the tag to bring a new order into production.

Figure 154 – CONWIP system on shop floor

The difference between a FIFO lane and a CONWIP system is that the latter has the option to distinguish normal orders from rush orders by designing a special (horizontal) lane and special tags for rush orders. To prevent all orders being assigned as rush orders, it is recommended to limit the associated tags to about 15% of the total number of tags and give these a special color. When an employee is looking for the next order to work on, waiting rush orders should be picked before normal orders. Only if there are no rush orders at all, a normal order should be picked.

The CONWIP system involves a number of benefits. First of all the CONWIP board visualizes all orders on the production floor. At a glance everybody can see the status of all orders that are present at the shop floor. When a certain operation contains many tags, it is clear that orders pile up and are waiting. Many tags in a certain column normally represent the bottleneck of the operation and visually indicate that the operation needs extra attention or support.

A second advantage of the system is that the board contains a number of tags that represent a fixed number of hours on the shop floor. As it is not possible to add more orders into production than the fixed number of hours, the average Lead Time of an order can be predicted by applying Little's Law [paragraph 6.2.1]. Since the number of rush order tags is different than the number of tags for normal orders, the average Lead Time will be lower. A good prediction of Lead Times will improve the predictability of the department, which will support the reduction of unevenness.

Heijunka box
Toyota introduced a simple tool to support both Volume leveling and Type leveling, which is called the 'Heijunka box'. In these boxes, work is allocated to certain time slots to ensure that everyone knows exactly what work should be undertaken when and how much time is available for a certain amount of work.

A typical Heijunka box has horizontal rows for each product family and vertical columns for predefined time intervals of production. Figure 155 demonstrates four different types of products (Invoice, Check request, Credit memos and Expense reports). An example is demonstrated of how the production time of one day is divided into eight time slots of one hour. Different durations of time slots can be used though. Very often the final slot is not representing a time slot, but is used to collect the work that has been completed during the day.

Kanban cards are placed in the slots of the Heijunka box. There are two options to do this. The first option is to place one Kanban card per time slot that contains a number of work orders. Each Kanban then represents one hour of work load. Only one Kanban can be placed per vertical column (per time slot). The second option is to use one Kanban for each order. In that case it is necessary to list the amount of Kanbans that can be placed per vertical column.

The Heijunka box is one of the 'Visual Workplace' tools that are used to visualize the operational process. Employees will walk to the box and see immediately what they need to work on and they can see immediately if they are ahead of schedule or behind.

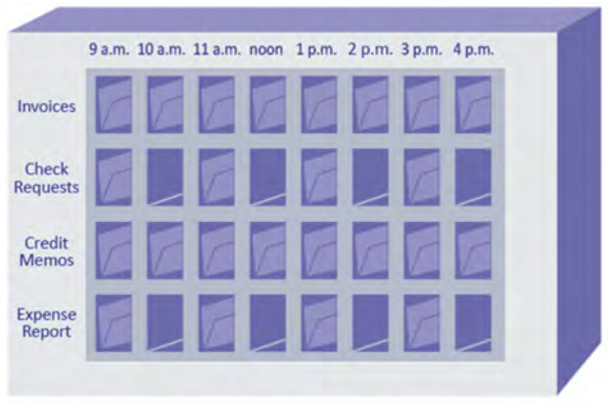


Figure 155 – Heijunka box (Accounts payable)

Modularization

Offering every customer, a tailor-made product at the right time. That is the principle of Modularization. Each product is made entirely to the customer's specification. Combining customization and Operational Excellence at the same time is possible by using a limited number of components. In one way you can compare Modularization with LEGO: one set of standardized parts and components with the same interface. The concept of modularization contributes to shorter Lead Times, higher quality, lower operational costs and reduced stock levels and inventory.

The Swedish truck and bus manufacturer Scania is one of the leading industry examples in Modularization. It has been developing its modular product range since the 1930s. The cabs are strongly modularized with a common frame, same door structure (different heights) and modularized side panels (different heights and lengths). The windscreen and rear wall are the same on all cabs. The axles are standardized and used in the 2, 3, 4 and 5-axle trucks and buses. Scania's engine range is based on the three series featuring five, six or eight cylinders, while using the same cylinder and components in all engines.

Applying standardized components lowers development time. For example, the Scania engine developers can focus on optimizing the combustion in one cylinder, which can then be used in all engines. Servicing vehicles is cheaper as well. Imagine when a truck driver faces a chipped windscreen being 1,000 kilometers away from home. The truck driver is able to drive to the first service point where they will have only one type of windscreen in stock. And this one windscreen fits!

Modularization is based on standardization of the interface's connection points between component series to ensure that they fit together in different combinations. These interfaces are designed in such a way that they do not change over time. This makes it possible to install new components with improved product performance without any need to change the associate components.

Now try to extrapolate this approach of Lego-like modular components to your own organization. Do you see the opportunities? Of course, your first reaction may be that it is not possible to meet customers' requirements (Black thinking hat). Then realize that the focus of Scania is to deliver customized cars to each of its customers. Now try to use your 'Green thinking hat' instead and imagine how your organization might look like if you were able to start product development from scratch. Keep in mind that Scania started 85 years ago with its modular concept. It is not done overnight either.

Figure 156 – Scania's Modular system

Order fulfilment

Order fulfilment is the complete process from point of sales inquiry to product delivery to the customer. The order fulfilment strategy has strong implications on how companies customize their products and deal with product variety. The following order fulfilment strategies can be distinguished [12.]:

- Engineer-to-Order (ETO):
  The product is designed and built to customer specifications. No product is the same. This strategy is very common for large systems and construction projects.
- Build-to-Order (BTO) or Make-to-Order (MTO):
  The product is based on a standard design. The production of components and the manufacturing of the final product are linked to the customer order and specification. This strategy is typical for vehicles and aircrafts.
- Assemble-to-Order (ATO):
  The product is built according to customer specifications using components from an existing stock. This requires modular product architecture. Typical examples are computers and subsystems of vehicles which are produced in this way.
- Make-to-Stock (MTS):
  The product is built against a sales forecast and sold to the customer from finished goods stock. This strategy is very common in the retail sector and consumer electronics.
- Digital Copy (DC):
  Products are digital assets. Inventory is maintained as a single digital master. Copies are created on-demand, downloaded and saved on customers' storage devices.

The same fulfilment strategies can be applied for transactional processes. Within transactional processes the chain of transactions and order statuses is called the order fulfilment pipeline.

	Manufacturing	Service
Engineer-to-Order (ETO)	Luxury yacht	Architectural design
	Office building	New laws
Make-to-Order (MTO)	Car	Treatment in hospital
	Boat	Trip around the world
Assemble-to-Order (ATO)	Computer	Passport
	Car engine	Phone bill
Make-to-Stock (MTS)	Coffee machine	Bus ticket
	Shampoo	Concert
Digital Copy (DC)	Music download	
	Software license	

Table 22 – Order Fulfilment

Each of the different order fulfilment strategies has a different de-coupling point in the process. The de-coupling point in the process is the point where the product becomes customer specific. Before this point the product is generic. After the de-coupling point the product is meant for one specific customer. Within the Engineering-to-Order strategy the de-coupling point is at a very early stage. Within the Make-to-Stock strategy there is no de-coupling point because all products are equal.

6.7.3 Quick Change Over (SMED)

The aim for One-Piece Flow or smaller batch sizes can cause logistical problems at complex equipment, because it requires a changeover. Changing a mold for instance requires a lot of time and changing-over after every single product does not make sense. According to Shigeo Shingo, a winning team cannot survive without quick change-overs. Undoubtedly, the best example for this is demonstrated by changing the tires in the pit stop during a formula 1 race. The world record for changing all four tires is around 1,88 seconds, by the Red Bull team! This requires a smart design, proper preparation, training and excellent teamwork.

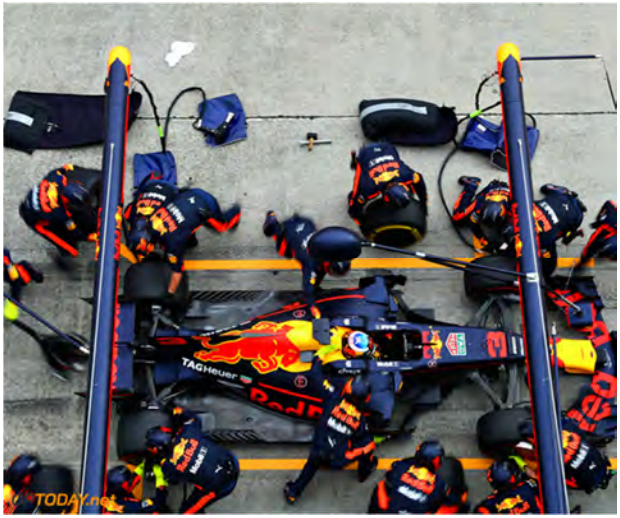


Figure 157 – Tire change Red Bull team

To translate the F1 pit stop approach to the manufacturing process, Shigeo Shingo developed the SMED-process at Mazda, Mitsubishi and Toyota from 1950 to 1960. Shingo called the initiative to reduce the changeover time ‘SMED – Single Minute Exchange of Dies’, where single minute refers to ‘one digit’, meaning less than 10 minutes’. SMED is an analytical method with the objective to reduce materials, skilled resources and time necessary to set-up equipment. This also includes the time that is needed to run smoothly after a changeover. The advantages of quick changeovers include increased availability, greater flexibility, shorter Lead Times, less start-up losses and prevention of investments.

The SMED approach incorporates an eight-step approach:

1. Choose project.
2. Evaluate current achievements.
3. Define internal & external activities.
4. Categorize internal activities externally.
5. Streamline the process (eliminate adjustment activities).
6. Test proposed changes.
7. Verify results.
8. Implement improvements.

An important element to reduce the changeover time is to move activities as much as possible outside the time of the actual changeover, which means before the moment that production is stopped. External activities like preparation and cleaning can be done while the machine is still running.

6.8 Value Stream Improvement

It is not the intention of drawing a Current State VSM to identify Waste, problems and improvement opportunities and to immediately solve each one. This is not efficient and will most likely not help achieve the real potential benefits. The purpose of the Current State VSM is to provide the basis for designing the Future State VSM. Green and Black Belts should define the Gap between the Current State and the target condition and then develop a Future State map.

6.8.1 Value Stream Mapping (Future State)

Designing the optimal Value Stream is done behind a desk. By following the steps below, you will find that the end result will be totally different than whatever you have imagined on the Gemba or by making some quick-wins. The resultant Future State map will be the optimal logistical flow that can be used for the next 1-3 years.

Questions that will be answered during constructing the Future State map are:

- What sources of Waste can be identified?
- Where can we implement continuous flow?
- Where do we need pull systems (Kanban) to manage upstream production processes?
- What is the pacemaker in our process?
- How often do we release work at the pacemaker process?
- How do we level the workload?
- How do we level the production mix?
- Which improvements do we need to become more Agile?
- How can we prevent failures and deliver 'First Time Right'?

In the previous sections we reviewed several tools and techniques that can be used to construct the Future State Value Stream Map. Not all tools have to be used in each situation. Which tools should be used depends on the situation. The following improvements have been made to the pen assembly process. The result is represented in the VSM Future State on the opposite page:

- Implement a Supermarket at dispatch for finished goods.
- Reduced stock levels at dispatch and daily shipments to client.
- Implement a Supermarket in the warehouse for Tubes.
- Reduced component stock levels at warehouse and daily shipments from supplier.
- Leveling of production volume.
- Schedule Pacemaker process.
- Combine all assembly operations, testing and packing into one 'U-cell'.
- Work balancing within the 'U-cell' between the four operators.
- Solved quality issue by Kaizen event at testing operation.
- Shorter distances between process steps.

Example: assume these actions have resulted in a lower total Cycle time, higher quality, less space, one operator less, less WIP and shorter Lead time. Also important is that the Cycle time of the U-cell now is 28/4 = 7 seconds. This is lower than the Takt time of 8.28 seconds. The VA% is calculated as follows:

$$VA\% = \frac{VA\ Cycle\ Time}{Lead\ Time} \times 100\% = \frac{12}{(414{,}025 + 12 + 16)} \times 100\% = 0.00290\%$$

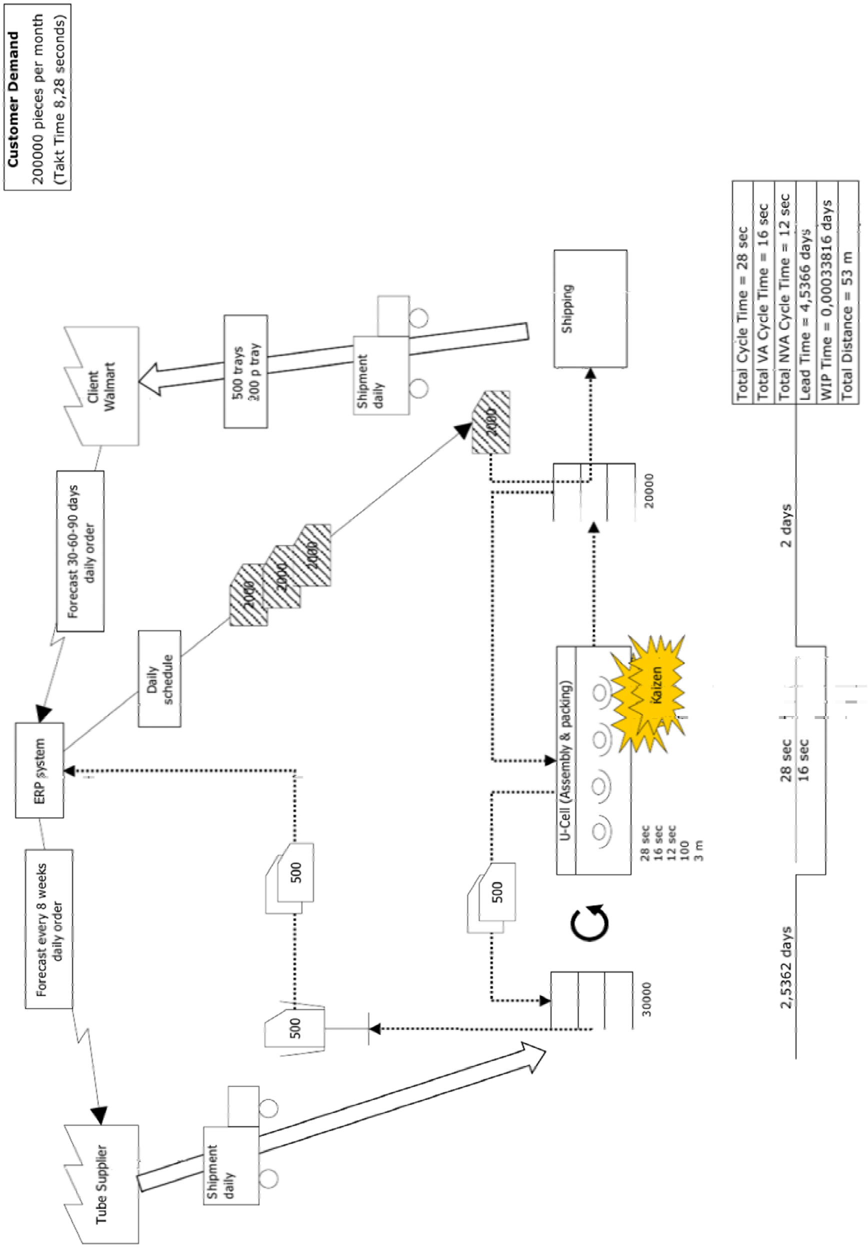


Figure 158 – Value Stream Map – Future State

Lowering the water level
As mentioned earlier, 'Seeking Perfection' is one of the Lean principles. A way to drive Continuous Improvement is 'Lowering the water level'. This is a metaphor of a boat on a river and a number of rocks at the bottom of the river. If a company is not Lean, problems are hidden in a 'sea of resources'.

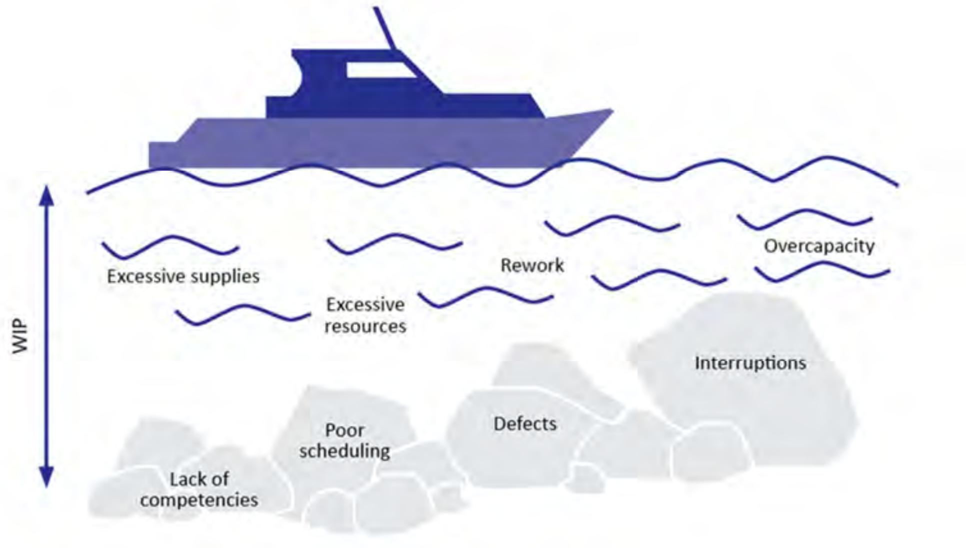


Figure 159 – When an organization is not Lean

This water level is equivalent to the amount of resources, labor, equipment and intermediate goods. It is also equivalent to the amount of orders and work in process on the shop floor. The higher the water level, the more resources and work in process is present on the shop floor. If an organization has many hidden problems, there are also many rocks at the bottom of the river. The organization also needs a lot of water to make sure that the process does not get stuck.

For someone who has no experience with Lean it may seem like it goes well with this organization. Everyone is very busy; all equipment runs and there are many orders. But a 'high water level' is an indication that there are hidden problems in the organization. If an employee experiences a problem, most likely this order is placed aside and the order is picked. As a result, orders will end up in a queue for processing, inspection or transport. As mentioned earlier these are all examples of Waste (Muda). We have previously explained that the average processing time will increase when increasing the level of work in process (Little's Law). Therefore, a high-water level is equal to long lead times. Further, if a problem is not solved, there is a risk that the same problem will occur again.

Lean states that problems should be fixed before continuing the operation. By lowering the water level, we highlight the problem areas and identify the 'rocks' that we need to eliminate first. Lowering the amount of WIP on the shop floor can be done by reducing the number of orders in the system. Problems will be exposed by 'lowering the water level' (Figure 160). By eliminating problems (rocks) we become Lean.

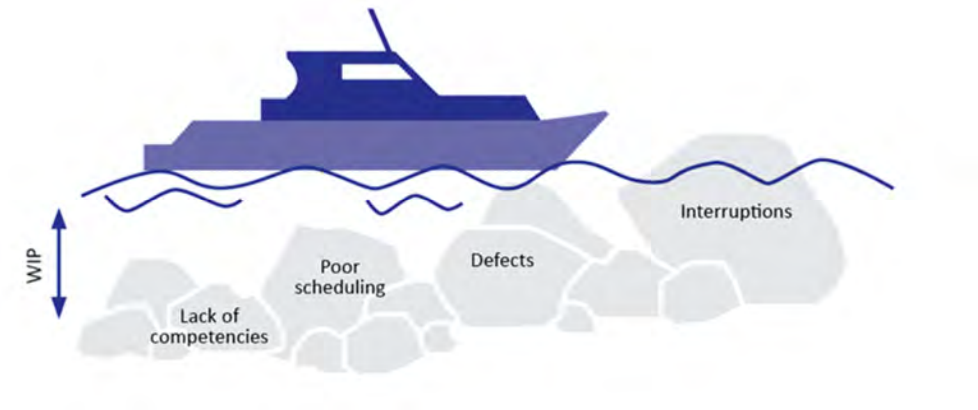


Figure 160 – When an organization starts to be Lean

Be careful not to lower the water level too fast. An operation might come to an abrupt end when it hits too many rocks at the same time. The ultimate risk is that the operation will stop completely and will not be able to deliver any orders anymore. This is, of course, not the intention of implementing Lean. The purpose of seeking perfection is to improve continuously, taking small steps. When hitting one rock, you should increase the water level a little bit, making sure production can continue. Then you should start a Kaizen initiative to remove the rock. Then you can continue lowering the water level again. So, the process of removing the obstacles should be steady, one step at a time.

6.8.2 Control Plan

Another important technique for First Time Right and risk management is the Control Plan. The Control Plan follows the same steps as the Process FMEA. During the preparation of the Process FMEA, it is determined which verification measures must be implemented in the process to identify any deviations. These are noted in the Detection column and must be transferred exactly to the Control Plan. The Control Plan is a direct reflection of the Process FMEA. A change in one document must therefore also be made in the other document. Changes to the Control Plan are reflected in the Detection column and detection evaluation of the Process FMEA (step 8). The PFMEA and the Control Plan are two different techniques, but they are linked in this way.

The Control Plan provides a detailed description of inspections and measurements on the process or product and thus includes all inspections on the manufacturing or assembly process of the finished product at the end of the line such as start-up checks, part measurements, visual inspections, statistical process control, checks on process settings, etc. The Control Plan also describes which measuring instrument should be used, how much and how often the inspection must be carried out. Finally, the Control plan indicates what must be done if a deviation is found, in other words a so-called 'Out of Control' situation. This document is therefore also called the 'Out-of-Control Action Plan' (OCAP). Sometimes an inspection plan is derived based on the Control Plan. This is a more practical document, specifically intended for the employees who carry out the process. It contains only the information that is useful and necessary for them. Figure 161 demonstrates an example of a Control Plan. Each of the columns is explained as well:

1			2				3					4
Part/ Process Number	Process Name/ Operation Description	Machine, Device, Jig, Tools, for Mfg.	Characteristic			Special Char Class	Methods					Reaction Plan
			No.	Product	Process		Product/ Process Specification/ Tolerance	Evaluation/ Measurement Technique	Size	Freq.	Control Method	

Figure 161 – Control plan

1. Location:
    a. Process number.
    b. Process step description.
    c. Equipment needed.

2. Characteristic that needs to be inspected:
    a. Product, process or dimension.
    b. Classification.

3. Method:
    a. Specification.
    b. Measurement Gage.
    c. Size: Number of units to be inspected.
    d. Frequency: How often an inspection should occur.
    e. Measurement method: How measurement needs to be performed and by whom.

4. OCAP / Reaction plan:
    a. What needs to be done in case of an 'Out-of-Control' situation.

Control

6.9 Process and Quality Control

The objective of the Control phase is that solutions that have been implemented to improve the process performance will be embedded in the process and organization, to assure that improvements will sustain after the project has been closed. This is a critical element to make an improvement project successful. Figure 162 presents an overview of several techniques that can be used in the Control phase.

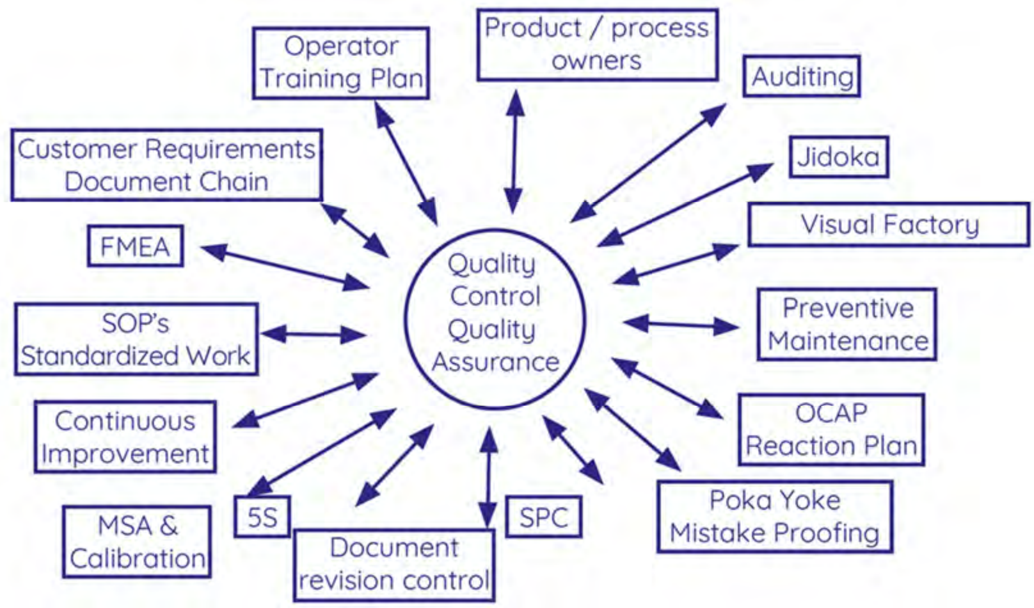


Figure 162 – Quality Control & Quality Assurance measures

6.9.1 First Time Right (FTR)

Making an error is human. You can expect dedication and commitment from employees, but you cannot expect that employees will never make mistakes. Below a number of human mistakes are listed:

- Forgetfulness.
- Misunderstanding.
- Incorrect identification.
- Lack of experience.
- Arrogance or being (too) fastidious about rules or details.
- Inadvertency or sloppiness.
- Slowness.
- Not following the standard.
- Surprise (unexpected machine operation, etc.).
- Intentional (sabotage).

You also have to keep in mind so-called ‘Red Flag Conditions’, meaning that the probability that errors will happen is high in certain situations. Consider the following conditions and realize what might happen:

- Lack of Standardized Work (everyone needs to be a specialist).
- Symmetry (a component can be mounted in different ways).
- Rapid repetition (too fast to handle).
- High volume (too much to handle adequately).
- Poor environmental conditions (high temperature, bad lighting making a task more difficult).
- Adjustments (changes in forms, equipment, design, process etc.).
- Start-up new series (changes in documents, tooling etc.).
- Many or mixed parts (confusing overview).
- Multiple steps for one person (confusing the ability to see progress at a glance).
- Non-frequent production (no experience, no rhythm).

It is the employee’s responsibility to be dedicated, but it is the system’s responsibility to prevent mistakes. In order to reduce the Cost of Poor-Quality, it is necessary to produce ‘First Time Right’ (FTR) by preventing mistakes and damage, rather than repairing or inspecting. In the control phase we focus on delivering the right products, fit for purpose and without quality problems. The best way to address this is during the design phase of the product or service and to design a feature or constraint to prevent the mistake. We will discuss this in the section about Poka Yoke. We will also review how to perform a process risk analysis (PFMEA) for a Control plan.

Figure 163 – First Time Right

Poka Yoke
Poka Yoke is a Japanese term that means 'Mistake-proofing'. The concept of Poka Yoke was adopted by Shigeo Shingo in the 1960s to industrial processes designed to prevent human errors. It is one of the elements in the Toyota Production System. It was originally called 'Fool-proofing' or 'Idiot-proofing', but later on it was changed to be 'Mistake-proofing' to help focus on the process and maintain respect for the person.

Poka Yoke refers to any constraint designed into the process or product to prevent incorrect operation by the user. Its purpose is to eliminate product defects by preventing, correcting, or drawing attention to human errors as they occur. Originally it was applied in manufacturing processes where a physical feature is designed into the product or tooling to help an operator avoid (Yokeru) inadvertent errors (Poka). Examples can be found in everyday life, like cable connectors that can only be mounted in one orientation. Another example would be an automatic transmission car that requires the gear lever to be in 'Park'-position before the key can be taken out. Also, transactional processes and healthcare examples of Poka Yoke can be found in forms, like the use of radio buttons, checklists and drop-down menus instead of text fields to prevent entering incorrect data.

As most of the physical features have to be defined in the design phase, Poka Yoke is an important element in the design of new products.

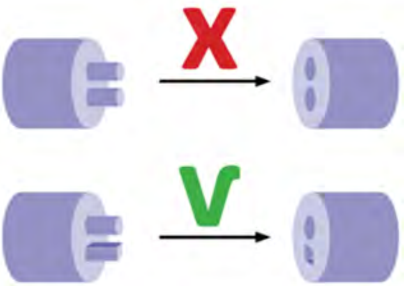


Figure 164 – Poka Yoke example 1

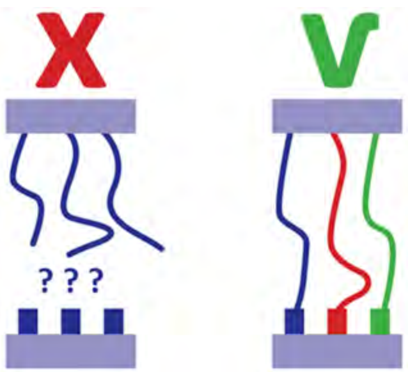


Figure 165 – Poka Yoke example 2

Jidoka

Jidoka is the principle that every person is authorized to stop the line when a quality problem occurs. Actually, it is each person's obligation to stop the line when they observe a problem. If a quality problem occurs, the Flow should be stopped and the issue should be resolved before the process can continue. This approach is an enabler to build-in quality at each process step rather than inspecting quality at the end of the line or putting parts aside when an abnormality occurs. If quality is inspected only at the end of the line, the problem will be detected much later and more products in between operation steps will contain the same quality problem.

Figure 166 – Andon light

Figure 167 – Emergency Stop

Providing machines with the ability to detect abnormalities and immediately stop operations is called Autonomation. This is very often visualized by so-called 'Andon lights' at the top of a machine. Employees can stop the line by pulling a cord, called the 'Andon cord' or by pressing a red 'Stop button'. However, other ways can be applied as well like scanners, signatures or changing a status in an IT system.

Figure 168 – Andon cord

An example of applying Jidoka in an office environment is empowering hospital staff to stop the process if procedures aren't being followed, because continuing the treatment might harm the patient. Another example is to stop the process when a calculation mistake is discovered in the system. It should be repaired instead of being reworked over and over again.

Jidoka is one of the two pillars of the Toyota Production System along with Just In Time. It is an important principle to produce products and to deliver services First Time Right. However, many operation managers are scared of applying Jidoka across the entire operational process. Theoretically the line might be stopped every minute at a different operation step when a problem occurs, driving the total organization crazy and having not a single product delivered by the end of the day. This is indeed a big risk if the quality performance level is low at the different operation steps. The real meaning of Jidoka has been understood incorrectly for a long time by the Western world. To prevent this, the following three elements should be taken into account:

1 – Implement slowly:
Start slowly, rather than stopping the line for every single abnormality from day one. Lines should be stopped for major problems and the organization should solve this problem and make sure it will not return again. Then slowly lowering the water level stop lines for smaller problems.

2 – Kaizen culture:
Implementing Jidoka will not work if there is no culture for Continuous Improvement, if employees are lacking the skills of problem solving or if there is no structure or time for solving problems. A Kaizen Continuous Improvement culture and applying the problem-solving tools as discussed in chapter 5 will be needed in order to implement Jidoka.

3 – Small buffers between lines:
Applying Jidoka should be aligned with other Lean principles such as One-Piece Flow and Stock reduction between lines. If these principles are not aligned, there is a big risk of shutting down lines completely when an abnormality occurs. To avoid this, small buffers between lines or departments should be held to keep on running other parts of the lines for a certain amount of time, while the abnormality is solved.

6.9.2 Process FMEA (PFMEA)

'Process Failure Mode and Effect Analysis' (PFMEA) is a structured risk analysis method that is used to identify potential failure modes in processes, products or services and to plan actions so that the negative effects will be minimized. It was one of the first systematic techniques of failure analysis. The FMEA is sometimes called PFMEA, meaning process-FMEA.

Figure 169 – Cause & Effect

FMEA was initially developed in the 1950s to study problems that might arise from the malfunction of military systems. In 1993, the Automotive Industry Action Group (AIAG) and the American Society of Quality Control (ASQC) established the standardized FMEA method as a part of APQP. In 1996, the VDA released their own FMEA method, where after in 2019 the AIAG and VDA harmonized their methods in one standard: The FMEA Handbook. Nowadays the FMEA methods are being applied in many different industries, varying from the high-tech industry to the service industry. FMEA includes review of the following:

- The process — the consecutive activities
- The objective — what requirements must the result (product or service) meet?
- Failure modes — what could go wrong (deviation from the objective)?
- Failure causes — why would the deviation occur?
- Failure effects — what would be the consequences of the deviation?

Teams apply FMEA analysis to evaluate processes for possible failures and to prevent them by correcting the processes proactively, rather than reacting to adverse events after failures have occurred. FMEA is particularly useful in evaluating a new process prior to implementation and in assessing the impact of a proposed change to an existing process. There are different types of FMEA. The two most common are:

- Design FMEA (DFMEA):
  Analyzes functions of the design. Used to analyze product designs before production release.
- Process FMEA (PFMEA):
  Analyzes functions of the process. Used to analyze manufacturing and assembly processes.

A FMEA identifies the opportunities of failure (failure modes), in each step of the process. Each failure mode gets a numeric score that reflects the likelihood that the failure will occur, the likelihood that the failure will not be detected and the amount of harm the failure mode may cause to a person or the damage the failure mode may cause to a system or equipment.

Setting up a PFMEA includes the following seven steps:

1. Planning & Preparation:
   Defining the goal, scope, timeline, team, tasks and resources for the analyses.
2. Structure Analysis:
   Reducing the product or process back to its system elements.
3. Function Analysis:
   Defining the function and requirements of each element in the system.
4. Failure Analysis:
   Defining possible failures, effects, causes and their relationship.
5. Risk Analysis:
   Assessing the risk of every possible failure by evaluating the severity, occurrence and detection.
6. Optimization:
   Defining the measures to control the important risks and evaluate the effectiveness of these measures.
7. Results Documentation:
   Summarize the results of the analyses and communicate to the stakeholders.

Figure 170 – Seven FMEA steps

At step 5, the risk-level is calculated based on three factors, Severity, Occurrence and Detection. Every factor gets a score on the range of 1 to 10. Guidelines to determine the rating for Severity, Occurrence and Detection are defined by the AIAG in special tables.

1. Severity — The severity of the effect, from a customer or process perspective
2. Occurrence — The chance that the deviation occurs.
3. Detection — The ability to detect the deviation before it occurs.

The risk-level is calculated by multiplying these three factors resulting in a 'Risk Priority Number' (RPN).

$$RPN = Severity \times Occurence \times Detection$$

The AIAG has introduced a number of tables for determining scores for Severity, Probability and Detection. These are very detailed and too extensive for most organizations. Table 23 provides a summary of these tables which is more practical to use.

<table>
<tr><th>Rating</th><th>Severity of Effect</th><th>Likelihood of Occurrence</th><th>Ability to Detect</th></tr>
<tr><td>10</td><td>Affects safety of user</td><td>Extremely high</td><td rowspan="2">Very Low</td></tr>
<tr><td>9</td><td>Noncompliance with regulations</td><td rowspan="2">Very High</td></tr>
<tr><td>8</td><td>Loss of primary vehicle function</td><td rowspan="2">Low</td></tr>
<tr><td>7</td><td>Degradation of primary function</td><td rowspan="2">High</td></tr>
<tr><td>6</td><td>Loss of convenience function</td><td rowspan="2">Moderate</td></tr>
<tr><td>5</td><td>Degradation of convenience function</td><td rowspan="2">Moderate</td></tr>
<tr><td>4</td><td rowspan="3">Appearance, sound, vibration, harshness, or haptics</td><td rowspan="3">High</td></tr>
<tr><td>3</td><td>Low</td></tr>
<tr><td>2</td><td>Very low</td></tr>
<tr><td>1</td><td>No discernible effect</td><td>Extremely low</td><td>Very High</td></tr>
</table>

Table 23 – FMEA-table for calculating RPN value (source: SmartFMEA)

For most organizations, it is sufficient to calculate the RPN value using this table and thus determine the greatest risks. However, for those working in the automotive or high tech industry it is recommended to use the 2019-AIAG tables, as applying the FMEA properly in these sectors is very important. Since the integration of the AIAG standard and the VDA standard in 2019, the 'Action Priority' (AP) has been introduced within these sectors as an alternative to the RPN value. A disadvantage of the RPN value is that all three factors weigh equally heavily. When determining the AP value, the Occurrence score is weighted more heavily than the Detection score. After all, Occurrence stands for prevention and Detection stands for the retrospective discovery of an already made mistake.

6.10 Total Productive Maintenance (TPM)

'Total Productive Maintenance' or 'Total Productive Management' (TPM) focuses on the effective and efficient use of equipment, by avoiding breakdowns, delays and machine-related rejections. This is achieved by methods used to ensure that more is produced using existing machinery. TPM is mainly used in production environments that are highly machine dependent such as automotive, food and processing industry. Organizations that apply TPM as a companywide improvement philosophy also include other areas like office and supply chain.

6.10.1 TPM principles

The goal of TPM is driving all Waste to zero: zero losses, zero defects, zero accidents. Typical types of Waste that are eliminated with TPM are losses related to Productivity, Quality, Cost, Delivery, Safety, Environment and Morale ('PQCDSEM'). Preventive maintenance was developed by U.S. factories that supplied the military during the Second World War. After the war preventive maintenance was introduced in Japan (1951). Nippon Denso (Toyota Group) was the first company to introduce preventive maintenance plant wide (1960). Nippon-Denso was awarded the distinguished plant prize for developing and implementing TPM by the 'Japanese Institute of Plant Maintenance' (JIPM). Therefore, Nippon-Denso became the first company to obtain the TPM certification. In 1987 the first real TPM initiative in the U.S. was developed by the Kodak's Tennessee Eastman facility.

Nowadays maintenance costs are a major issue for many organizations, but instead of just looking at actual costs, most organizations look at the Total life cycle costs of a piece of equipment. Investment in a plant occurs from its early development. The return of the investment, therefore, should also begin soon after its commissioning. It should be the objective of every company to maximize the lifetime profitability of its equipment. To realize this objective, the eight pillars of TPM play an important role.

The TPM approach is visualized in a House of Quality with eight pillars, as demonstrated in Figure 171. We will briefly review each of the pillars. It is not the intention to review the implementation of TPM in detail, but to address the importance of reliable equipment in achieving stable and effective processes. As such, it is very important in Lean Six Sigma initiatives. The first two pillars are very effective in the first two maturity levels. Specifically, the pillar 'Autonomous Maintenance' involves operators in 5S and problem-solving initiatives. This will contribute to the creation of an improvement culture based on ownership and it will improve equipment reliability.

Benefits of effective TPM are:

- Quality improvement through reduced failures and malfunctions.
- Productivity improvement through fewer losses in the company.
- Customer satisfaction through higher delivery and quality performance.
- Employee ownership through Autonomous Maintenance.
- Employee confidence through zero failure, zero defect and zero accident.
- Employee satisfaction and Safety through improved working conditions.
- Cost reduction through reduced losses and Non-Value-Added activities.

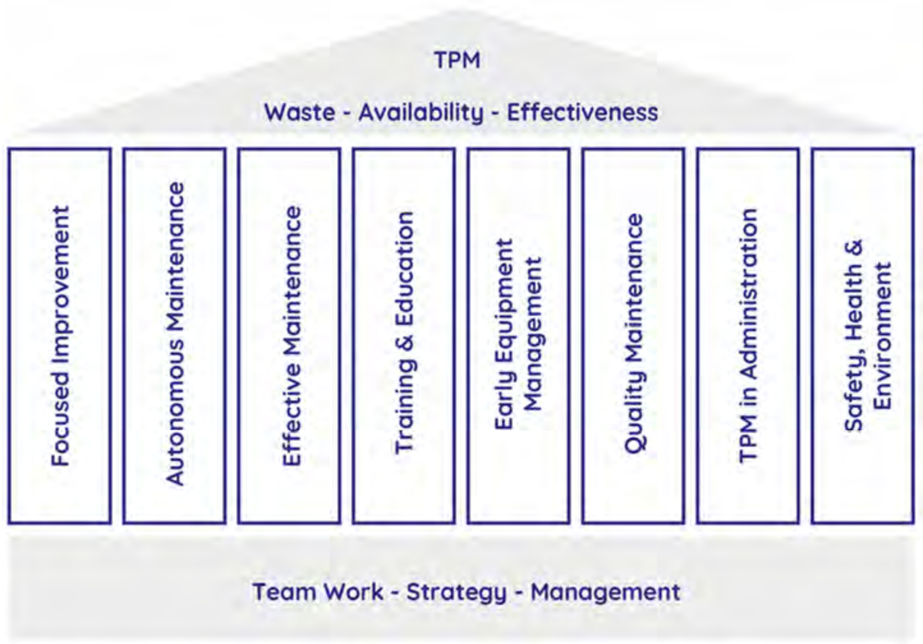


Figure 171 – TPM House of Quality

1 – Focused Improvement:
Focused Improvement (also called Kobetsu Kaizen), is a process of Continuous Improvement activities with Zero Wastes, Zero Breakdowns, Zero Defects and Zero Accidents as objectives. The Focused Improvement process is driven by the Overall Equipment Effectiveness (OEE) performance measure.

2 – Autonomous Maintenance:
Autonomous Maintenance (also called Jishu Hozen), deals with making operators responsible for their piece of equipment and tooling, rather than having maintenance done by special maintenance technicians. Giving operators the responsibility for good equipment condition, cleanliness and lubrication helps to achieve a high level of ownership amongst operating teams. This pillar is a necessary requirement for Zero breakdowns and has an indirect effect in achieving Zero Waste, Zero Defects and Zero Accidents.

3 – Effective Maintenance:
Effective Maintenance is about improving the overall plant maintenance programs. It incorporates a mix of maintenance approaches like periodic maintenance, inspection-based maintenance, condition monitoring and corrective maintenance. Manufacturing operations frequently utilize only one or two of these approaches, leading to high maintenance costs and low equipment availability. The objective of the Effective Maintenance pillar is to set up an effective mix of these approaches to deliver optimum availability at lowest cost. This pillar is also a necessary requirement for Zero breakdowns and has an indirect effect in achieving Zero Waste, Zero Defects and Zero Accidents.

4 – Training & Education:
The objective of this pillar is to address the knowledge gaps amongst the workforce and management who have been identified in the first pillars. For example, this can include operators who do not understand the operating principles of their equipment or maintenance personnel who are unfamiliar with the equipment. Also, managers can be unfamiliar with operation improvement methods or measures like OEE. This pillar captures the knowledge gaps and develops appropriate solutions for training and education.

5 – Early Equipment Management:
Early Equipment Management is about applying lessons learned about maintenance into equipment development. The knowledge which has been gained during the first four pillars, is now directed toward the development, design and implementation of new equipment before they are installed in the plant. In this way, new equipment should be capable of vertical start-up where they achieve their planned performance level immediately, rather than after a period of commissioning and bedding in.

6 – Quality Maintenance:
Quality Maintenance aims to achieve a production system that is incapable of producing quality defects. It builds on the work done during the first four pillars and brings in additional techniques such as Poka Yoke, which means Mistake-proofing in Japanese. A Poka Yoke is a mechanism that helps an equipment operator to avoid (Yokeru) mistakes (Poka). The cheapest way is to incorporate Poka Yoke solutions in the design phase of new products. This pillar is the final step in the drive toward Zero Defects.

7 – TPM in Administration:
As the other pillars deliver constantly improving performance in the equipment, more and more of the problems which occur will be as a result of the administration of the operation. This could be in the planning process, resourcing, documentation or procedures, etc. This pillar takes the approaches used on the manufacturing processes and applies them to the administration processes.

8 – Safety, Health & Environment:
This pillar ensures that all the improvements developed by the other pillars do not reduce the Safety, Health or Environmental performance of the organization. It also ensures that the approaches used to achieve manufacturing performance improvement are equally applied to Safety, Health and Environmental issues. As such it is not the ‘last’ pillar to apply. On the contrary, its principles should be applied in parallel to all other pillars.

6.10.2 Overall Equipment Effectiveness (OEE)

In the era of the Industrial revolution, many manufacturing operations invested in expensive equipment. It was important to get the most out of each equipment. The goal was to Increase utilization on equipment. Utilization is defined as the proportion of the available time that a piece of equipment or a system is operating:

$$Utilization = \frac{Operating\ hours}{Available\ hours} \times 100\%$$

It is necessary though to break through the conceptual barrier of throughput thinking and leave utilization thinking behind, as it will lead to excessive work in process which is not in line with Lean concepts. Teams that are working on Continuous Improvement initiatives in a Lean environment should focus on one of the following four concepts instead: effectiveness, efficiency, productivity and agility.

The ‘Overall Equipment Effectiveness’ (OEE) is a metric that is commonly used as a Key Performance Indicator in conjunction with programs in heavily machine-oriented industries like food and automotive. The OEE metric is used to evaluate how effectively a manufacturing operation is utilizing its equipment. It is therefore often used within ‘Total Productive Maintenance’ (TPM) programs [section 6.10].

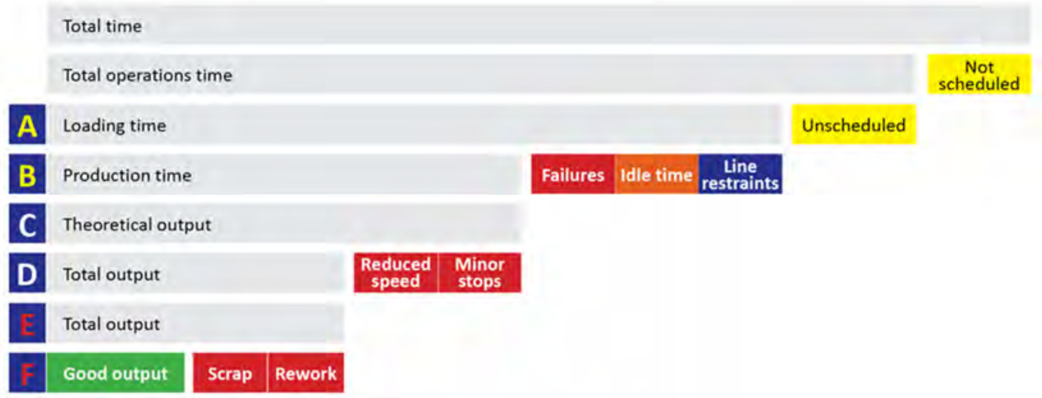


Figure 172 – Overall Equipment Effectiveness

The OEE measure is the mathematical product of three elements: Availability, Performance and Quality:

Figure 173 – Overall Equipment Effectiveness

Loading Time:
Before we can calculate the OEE, we need to first define the scheduled machine time, also called Loading time. The total time is by definition 24 hours x 7 days = 168 hours, but if the equipment is running only one shift for 5 days, the Total operations time is 8 hours x 5 days = 40 hours. Secondly, we have to take into account the Unscheduled time which is defined as time that the equipment is deliberately not scheduled for production because of preventive maintenance, no orders, engineering tests etc.

Now let's take a closer look at how to calculate the Availability rate, Performance rate and Quality rate.

Availability Rate – Time Loss:
The Availability rate is defined as the percentage that the machine is running within the available scheduled time.

Time Loss	Description	Examples
Failures	No output due to machine related technical problems.	Equipment or tooling problems Major adjustments Unscheduled maintenance
Idle time	No output due to resource problems.	Setup/Changeover, warming up Waiting for raw materials Waiting for operator
Line restraints	No output due to buffer related problems.	Empty input buffer Output buffer full

Table 24 – Availability Rate

Example: Assume a piece of equipment that is scheduled to be available for 22.5 hours a day. This is called the Loading time of the machine. Within this period of time the machine is running production for 19.5 hours. The remaining time the machine is not running caused by breakdowns (1.0h) and waiting time (2.0h).

-	Unscheduled	1.5h
P	Production time **Running time**	19.5h
F	Failure time **Breakdown time**	1.0h
I	Idle time **Waiting time**	2.0h
L	Line Restraints time	0h

Loading Time = 22.5h

The Availability rate can be calculated as shown in the following equation:

$$Availability\ Rate = \frac{Production\ time}{Loading\ Time} = \frac{19.5}{22.5} = 87\%$$

Performance Rate – Speed Loss:

The performance rate is defined as the theoretical maximum speed in relation to the actual speed. The maximum speed is called 'Name Plate Capacity' (NPC). Minor stops and reduced speed prevent the equipment from running at its maximum speed.

Speed Loss	Description	Examples
Reduced Speed	Not running at the theoretical maximum speed. A.k.a. Ideal Run Rate or Name Plate Capacity (NPC).	Not reaching design specifications Deliberately running below NPC Equipment wear Operator inefficiency
Minor stops	Stops that are limited to a few minutes, caused by minor problems that can be fixed by the operator.	Component jams Misfeeds Blockage Cleaning/Checking

Table 25 – Performance Rate

Example: Assume the machine that we observe was originally designed to produce 480 pieces per hour. After observing the equipment for one hour (without idle time or breakdowns), we count 428 pieces finished goods.

The Performance rate can be calculated as shown in the following equation:

$$Performance\ Rate = \frac{Total\ output}{Theoretical\ output} = \frac{428}{480} = 89\%$$

Quality Rate – Yield Loss:
The Quality rate is defined at the percentage of products that were produced 'First Time Right' (FTR).

Yield Loss	Description	Examples
Scrap	Product/service that does not meet its specification (not First Time Right) and cannot be reworked.	Broken or damaged part Missed call Incorrect treatment patient
Rework	Product/service that does not meet its specification (not First Time Right), but can be reworked.	Part incorrectly calibrated Service complaint Late delivery

Table 26 – Quality Rate

Example: Assume we observe the quality of the machine over a longer period and count the number of good products and the amount of products that were not First Time Right (scrap and rework, also called Yield loss). Assume we count 4320 products in total (good and bad) and we count 3892 good products.

The Quality rate can be calculated as shown in the following equation:

$$Quality\ Rate = \frac{Good\ output}{Total\ output} = \frac{3{,}892}{4{,}320} = 90\%$$

Overall Equipment Effectiveness (OEE):
The OEE can now be calculated as shown in the following equation:

$$OEE = Availability\% \times Performance\% \times Quality\% = 87\% \times 89\% \times 90\% = 70\%$$

Total Team Effectiveness
While OEE is mainly used in manufacturing environments, 'Total Team Effectiveness' (TTE) is a comparable metric that is used in transactional environments to measure the effectiveness of a team. The TTE is based on the following four elements:

- Presence: employee is present at the organization.
- Availability: hours that are spend on the tasks.
- Productive hours: hours that a performed task will take in theory. *)
- Effective hours: hours that the task would take in case of an optimal process.

*) *The norm for the maximum speed is determined by the times of the top 5% among employees.*

We will explain how to define TTE with an example:

Your team has 100 contact hours. Considering sickness, days off and overtime, the team is present for 90 hours. Because of projects, breaks and meetings the employees are not available for 10 hours. The norm for a mutation is 10 per hour. On a specific day, 500 mutations were processed. The control and rework took 10 hours on this day. What is the TTE?

$$Presence = \frac{Hours\ present}{Contact\ hours} = \frac{90}{100} \times 100\% = 90\%$$

$$Availability = \frac{Hours\ available}{Hours\ present} = \frac{(90-10)}{90} \times 100\% = 89\%$$

$$Productivity = \frac{Productive\ hours}{Hours\ available} = \frac{(500/10)}{(90-10)} \times 100\% = 63\%$$

$$Effectivity = \frac{Effective\ hours}{Productive\ hours} = \frac{(50-10)}{(500/10)} \times 100\% = 80\%$$

The TTE can be calculated using the following equation:

$$TTE = \frac{Effective\ hours}{Contact\ hours} \times 100\% = \frac{(50-10)}{100} \times 100\% = 40\%$$

Or

$$TTE = Presence\% \times Availability\% \times Productivity\% \times Effectivity\% = \\ = 90\% \times 89\% \times 63\% \times 80\% = 40\%$$

CIMM assessment level III – Creating stable & efficient processes

Level III focuses on creating stable and efficient processes. Is the culture in your organization strong and flexible enough to deploy the next level? Perform the assessment below by scoring each statement with a rating of 1 to 5. A score of '1' means that the statement does not reflect the situation within your organization; a score of '5' means that the statement fully reflects the situation within your organization.

As there are 15 statements, the maximum score is 75. If you score less than 50 points, we recommend not to start the deployment of the next level, but to continue to deploy the current level first.

Process level III – Creating stable & efficient processes (Predictable)
3.1 – Waste elimination
Key processes are clearly defined and accessible for all.
Value Stream Mapping is applied on a regular basis for important processes.
The gap between the current performance and desired performance is defined.
Non-value-adding activities are identified and eliminated continuously.
An improvement plan is defined, objectives are described SMART.
3.2 – Lean Management (Flow & Pull)
KPIs are aligned with strategic goals.
Flow is present and visible.
Pull systems are in place (e.g. Kanban, Two bin, CONWIP).
There is a clear focus on bottleneck operations.
The organization is flexible and effective. Teams are self-steering and empowered (Agility).
3.3 – Risk management & First Time Right
Continuous improvement is based on Risk management (e.g. Process FMEA, Control Plan).
Relevant Lean performance measures are monitored (e.g. takt time, cycle time, lead time, etc.)
First Time Right techniques are applied (e.g. Poka Yoke, Jidoka, Autonomation).
A competence development program is in place.
System security and preventive maintenance programs are in place.

Each person in the organization has a certain role and responsibility at creating stable & efficient processes. The assessment distinguishes responsibilities and behaviors for top management, middle management and people working at the shop floor. There are again 15 statements with a maximum score of 75.

People level III – Creating stable & efficient processes (Practitioner)
3.1 – Waste elimination
Top management creates an awareness of waste within the organization.
Management coaches employees to identify the 8 types of waste.
Management stimulates employees to eliminate waste in the process.
Employees contribute to the elimination of waste and to sustain improvements.
Employees are able to distinguish necessary, non-value adding and value adding activities.
3.2 – Lean Management
Top management challenges process owners to work in one process by applying 'Flow' and 'Pull'.
Management takes actions to achieve a continuous Flow in the process.
Management controls the organization on fact-based performance indicators.
Employees are aware what results are expected of them on a daily basis.
Employees adhere standardized work which leads to a continuous flow and customer-driven work.
3.3 – Risk management & First Time Right
Top management appoints process owners and challenges them to identify and mitigate risks.
Management works according the 'First Time Right' principle.
Management acknowledges mistakes as a possibility to improve and appreciate if employees reveal risks.
Employees are aware of possible risks in the process and feel comfortable to mention abnormalities.
Employees work according to the 'First Time Right' principle.

“Uncontrolled variation is the enemy of quality.”

— W. Edwards Deming —

7 CIMM level IV – Creating capable processes (Capable)

The fourth level focuses on reducing variation in the stable process that is created in the first three levels. The objective is to increase the capability of the process performance. Rather than increasing quality with a step-by-step approach like the Kaizen approach, Six Sigma focuses on quality breakthrough improvement projects. A Six Sigma improvement project will take a few weeks or a few months rather than a few days. As a consequence, the Six Sigma approach is much more top-down driven than the Kaizen bottom-up approach.

At this level we will apply Six Sigma and statistical tools, to analyze the performance of processes. In order to apply statistics, data will be needed. Therefore, at this stage it is important to have a performance measurement system in place that is able to deliver process performance data at the level of the products or services that are produced. Green and Black Belts are expected to analyze the data by using statistical software like Minitab or other software. Most of the tools explained in this book are demonstrated using Minitab. Yellow and Orange Belts are expected to understand and interpret many of these graphical outputs, but are not expected to generate them or to analyze the data.

Projects at this level follow the DMAIC roadmap. As discussed in section paragraph [3.2.4], the Define phase determines, among other things, the problem definition, the scope and the intended savings. The Measure phase is an essential step in a Six Sigma project. Six Sigma projects make extensive use of statistical tools. Data is needed to apply these tools. It is important that these data are reliable and that there is a measuring system or measuring procedure that can measure these data accurately enough. In the Analysis phase, Green and Black Belts analyze the data. The goal of every Six Sigma project is to get the CTQ on target and to reduce the variation of the CTQ. The purpose of the Analyze phase is to identify, validate and determine factors of influence that cause variation. In the Improve phase, solutions to reduce the variation are implemented and verified. To determine the optimal setting for the process, techniques such as a regression analysis and Design of Experiments are applied. Process capability analysis is also widely used in Six Sigma projects. In this chapter, we'll take a closer look at these tools.

The Six Sigma DMAIC roadmap and a number of tools that can be used at this CIMM-level are presented in Figure 174. It is important to realize that it is not necessary to use each of these tools in a certain Six Sigma project. The Figure only demonstrates tools that are commonly used. Other tools can be used as well. The roadmap used in this level is again the DMAIC approach. The tools listed in Figure 174 are each placed in one of the DMAIC phases. However, many tools can be used in other phases as well.

Figure 174 – Six Sigma DMAIC roadmap and tools

Measure

7.1 Statistical techniques

Statistics is the science that deals with the collection, processing, interpretation and presentation of data. Statistics deals with all aspects of data, including planning and conducting experiments, collecting data and analyzing data. In section 6.3 we have already discussed data types, measurement scales and descriptive statistics. In this section we will discuss the aspects of natural variation (Common cause) and exceptional variation (Special cause). We will also discuss the process of sampling.

7.1.1 Variation

The primary focus of a Six Sigma project is to improve process stability, reduce variation and improve process capability. Statistical techniques are used for this. However, it is also possible to use a Kaizen or Lean initiative instead of statistical techniques when problems are related to an incident or instability. Statistical techniques are used on centering the process (Mean) and reducing process variation (Spread) to improve process capability.

There are two types of variation that cause a process to perform at an inadequate level:

1. Special cause variation
2. Common cause variation

It is important to distinguish between both types of variation, so that a suitable intervention can be applied. In process improvement initiatives it is recommended to focus on solving special cause variation prior to common cause variation, because normally the reasons for special cause variation are found more easily than the reasons for common cause variation.

Examples of different types of variation (Industry)

Instability	Special Cause	Common Cause
Quality spill (Incident)	Performance varies from day to day	Natural variation
Missing O-ring	O-rings from this bag are more difficult to mount	Some O-rings are tighter than other
No electrical contact	Different fixtures have different resistance	Natural process variation (of resistance)
Damaged components	Some boxes demonstrate more variability than others	Differences from one component to the other
Lead time for rush order	Lead time for changing work load	Lead time for fixed workload

Examples of different types of variation (Transactional)

Instability	Special Cause	Common Cause
Doctor is called for emergency	Waiting time on Monday is longer than on Friday	Natural variation of Waiting time during a day
Forgot to call back a client	No time today. We will call him back tomorrow!	Response time in normal operation
Email sent to incorrect person	Answering 200 mails after returning from holiday	Answering about 50 mails each day
Missing signature or approval	Response time Manager A is different than Manager B	Response time of Manager A
Late delivery caused by accident	Longer travel times during rush hours	Average speed on highway

Table 27 – Examples of different types of variation

Special cause variation
Special cause variation is caused by factors that result in a non-random distribution of the output. Special cause variation is a shift or a sudden change, caused by an incident or certain change in surroundings. Special cause variation is also called exceptional or assignable variation. A process that has special cause variation is called "Out-of-control '.

Figure 175 demonstrates that process ‘A’ has very little natural variation, but the process demonstrates special cause variation. The graph does not clarify the reason for that, but by making this graph and discussing it with people involved can generate hypotheses about the reasons. Possible reasons may be a door slamming, a loose tooling, a component damaged, dirt or an employee who makes a mistake due to lack of sleep. Within Lean Six Sigma these improvement possibilities are considered as ‘Low hanging fruit' initiatives, since the causes are often readily apparent.

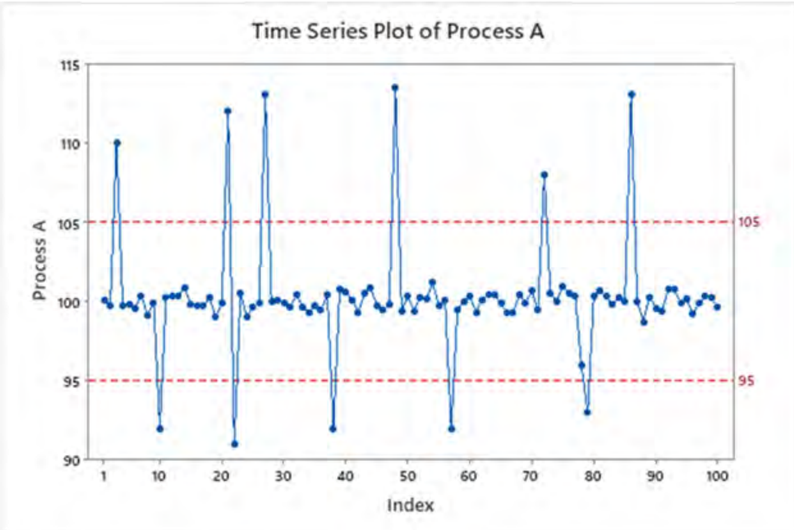


Figure 175 – Special cause variation

As an example, we will demonstrate the verification process of an electronic sensor, with a specification for Voltage of 3.5±1.0[V]. The process demonstrates a Yield of 94% and 6% Yield loss. The sensors are measured four pieces simultaneously in a fixture. We generate a ‘Times Series Plot' for 100 measurements. Figure 176 demonstrates six outliers with an extreme value of 0 [V]. By using the ‘Brush’ option in Minitab we can visualize the available variables, like the number of the fixture that is part of the data set. This demonstrates that all six outliers came from the same fixture (Nr. 3). After detailed investigation it turned out the reason for the outliers was a bad electrical contact. Further investigation proved that the underlying root cause appeared to be an incorrect preparation of the fixture.

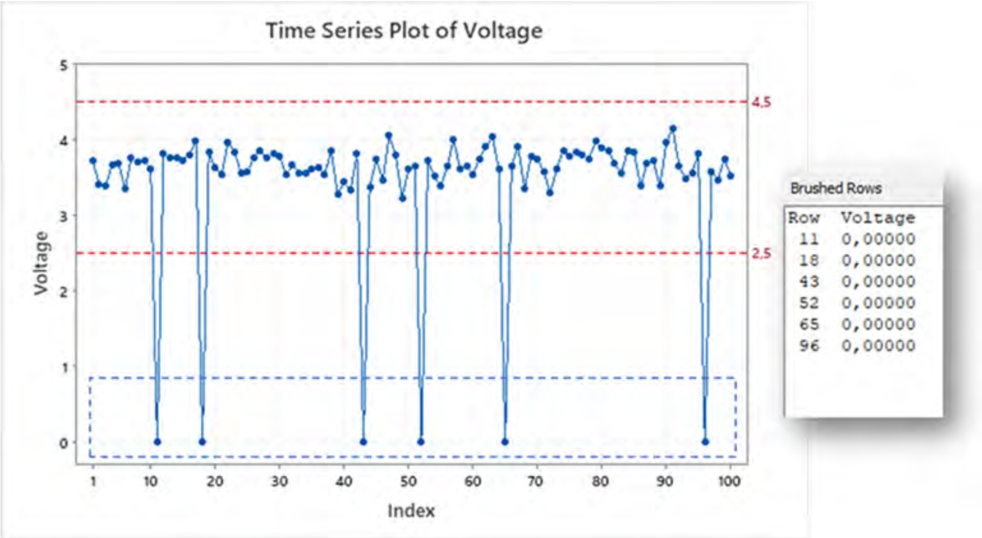


Figure 176 – Extreme Special cause variation

Special cause variation is not always extreme, but sometimes less obvious. Figure 177 demonstrates that process 'B' shows little natural variation, but suddenly the Mean of the process has shifted. Possible reasons for this behavior might be the use of different components, different suppliers, different operators, different set-up or different machines.

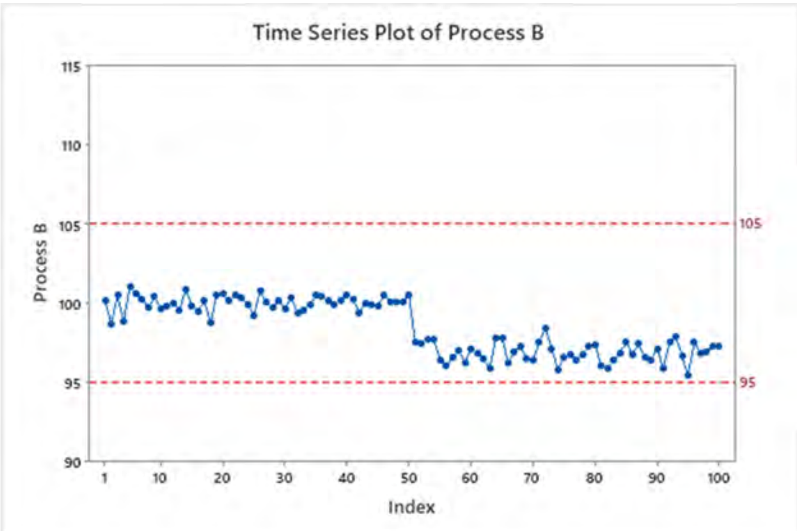


Figure 177 – Special cause variation

Common cause variation
Common cause variation is caused by the process itself. Every process has some amount of fluctuation caused by unknown factors, resulting in a steady but random distribution of output around the average of the data. Common cause variation is a measure of the process potential or process technology. Common cause variation is the remaining variation after removing instabilities and special cause variation. This type of variation is also called natural variation, random variation, noise, non-controllable variation, inherent variation, or within-subgroup variation. If a process shows only natural variation it is in a state of statistical control.

Figure 178 and Figure 179 demonstrate two Time Series plots. You can see that process 'C' has relatively little variation compared to process 'D', but both processes demonstrate a stable process with only common cause variation. A process showing only Common Cause Variation is 'Stable', 'Predictable' and 'In-Control'. Yet, it does not mean that the results will automatically match the quality standards required. It only means that the results are stable and predictable.

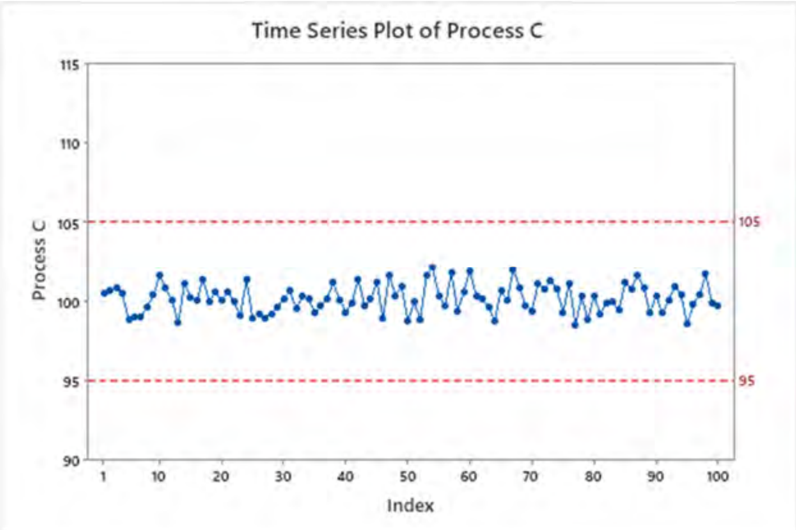


Figure 178 – Common cause variation

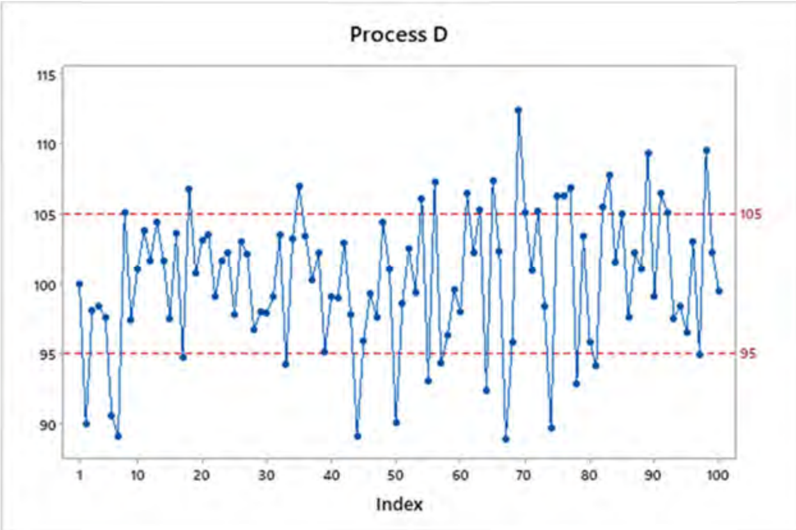


Figure 179 – Common cause variation

Multi-Vari chart
(Minitab: Stat > Quality Tools > Multi-Vari Chart)

Three major families of variation can be distinguished. The first step in the problem-solving process should be to determine in which of the following groups we could place the problem to be solved. For example, if the largest variation is 'Temporal', the causes of variation associated with 'Positional' or 'Cyclical' can be either ruled out or given a much lower priority (Bohte, 2000). The following overview of families of variation is described in the book 'World Class Quality' from K. Bohte [7.].

A. Positional variation (Within-Unit family)
    - Machine-to-Machine
    - Line-to-Line
    - Operator-to-Operator
    - Part location-to-Part location
B. Cyclical variation (Unit-to-Unit family)
    - Unit-to-Unit
    - Group-to-Group
    - Batch-to-Batch
    - Supplier-to-Supplier
C. Temporal variation (Time-to-Time family)
    - Hour-to-Hour
    - Shift-to-Shift
    - Day-to-Day

Positional variation means that the issue can be traced back to a certain location while the issue is not present at other locations. For example, the issue can be isolated to a certain machine or production line, to a certain department or business unit, or even to a certain employee or operator. An example of positional variation is that the issue can be found at a certain location within the part itself, whereas it is not present at another location of the part. To be more concrete, it could be that damaged parts all show a similar tool mark at the same location.

Cyclical variation is also known as periodic variation. An example is variation between consecutive units taken from a process at certain time frames. Cyclical variation means that the issue can be traced back to certain components that are used to assemble a part. For example, the issue can be isolated to a certain box of components, a certain batch or a certain supplier. Cyclical variations may also be seasonal in nature, or follow the business cycle.

Temporal variation means that the issue is not always present. Temporal variation is a function of time. Issues arise after or during a certain period of time. Examples include products that are over the expiration date, wear of tooling or equipment and operators getting tired or distracted. Temporal variation may also follow environmental variation like changes in humidity or temperature.

Applying the 'Multi-Vari Chart' can help to distinguish which family of variation has the largest contribution to the variation that is causing the issue. Multi-Vari charts are a way of presenting such data in a graphical form. The chart is very helpful in the preliminary stages of data analysis to get a first look at the data. The chart displays the means at each factor level for every factor. As an example, we will analyze the performance of a call center. The center has three departments (A, B and C). Each department receives three types of questions that have to be answered. The quality level is monitored by asking the clients if the answer was satisfactory or not at the end of each call. A Multi-Vari study demonstrates that the level of 'Not satisfactory' for department A is above average for each type of request. This is an excellent example of 'Positional variation'.

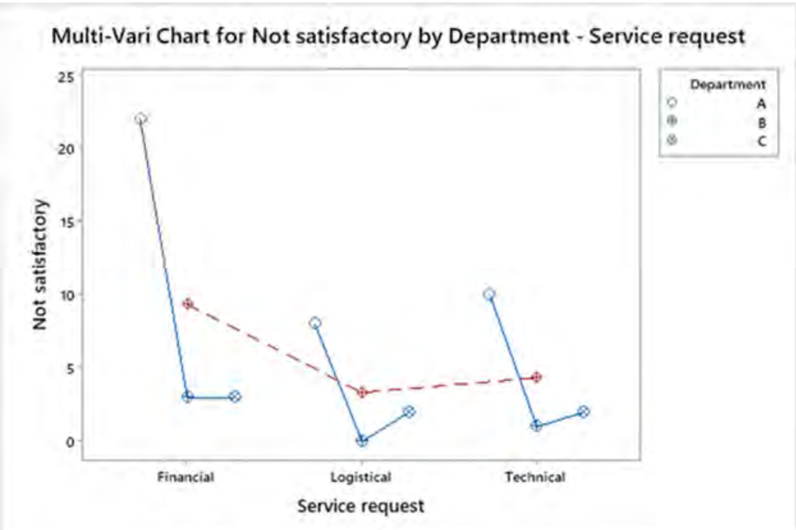


Figure 180 – Multi-Vari chart

7.1.2 Sampling

Sampling methods

Preparing samples, shutting down a line to perform a test and the amount of effort that people put into performing the test is expensive. Therefore, proper preparation is needed. A data collection plan should be composed in advance that already includes the numbered samples and columns specifying the data that need to be collected. The preparation should also include a number of test samples that can be used to set up the tooling and to evaluate the measurement procedure itself before the start of the actual data collection effort. Changing tooling, samples or procedure after you have started the measurement procedure, can invalidate the entire test.

For service organizations with system data it is important to be clear on what database and time period the data should be collected from. Proper time should be spent to define what data should be taken from the business system. First, if you decide that data about 'waiting times' should be collected, it is important to decide the start and end point that defines 'waiting time'. Second, you should make sure these data are actually available in the system and can be exported or extracted from the system. If possible, you should try to reach the detail level of defining specific Records and Tables from the database. As project manager you should take care that if others decide what Record would be suitable, it is a good fit for the operational definition that you have in mind. Collecting the wrong data is a Waste in itself and can result in erroneous conclusions and subsequently lead to the wrong actions being taken.

The total collection of objects is called the 'Population'. Only when all objects of the population are measured, the true mean and standard deviation can be known. Generally, it is not realistic to measure all objects of the population. Fortunately, it is not necessary to measure the entire population. If we apply statistics in a proper way, a subset or 'Sample' of the population can be used. When sampling data, it is always important to achieve a representative sample that is an accurate, proportional depiction of the population under study. There are different ways of sampling:

Sampling methods	Description
Simple random sampling	Subset (sample) of elements chosen from a larger set (a population). All possible samples of size n are equally likely to occur
Systematic sampling	The elements of the population are put into a list. The first sample is randomly chosen from the first k-1 elements and then every k-th element in the list is chosen (systematically).
Stratified sampling	The population is divided in non-overlapping subgroups, or strata, and then elements are randomly selected proportionally from the different strata.

Table 28 – Description of different sampling methods

1 – Simple Random Sampling:
All objects in the sampling frame have an equal probability of being selected. The sampling frame is not divided. All pairs (triples, etc.) have equal probability of being selected. The disadvantage of simple random sampling is that, because of the random selection, it is possible that you get a sample that is not representative of the population. For example, a random sample of 500 people from the voters of a country can contain too much or not enough voters from different groups.

Figure 181 (left) illustrates that 48 units are randomly sampled from a population of 400. The samples are not evenly distributed across the population.

2 – Systematic Sampling:
Systematic Sampling is using a regular interval. The starting point is randomly chosen and sampling then proceeds with the selection of every k-th item. For example, we want to select 27 samples from a population of 4,860 photographic films. We start at a random number between 1 and 180 and then proceed to sample with an interval of 180. The disadvantage of systematic sampling is that it is vulnerable to periodicities in the ordered list.

Figure 181 (mid) illustrates how the 48 samples are sampled in a systematic way. The starting point is randomly selected between 1 and 6 and in a column every 6thunit is sampled.

3 – Stratified Sampling:
A stratifying factor, also referred to as stratification or a stratifier, is a factor that is used to separate data into subgroups. This is done to investigate whether that factor is a significant special cause factor. If a population contains a number of distinct categories, the sampling frame can be subdivided in separate homogeneous groups (strata). Each stratum is then sampled as a sub-population. Stratified Sampling is proportional when the number of samples per stratum is proportional to the stratum size. Stratified Sampling makes it possible to compare different categories. It also reduces the probability of over-representation of specific groups.

Figure 181 (right) the population is subdivided into non-overlapping blocks (strata). Within each block 3 samples are randomly selected.

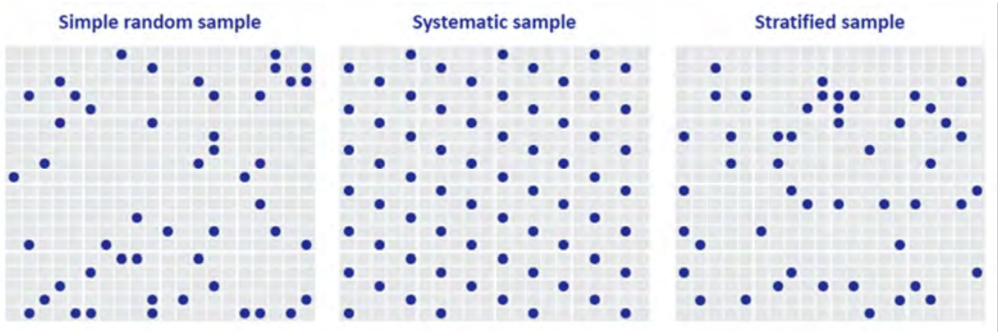


Figure 181 – Sampling methods

Sample size

It is seldom possible to investigate the complete population because the population is too large to measure all objects or the population only partially exists (e.g. production process industry). Therefore, we need to estimate the parameters of the population instead. To do this we need a sample, a subset from the population. In this section we will discuss how Sample sizes are calculated.

Confidence intervals are used to quantify the reliability of the estimates of the parameters of the population. The size of the sample has a great influence on the reliability of the outcome. It is the most important parameter that we have in order to optimize the reliability of a survey. A sample which is too small gives uncertain results and is therefore wasted money, effort and time. A sample which is too large, although resulting in better reliability, requires more time and resources. Determining the optimal sample size is an important stage in the preparation of a research plan. This should take into account both the practical feasibility as well as the desired statistical reliability of the test. If later on in the defining the conclusions of the test, it appeared that the sample size had been too small, it will be difficult, if not impossible, to carry out additional tests under the same conditions.

The accuracy of the estimate improves as the Sample size n increases. The standard deviation of the mean is a factor $1/\sqrt{n}$ smaller than the standard deviation of the population. The probability that the average $\bar{x}$ of the sample is close to the true mean μ increases with the Sample size n, as is illustrated in Figure 182.

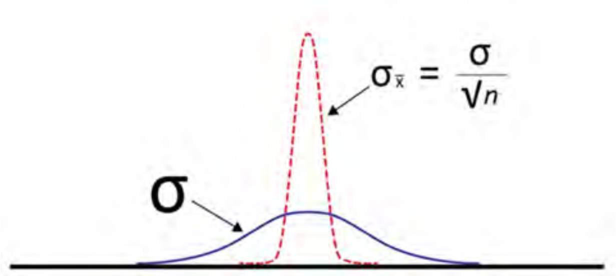


Figure 182 – Distribution of the mean versus distribution of the population

The narrower the confidence interval the better the estimate. Figure 183 shows that the width of the confidence interval decreases as the sample size n increases.

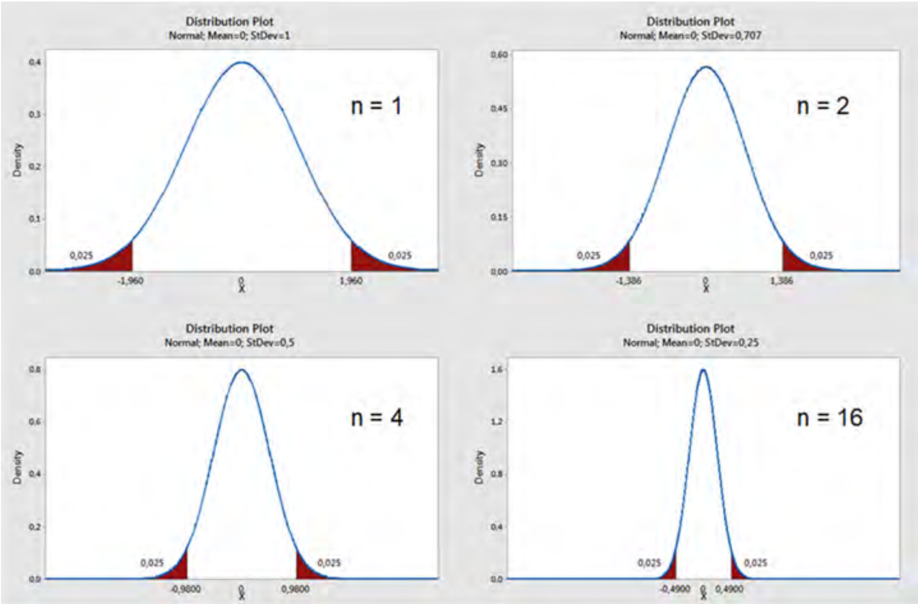


Figure 183 – Influence of Sample size n on the Confidence Interval width

Power

In section [7.4.1], we explained that a Type-II error is the situation that we accept the null hypothesis although the hypothesis is not true. The probability of this error is called 'β'. The complementary of this probability is '1 – β'. This is the probability that we reject the null hypothesis assuming the alternative hypothesis is true. This is called the 'Power' of the statistical test. Power is the probability to detect a specified difference (also called 'effect size' or δ) when this difference truly exists.

Calculating statistical Power before collecting data to ensure that the hypothesis test will detect significant effects is called a 'Prospective' study. Understanding the Power of tests that have already been conducted is called a 'Retrospective' study. Power is important for the interpretation of research for the following two reasons:

- In prospective study, the Power is the probability of success in order to demonstrate the effect of a certain size in this study indeed.
- In the retrospective study, and if the null hypothesis is not rejected, the Power provides the probability that the effect of a certain size really does not exist.

The Power should be as large as possible. The Power of a test is determined by four factors: the sample size n, the alpha level, the effect size δ and the standard deviation σ of the population. The Power can be increased as follows:

- A smaller value for the critical Z-value Figure 184. This will reduce β and thus increase the complementary $1 - \beta$. However, it will also increase the Type-I error α.
- A smaller variation in the observations, by measuring more accurately.
- A smaller spread in the observations, by taking more samples.

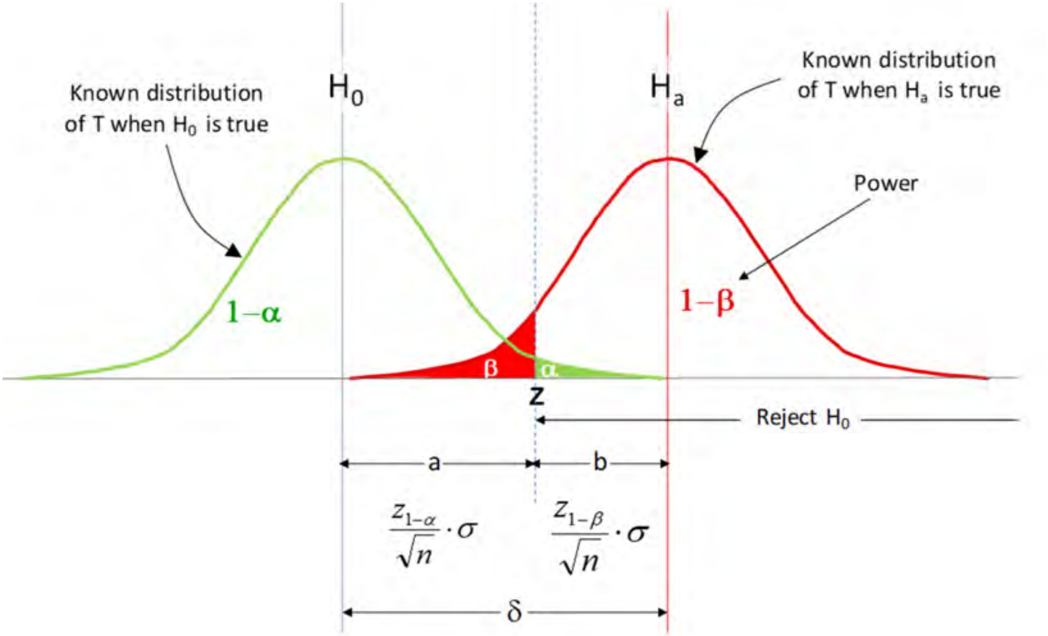


Figure 184 – Sample Size calculation (1 Sample Z – One sided)

In general, it is not easy to calculate the required sample size. Green Belts and Black Belts can apply Minitab to calculate the sample size for several distributions. Minitab provides power, sample size, and difference (effect) calculations for a number of tests, Confidence Intervals and Factorial Designs [7.8.2].

We will now work out an example how the sample size n is calculated for a one-sided Z-test, for a desired Power. This calculation is based on the normal distribution. If the Central Limit Theorem is used, we can also apply this method to calculate the sample size for other distributions.

Example: John is a quality engineer and wants to know if he has improved the process of making stamped plates. The initial process performed on an average thickness of 15.05 [mm] and the target was 15.00 [mm]. To show statistically significant that the process is improved, John wants to take enough samples to realize a power of the test of 90% which is equivalent with a beta of 0.10. John also wants to have a probability of 5% to reject the null hypothesis if the null hypothesis is true, in other words, the significance level alpha is equal to 0.05. From historical data Johns knows that the thickness of the plate has a standard deviation of 0.07 [mm]. John defines that an improvement of 0.05 [mm] minimum, will result in a Power of 90%. So the effect size δ that John is looking for is 0.05 [mm].

John defines the following hypotheses:

- H_O: Thickness = 15.05 [mm)
- H_A: Thickness < 15.05 [mm]

Because we are only looking for a decrease in thickness only, John will perform a one-sided *Z*-test. The sample size *n* for a one-sided *Z*-test can be calculated with the following equation.

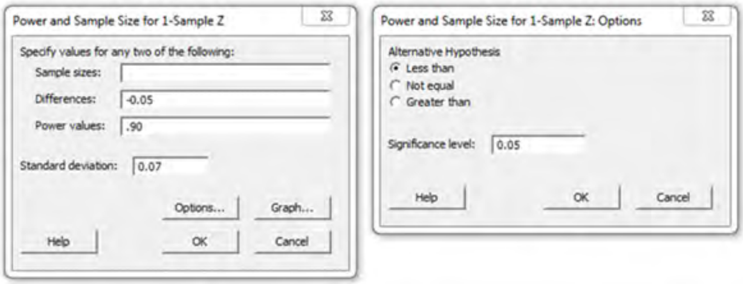
The proper (1 – α) and (1 – β) *Z*-values can be found in Table C.1.

$$n = \frac{\sigma^2 \cdot (Z_{1-\alpha} + Z_{1-\beta})^2}{\delta^2}$$

When John fills in all the details, the next value for the required sample size is found:

$$n = \frac{\sigma^2 \cdot (Z_{0.95} + Z_{0.90})^2}{\delta^2} = \frac{0.07^2 \times (1.645 + 1.282)^2}{(-0.05)^2} = 17$$

We will now perform the same calculation using Minitab:
(Minitab: Stat > Power and Sample size > 1 Sample Z)



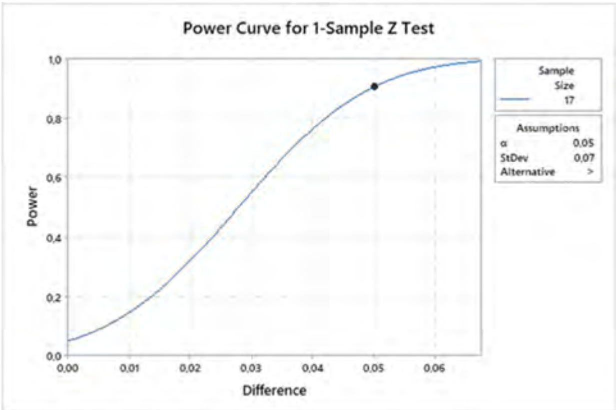


Figure 185 – Power Curve for 1-Sample Z Test

In the Minitab session window, we can see the Sample Size of 17. We also see that the Actual Power of the test is better than the Target Power 90%.

Power and Sample Size

```
1-Sample Z Test

Testing mean = null (versus < null)
Calculating power for mean = null + difference
α = 0.05  Assumed standard deviation = 0.07

            Sample  Target
Difference    Size   Power  Actual Power
     -0.05      17     0.9      0.903238
```

7.1.3 Basic probability concepts

For some Black Belts it may be useful to have knowledge of probability concepts such as independence, mutually exclusive events, multiplication rules, complementary probability and joint occurrence of events. This topic is not mentioned in the official LSSA skill set though.

Definitions and Statistics symbols:

- Sample Space — All possible outcomes of an experiment.
- Event — Set of possible outcomes of an experiment.
- Probability — Likelihood of the occurrence of an event.
- P(A) — Probability Function; Probability of event 'A'.
- $P(A \cap B)$ — Probability of events intersection; Probability of events 'A' and 'B'.
- $P(A \cup B)$ — Probability of events union; Probability of events 'A' or 'B'.
- $P(A \mid B)$ — Conditional probability function; Probability of event 'A' given event 'B' occurred.

Independent events
Independent events are events for which the probability of any one event occurring is unaffected by the occurrence or non-occurrence of any of the other event(s). Event 'A' and 'B' are independent if:

$P(A \mid B) = P(A)$.

For example, two separate tosses of a coin are independent events. The result of the first toss has no effect on the probability of the 'Heads' or 'Tails' on the second toss.

Complementary probability
Note that probability is always between 0 and 1, also noted as $0 \leq P(A) \leq 1$. The Complement probability of an event is the opposite of an event, meaning the set of all outcomes of an experiment that are not included in an event. The complement of event 'A' is written as 'A^{C}' and is often read aloud as 'not A'. The concept of Complementary probability is used in the Bernoulli trial (or Binomial trial).

$P(A^{C}) = 1 - P(A)$

Joint probability of events
Joint probability is the probability of two events occurring together and at the same point in time. Joint probability is the probability of event 'A' occurring at the same time event 'B' occurs.

$P(A \cap B)$

Joint probability can only be applied to situations where more than one observation can occur at the same time. Joint probability can be calculated as the probability of rolling a 1 and a 4 using two different dice.

Mutually exclusive events (disjoint events)
Mutually exclusive events are events that can't happen at the same time. Turning 'Left' and 'Right' in a car at the same time are two mutually exclusive events. Also, when tossing a coin 'Heads' and 'Tails' are mutually exclusive events. When two events 'A' and 'B' are mutually exclusive it is impossible for them to happen together and the probability of 'A' or 'B' is the sum of the individual probabilities:

$P(A \cap B) = 0$

$P(A \cup B) = P(A) + P(B)$

Let's review another example when events are mutually exclusive. 'Aces' and 'Kings' are mutually exclusive as a card cannot be both, while 'Kings' and 'Hearts' are not mutually exclusive, as one card can be both.

$P(A \cup B) = P(A) + P(B) - P(A \cap B)$

16 Cards = 13 Hearts + 4 Kings − the 1 extra King of Hearts

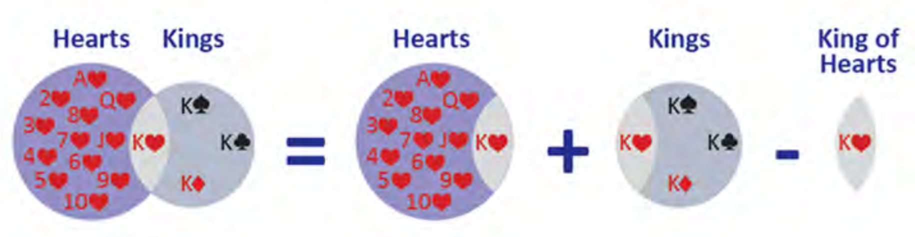


Figure 186 – Hearts and Kings are not mutually exclusive

Multiplication rule
Multiplication rule is the probability that both of two events occur.

If events 'A' and 'B' are independent, we write: $P(A \cap B) = P(A) X P(B)$

If these events were NOT independent we write: $P(A \cap B) = P(A) X P(B \mid A)$

Let's explain this with an example: A bag contains 3 red balls and 3 black balls. One ball is drawn from the bag and set aside. Then a second ball is drawn. Consider the following two events:

'A' = 'The first ball is red'
'B' = 'The second ball is red'

Note that events 'A' and 'B' are not independent as the first ball is not put back. The color of the first ball has an effect on the probability of the second ball. So, $P(A) = 3/6 = 1/2$ and $P(B \mid A) = 2/5$. The multiplication rule says that $P(A \cap B) = P(A) X P(B \mid A) = 1/2 X 2/5 = 1/5$.

7.2 Distributions

Most statistics books provide an overview of 'Statistical distributions'. Each distribution has its own properties and application, but going through these choices can be frustrating. The choices seem endless and the descriptions tend to be abstract to anyone without a statistical background. Yet, it is important to understand the basics of distributions as these are used in many of the tools that will come later on in this book. In this section, we will put emphasis on the aspects of the most common used distributions and explain when to use a certain distribution.

In this section we will review continuous distributions and discrete distributions. We will also review the following topics:

- Probability Density Function.
- Cumulative Probability Function.
- Individual Distribution Identification.
- *Z*-transformation.
- Normality test.
- Skewness and Kurtosis.
- Central Limit Theorem.
- Data transformation.

In section [7.2.1] we will review the following continuous distributions:

- Normal distribution.
- Student's *t*-distribution.
- Chi-square distribution.
- F-distribution.
- Weibull distribution.
- Lognormal distribution.
- Exponential distribution.

In section [7.2.2] we will review the following discrete distributions:

- Bernoulli-experiments.
- Binomial distribution.
- Hypergeometric distribution.
- Poisson distribution.

7.2.1 Continuous distributions

(Minitab: Graph > Probability Distribution Plot)

A probability function assigns a probability to each measurable subset of possible outcomes that a random variable can take on. When the outcome is on a continuous scale, it is called a 'Probability Density Function' (PDF). Example: A machine that cuts axes demonstrates variation in the length of the axes. Figure 187 demonstrates the amount (frequency) of axes within a certain length range. The PDF is the curve that approximates the shape of the bars that display the values.

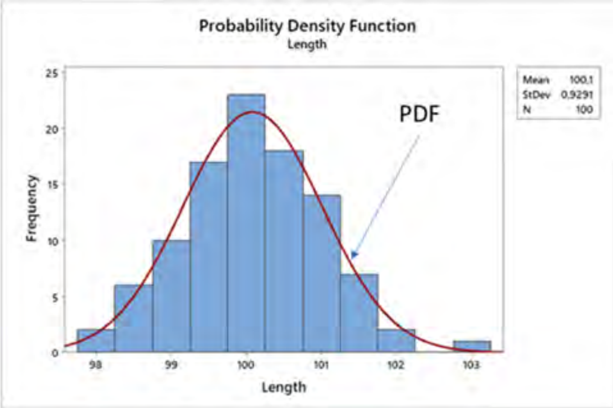


Figure 187 – Probability Distributions Function (PDF)

The 'Cumulative Distribution Function' (CDF) gives the cumulative probability associated with a distribution. Specifically, the cumulative distribution function gives the area under the probability density function, up to the value you specify. The CDF can be used to determine the probability of a response being below a certain value, above a certain value or between two values. Example: Using the Mean and Standard deviation of the example above, we will use the Cumulative distribution plot to determine the probability that we will find axes shorter than 99 [cm]. The probability that the machine will produce axes shorter than 99 [cm] is almost 16% (marked area in Figure 188).

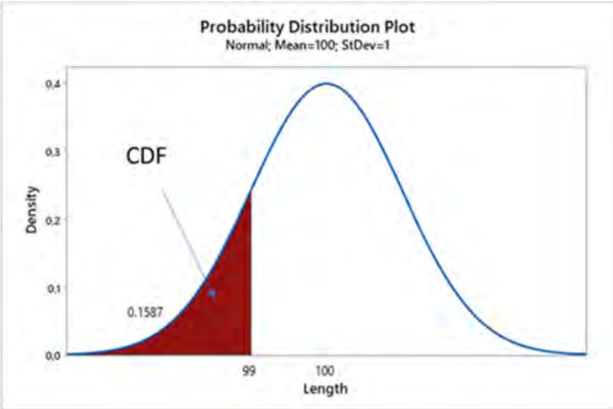


Figure 188 – Cumulative Distribution Function (CDF)

Distribution identification

(Minitab: Stat > Quality Tools > Individual Distribution Identification)

The Minitab function ‘Individual Distribution Identification’ is helpful to evaluate the optimal distribution for your data based on the probability plots. Minitab performs ‘Goodness-of-Fit’ tests on the data for a variety of distributions and estimates their parameters. The tool helps you to select the distribution that best fits your data and is most appropriate for your analysis.

Example: We apply the ‘Individual Distribution Identification’ on a set of data from a population with unknown distribution (Figure 189). The large *p*-value for the ‘Weibull’ indicates that almost all data points fall within the confidence bounds of the Weibull probability plot. This suggests that the Weibull distribution is a good assumption.

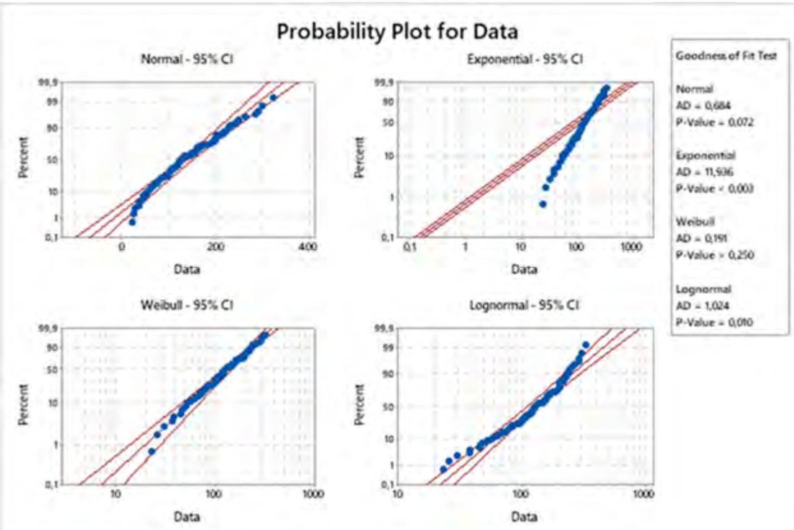


Figure 189 – Individual Distribution Identification

Normal distribution

There are many different types of distributions, but the Normal distribution (or Gaussian distribution) is the most common statistical distribution. This is because normality arises naturally in many physical measurements (e.g. dimensions of produced products, temperature), biological measurements (e.g. body temperature, length of bones) and social measurements (e.g. media campaign responses, number of tweets, IQ).

The Normal distribution is bell-shaped. Normal distributions are characterized as $N(\mu;\sigma)$, where μ is the population mean and σ is the population standard deviation. The amount of data at a certain distance from the Mean can be calculated using the following mathematical equation, describing the normal probability density function:

$$f(x) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

The so-called Standard Normal Distribution is characterized as $N(0;1)$ with a mean $\mu = 0$ and standard deviation $\sigma = 1$.

About 68.3% of the data within the population is within $\mu \pm 1\sigma$
About 95.4% of the data within the population is within $\mu \pm 2\sigma$
About 99.7% of the data within the population is within $\mu \pm 3\sigma$

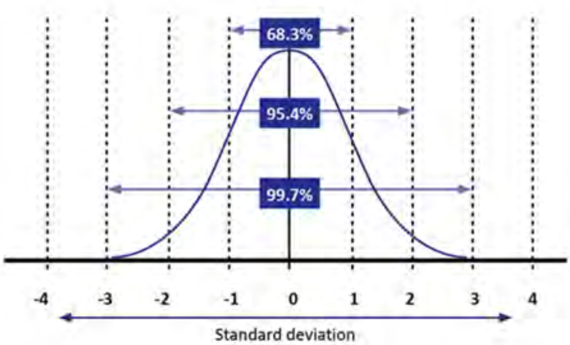


Figure 190 – Normal distribution and Standard deviation

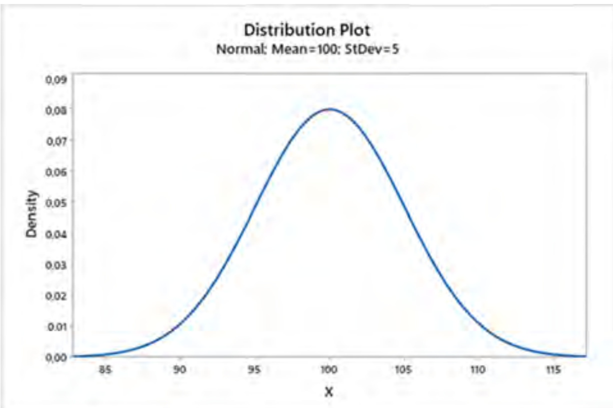


Figure 191 – Normal distribution with μ =100 and σ = 5

Normality test, Skewness & Kurtosis
(Minitab: Stat > Basic Statistics > Normality Test)

Many statistical procedures rely on normality of the population distribution. Before you apply the Normal probability distribution, you need to test if the population is distributed normally. You can use Minitab to perform a normality test. The null hypothesis [see section 7.4] for a normality test states that the population has a normal distribution. The alternative hypothesis states that the population has a non-normal distribution.

There are different techniques to test for normality, but the most common one is the 'Anderson-Darling' (AD) test. This test compares the empirical cumulative distribution of your sample data with the expected cumulative normal distribution. If the observed difference is sufficiently large, it will result in a low *p*-value. If $p < 0.05$ we have to reject the null hypothesis of population normality. In Figure 192 all points are 'close' to the diagonal line and $p > 0.05$, so we can assume normality.

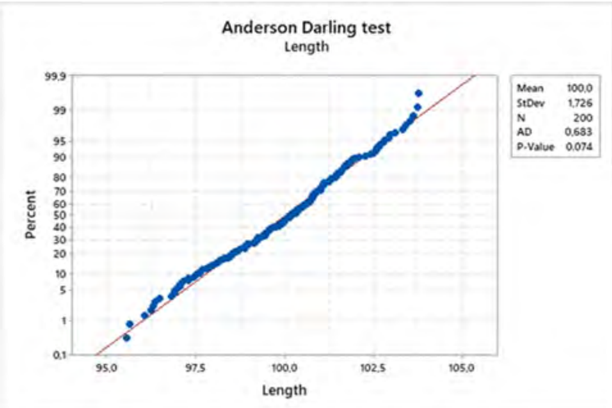


Figure 192 – Normality test

Minitab can also be used to calculate the Skewness (indicates lack of symmetry) and Kurtosis (indicates the sharpness) of the data set. *(Minitab: Stat > Basic Statistics > Display Descriptive Statistics > Options)*

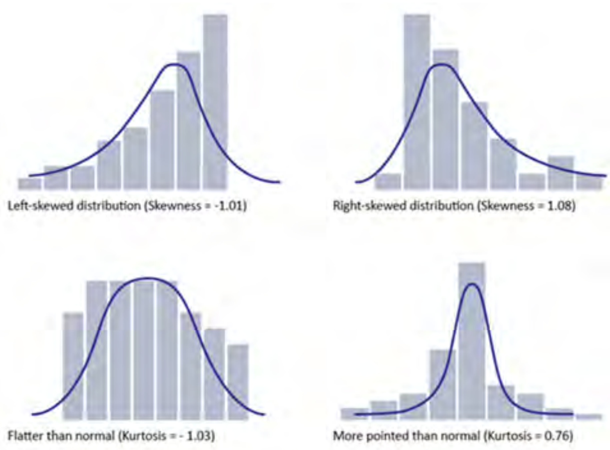


Figure 193 – Skewness & Kurtosis

Z-Transformation
The *Z*-value indicates how many sigma an observed value *X* is from the Mean of a Normally distributed set of data. Using this process to transform *X* to *Z* is called Standardizing. Its purpose is to compare a sample (with a certain μ and σ) to the standard normal distribution (with μ = 0 and σ = 1).

After determining the *Z*-value, we can look up the percentage on the left side of the value in a standardized normal distribution Table. This can be explained best by an example: The population of bars has an average length of 10 [cm] and a standard deviation of 0.8 [cm]. A certain bar has a length of 11.6 [cm]. How likely is it that we will find bars, less than 11.6 [cm]? We can calculate the Z-value using the following equation:

$$Z = \frac{(X - \mu)}{\sigma} = \frac{(11.6 - 10)}{0.8} = 2.0$$

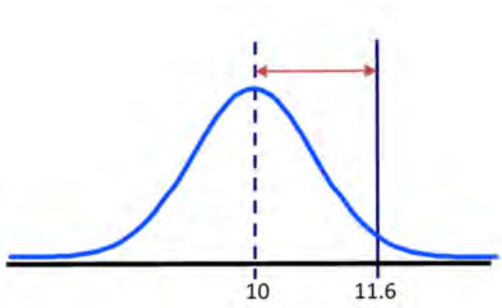


Figure 194 – Z-transformation

Now that we know that the *X* = 11.6 corresponds with a *Z*-value of 2.0, we can look up the percentage on the left of X in a Table. This tells us that the chance of finding bars less than 11.6 cm is 97.72%.

The *Z*-transformation is used to calculate probability of exceedance with a calculator, if we only have a standardized normal distribution table. Such a table is shown in Appendix C.1. However, we can also use Minitab or other statistical program. In addition, the *Z*-transformation can be used to determine which value *X*, μ or σ should be given to effect a certain change. For example changing σ to affect a failure rate.

Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.1	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

Table 29 – Standard Normal probability Table (Appendix C.1)

Weibull distribution

Time is an important response variable in many processes. Examples are time to failure, response time, waiting time and delivery time. Within both manufacturing processes and transactional processes many improvement projects have a focus on reducing Time. It is important to realize that the measure Time normally does not follow a Normal distribution. Therefore, you cannot apply the same analysis as for Normal distributions. Black Belts can transform the data to follow a Normal distribution (e.g. using Box-Cox or Johnson transformation), or they can use the distribution identification function in Minitab to investigate the probability plot that fits best the data. Time-based data is often Weibull distributed, which we will discuss in this section.

A Weibull distribution is characterized by three parameters: Shape, Scale and Threshold. In the case that the Threshold parameter is zero, the Weibull is called a 2-parameter distribution. A special case of the Weibull distribution is the exponential distribution, in which case the Shape parameter is equal to one. This is called a distribution with no memory, because the expected waiting time (or failure rate) does not change with time.

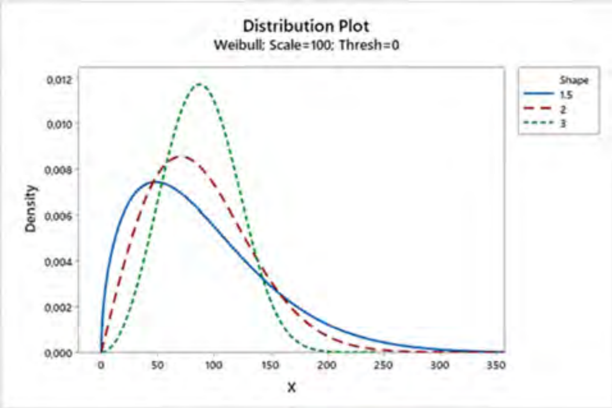


Figure 195 – Weibull distribution plots

Example: We will review a complaint procedure. The probability density function in Figure 196 demonstrates the probability of 'Lead Time' for resolving complaints. Using the cumulative probability function demonstrates that clients have a 93% probability that their complaint is not resolved within 42 days. A small percentage of the clients have to wait even more than 365 days before their complaint is resolved.

Figure 196 – Weibull distribution plot

It is good to realize that transactional processes normally are made up of a series of execution steps (e.g. entering data, answering email, filling in a form), each followed by a waiting step (e.g. queuing, waiting for approval). The Cycle Times for the execution steps typically follow a Normal distribution, while the waiting steps often follow a Weibull distribution. As the waiting times are generally much longer than the execution times, the distribution of the entire process often follows a Weibull distribution.

The Weibull distribution is not only limited to the variable 'time'. In industry the Weibull distribution is often used to describe reliability and lifetime of products. It is also used to describe the distribution of wind speed and the size of particles generated by grinding, milling and crushing operations. So, the Weibull distribution is versatile.

Student's t-distribution

The Student's t-distribution, or simply 't-distribution', is used in several statistical analyses, including Linear Regression Analysis and Hypothesis testing. The Student's t-distribution is used to calculate the Confidence Interval of the population mean when the true standard deviation is unknown [see section 7.5].

The t-distribution is characterized by only one parameter: the 'Degrees of freedom' (*df*). The t-distribution PDF is different for each number of degrees of freedom. The t-distribution is symmetric around 0 and bell-shaped, like the standard normal distribution with mean 0 and variance 1. The PDF curve is a bit lower and wider, meaning it is more prone to produce values that fall far from its mean. When we have a sample from a normal distributed population (t-distributed with *n*-1 degrees of freedom), the distribution resembles a normal distribution for large samples.

$$\frac{\bar{x} - \mu}{s/\sqrt{n}} \cong t_{n-1}$$

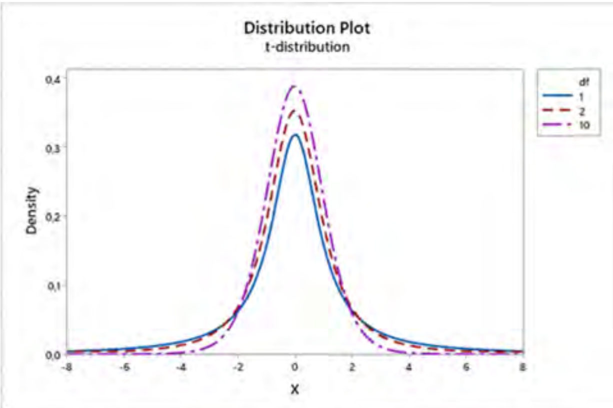


Figure 197 – Students' t-distribution plot

The Students' t-distribution Table can be found in Appendix C.2.

Chi-square distribution

The Chi-square distribution can be found under different names: Chi-square, χ^2-distribution or Central Chi-square distribution. The Chi-square distribution is a distribution of the sum of *K* squared mutually independent standard normal distributed random variables. The distribution has k degrees of freedom (*df*), where Z_i is standard normal distributed.

$$\chi^2 = Z_1^2 + Z_2^2 + \ldots\ldots + Z_k^2$$

The distribution has *k* degrees of freedom (*df*). The shape of the distribution depends on the degrees of freedom k and is right skewed. This Skewness decreases when the degrees of freedom increase. When the degrees of freedom are 30 or more, the distribution can be approximated by a Normal distribution. This is a consequence of the Central Limit Theorem [see section 7.2.2].

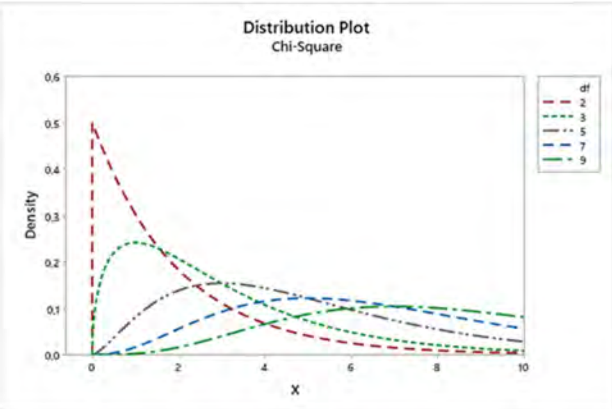


Figure 198 – Chi-square distribution plots

So, if we take a sample from a population (with a sample size of *n*) we could standardize the x_i:

$$z_i = \frac{x_i - \mu}{\sigma}$$

In this case, the following equation is Chi-square distributed with $df = n$.

$$\sum_1^n (z_i)^2 = \sum_1^n \left(\frac{x_i - \mu}{\sigma} \right)^2$$

We can then prove that:

$$\frac{(n-1) \cdot s^2}{\sigma^2} \cong \chi^2_{[n-1]}$$

and with this we can test if a sample has a similar spread as the population.

Note that we have 'lost' one degree of freedom! This occurs because as we calculate the probability of the n^{th} (or last) value in the sample we find that it is entirely determined by the sum of the other values, resulting in the loss of one degree of freedom.

The Chi-square probability distribution is widely used in Hypothesis testing and in the construction of Confidence Intervals for the standard deviation of a population. The Chi-square distribution is used to test if the variance of a normally distributed population has a given value. The distribution is also used in tests to determine whether there is a significant difference between the expected frequencies and the observed frequencies in one or more categories. An example of applying the Chi-square distribution in 'Goodness-of-Fit' test is explained in section [7.5.3].

The Chi-square distribution Table can be found in Appendix C.3.

F-distribution

The F-distribution is a continuous probability density distribution, also known as Fisher–Snedecor distribution (named after R.A. Fisher and G.W. Snedecor). The F-distribution is used to test the assumption that two populations have the same variance. In section [7.5.3] we will give an example of using the F-distribution to test if two variances are the same or not. The F-distribution is the distribution of the quotient of the variances of two samples coming from two populations, with sample sizes n and m, each divided by its degrees of freedom. The numerator of this equation is always the biggest s^2, and the denominator is always the smallest s^2. Therefore, the F-value is always $\geq$ 1. A F-value close to 1 indicates that variances are equal.

$$F_{[n-1;m-1]} = \frac{\chi^2_{[n-1]}/(n-1)}{\chi^2_{[m-1]}/(m-1)} = \frac{s_1^2}{s_2^2}$$

The F-distribution is skewed to the right and described by the degrees of freedom of its numerator (*n*-1) and denominator (*m*-1). In Figure 199 a number of F-distributions are plotted and shows the effect of different values of the degrees of freedom on the shape of the distribution.

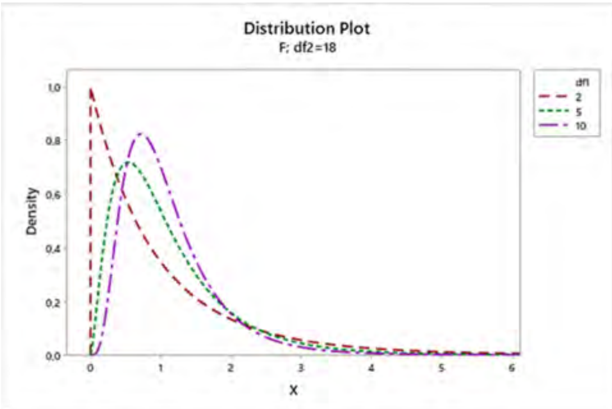


Figure 199 – F-distribution plots

The F-distribution Table can be found in Appendix C.4.

Lognormal distribution
The lognormal distribution differs from the normal distribution in several ways. A big difference is in the shape: where the normal distribution is symmetrical, a lognormal distribution is not. The lognormal distribution is a right skewed distribution, because the right portion of the distribution extends further than the left portion. Its shape is similar to that of the Weibull distribution. The lognormal distribution is determined by 3 parameters: Location, Scale and Threshold. The origin (at the left) of the lognormal distribution is always zero.

A random variable follows the lognormal distribution if the logarithm of this variable is normally distributed. In other words, if the random variable Y is normally distributed, the random variable $X = e^Y$ has a lognormal distribution.

The lognormal distribution is a probability distribution in which the change is expressed in percentages instead of in absolute change. The Lognormal distribution is often used for reliability analyzes in which the time to failure (or repair) is modeled as lognormal. In the financial world, the lognormal distribution is often used for modeling changes in stock prices. In business and sociology, the size of businesses and cities are modeled as lognormal, and in biology, values such as blood pressure, length of hair and nails are modeled as lognormal. Sometimes the Weibull distribution is also used instead of the lognormal distribution.

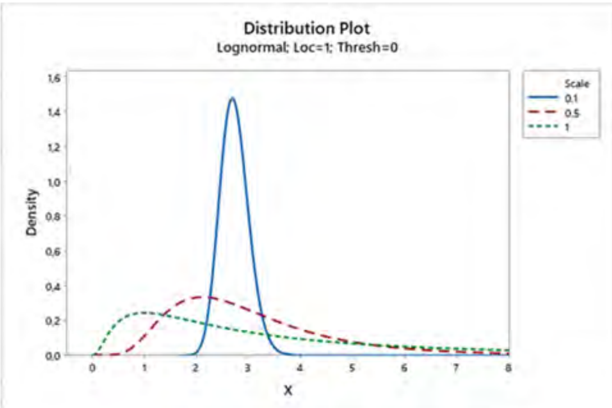


Figure 200 – Lognormal distribution plots

Exponential distribution
The Exponential distribution is often used to model the behavior of units that have a constant failure rate. The Exponential distribution has a wide range of applications in analyzing the reliability and availability of electronic systems and queuing theory. For example, applications include the time to failure of electronic components, the time between deliveries to customers and the time for radioactive nucleus decay. The 1-parameter Exponential distribution is described by its scale parameter. The 2-parameter Exponential distribution is described by its Scale and Threshold parameters. The exponential distribution is a special case of the Weibull distribution with shape equal to 1.

A special property of the Exponential distribution is that it has no Memory. This property designates that the remaining life of a component is independent of its current age. For example, a system that experiences wear and therefore becomes more likely to fail later in its life is not memoryless.

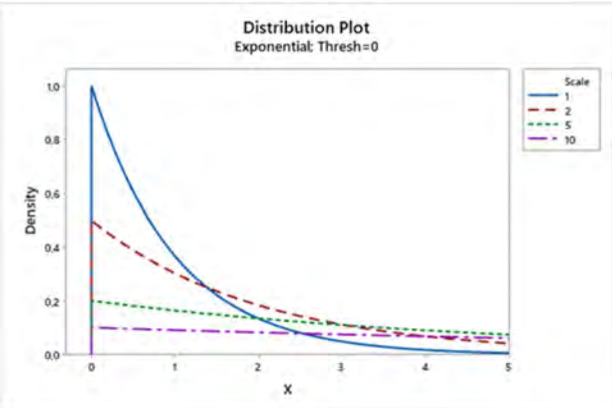


Figure 201 – Exponential distribution plots

7.2.2 Discrete distributions

As mentioned in section [6.3.1], data can be divided into continuous and discrete data. Because of this, distribution plots can also be divided into continuous distributions and discrete distributions. In this section we will review Bernoulli trials, the Central Limit Theorem and the following discrete distributions:

- Bernoulli-experiments.
- Binomial distribution.
- Hypergeometric distribution.
- Poisson distribution.

Bernoulli trials

A Bernoulli trial is a random experiment with exactly two possible outcomes: 'Success' and 'Failure'. The outcome is binary. The probability of success is the same every time the experiment is conducted and is represented by P(Success) = p. The probability of a failure is given by P(Failure) = 1 – P(Success). A common example of a Bernoulli trial is flipping a coin. Instead of 'Success' and 'Failure', you can also use '1' and '0':

- $P(1) = p$
- $P(0) = 1 - p$

The Binomial distribution is a discrete probability distribution of the number of successes in a sequence of mutually independent Bernoulli trials, each with the same probability of success. In the case of flipping a coin there are exactly two outcomes. With a fair coin you have a probability of 50% to observe 'Heads'; (p = 0.5) and 50% to observe 'Tails'; (1 – p = 0.5). A visualization with a p = 0.5 is the 'Galton board'. If the rows are numbered from 0 to N - 1, the path of each falling ball is a Bernoulli trial consisting of N steps. The distribution of the heights of the ball heaps will approximate a normal distribution (Figure 202).

Another example is rolling a dice. Assume we define 'a six' as 'Success' and the complementary event 'not a six' as 'Failure'. Since there are six outcomes, the chance of success is $P(6) = 0.167$. The chance of getting 1 through 5 is $1 - p = 1 - 0.167 = 0.833$.

In both examples the probability of the outcome of a trial does not depend on previous outcomes. If we flip the coin 5 times and would like to know the probability of getting 'Heads' five times in a row: P(5x Heads) = $p^5 = (0.5)^5 = 0.0312$.

Figure 202 – Galton board

Binomial distribution

Assume we are interested in our chances of observing 'Heads' ten times in a row when flipping a coin 100 times, or observing '6' three times, when we roll the dice 20 times. These types of questions can be answered by looking at a Binomial distribution. Binomial distributions are usually associated with evaluating the number of defective items in a sample. The probability distribution of *X* is called a Binomial distribution with n Bernoulli trials and probability of Success *P*(*X*=Success) = *p*.

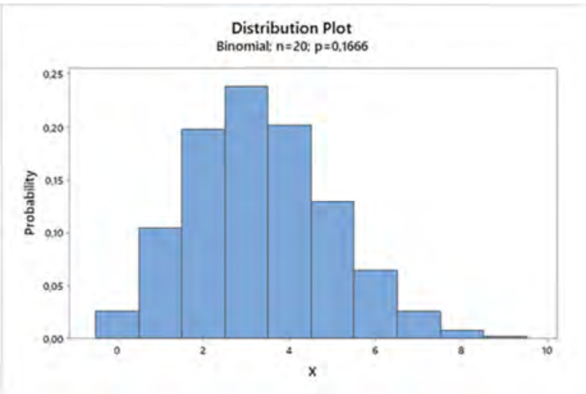
$$P[X = x] = \binom{n}{x} \cdot p^x \cdot (1-p)^{n-x} = \frac{n!}{x!\,(n-x!)} \cdot p^x \cdot (1-p)^{n-x}$$

Assume we roll a dice 20 times and we would like to know the probability of observing a '6' three times.

$n = 20$
$x = 3$
$p = 1/6$

$$P[X = 3] = \binom{20}{3} \cdot \left(\frac{1}{6}\right)^3 \cdot \left(1 - \frac{1}{6}\right)^{20-3} = \frac{20!}{3!\,(20-3)!} \cdot \left(\frac{1}{6}\right)^3 \cdot \left(\frac{5}{6}\right)^{17} = 0.2379$$

With Minitab we can calculate the probability for a series of number of successes and plot this in the session output window. We can also construct a Distribution plot of the binomial distribution with the probability of each discrete x.



Probability Density Function
Binomial with n = 20 and p = 0.1666

x	P(X = x)
1	0.104453
2	0.198366
3	**0.237925**
4	0.202139
5	0.129307
6	0.064622
7	0.025837
8	0.008393
9	0.002237
10	0.000492

Figure 203 – Binomial distribution plot

The mean and standard deviation of a Binomial distribution can be calculated as follows:

$$\mu = n \cdot p = 20 \times \frac{1}{6} = 3.33$$

$$\sigma = \sqrt{n \cdot p \cdot (1-p)} = \sqrt{20 \times \frac{1}{6} \times \frac{5}{6}} = 1.67$$

The cumulative Binomial distribution Table can be found in Appendix C.5.

A Multinomial distribution is a generalization of a Binomial distribution. Within a Binomial distribution each trial can result in two – and only two – possible outcomes, whereas within a Multinomial distribution, each trial can have two or more possible outcomes.

Hypergeometric distribution

The Hypergeometric distribution is a discrete distribution used for samples drawn from relatively small populations without replacement and two possible outcomes 'success' and 'failure'. Once an item is taken from the population, it cannot be taken again. As the population is small, the probability sampling 'success' depends on the outcome of the previous samples.

This is an important difference to the Binomial distribution with, in theory, an infinite population. Both distributions describe the number of times an event happens in a fixed number of trials. The trials in a Binomial distribution are independent, while in a Hypergeometric distribution each trial changes the probability for the subsequent trials because the population is finite and relatively small. When the sample size is larger than 10% of the population, you should use the Hypergeometric distribution. If the sample size is less than 10% of the population, the Binomial distribution can be used as an approximation.

The Hypergeometric distribution is described by 3 parameters: population size, event counts in population and sample size.

Example: Suppose you randomly sample 5 cards from a deck of 52. The question is, what is the probability that two of the sampled cards will be aces. The calculation is done using the following parameters and equation:

- Population size $N = 52$
- Number of successes in the population $M = 4$ (each deck contains 4 aces)
- Sample size $n = 5$
- Number of successes in the sample $x = 2$

$$P[X=2] = \frac{\binom{M}{x}\binom{N-M}{n-x}}{\binom{N}{n}} = \frac{\left(\frac{M!}{x!\,(M-x)!}\right)\left(\frac{(N-M)!}{(n-x)!\,((N-M)-(n-x))!}\right)}{\left(\frac{N!}{n!\,(N-n)!}\right)}$$

$$= \frac{\left(\frac{4!}{2!\,2!}\right)\left(\frac{48!}{3!\,45!}\right)}{\left(\frac{52!}{5!\,47!}\right)} = 4.0\%$$

Conclusion: the probability of finding 2 aces in a sample of 5 cards is 4.0%.

We can also use Minitab to do the calculation for us:

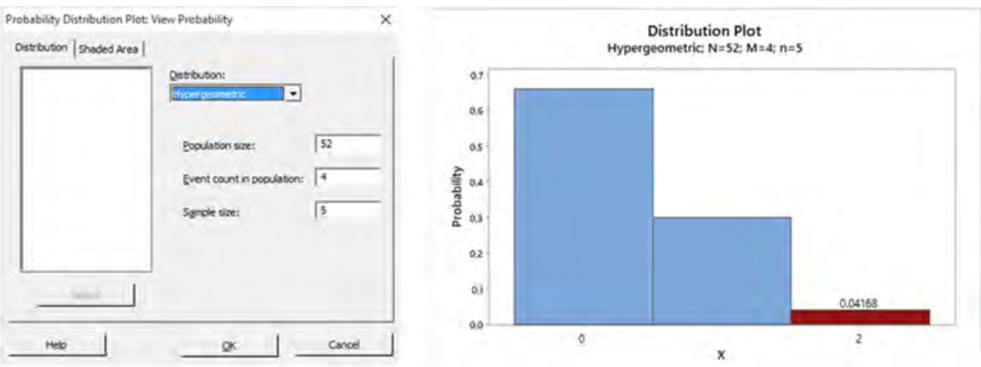


Figure 204 – Hypergeometric distribution plot

Poisson distribution

The Poisson distribution expresses the probability of a given number of events occurring in a fixed interval of time or the number of defects that occurs in a unit or product. The occurrences of events or defects are mutually independent. The Poisson distribution can be used for the number of events per interval (e.g. time, area, volume). The distribution is fully described by only one parameter λ:

$$P[X = x] = \frac{\lambda^x \cdot e^{-\lambda}}{x!}$$

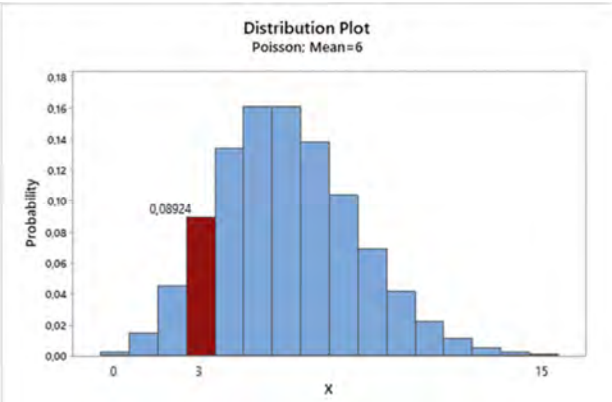
The mean and standard deviation of a Poisson distribution can be calculated as follows:

$$\mu = \lambda$$
$$\sigma^2 = \lambda \quad (= \mu)$$
$$\sigma = \sqrt{\lambda}$$

Example: the average number of incidents in a weekend is '6'. What is the probability that in the next weekend '3' incidents occur? We can answer this by using the equation:

$$P[X = 3] = \frac{6^3 \cdot e^{-6}}{3!} = \frac{216 \cdot 0.00248}{6} = 0.089235$$

This can also be answered by generating a Poisson probability distribution plot and looking for the probability of $x = 3$.



Probability Density Function
Poisson with mean = 6

x	P(X = x)
1	0.014873
2	0.044618
3	0.089235
4	0.133853
5	0.160623
6	0.160623
7	0.137677
8	0.103258
9	0.068838
10	0.041303

Figure 205 – Poisson distribution plot

The cumulative Poisson distribution can be used as an approximation of the Binomial distribution for $n > 20$ and $p < 0.05$. In that case $\lambda = n \cdot p$.

The Poisson distribution Table can be found in Appendix C.6.

Central Limit Theorem

The sum of a large number, n, of mutually independent and equally distributed random variables will approach a normal distribution when *'n'* increases. The variables themselves do not need to have a normal distribution. This means also that when we sample subgroups and calculate the averages, these averages will be approximately normal distributed for large *'n'*.

The 'Central Limit Theorem' (CLT) is not a technique, but a statistical theorem that is used behind the scenes for other tools. This is important because many statistical techniques assume normal distributions. Hypothesis testing or Confidence Intervals for means assume that we deal with normal distributions. The CLT states that it is allowed to assume Normal distribution for averages when we take enough samples, although the population is not normally distributed. The Central Limit Theorem can be applied to both continuous and discrete distributions.

As a rule of thumb, the smallest sample size that can be drawn from a non-normal continuous distribution of observations to produce a normal sampling distribution of sample means is n = 30. For a discrete distribution of proportions then the sample size and proportion should adhere to the rule $np \geq 10$. For discrete count distributions then the average occurrence rate n should be greater than 10. However, it should be noted that the true answer to the question: *"What sample size must be taken to allow use of the central limit theorem and normal approximation?" is "It depends!"*

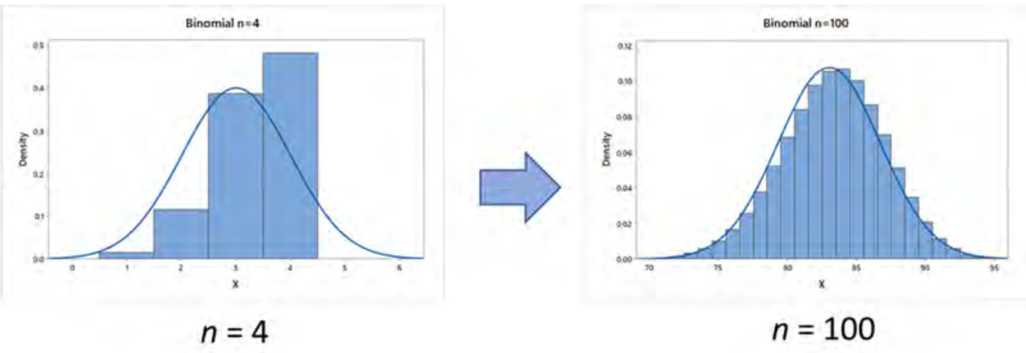


Figure 206 – CLT for Binomial distribution

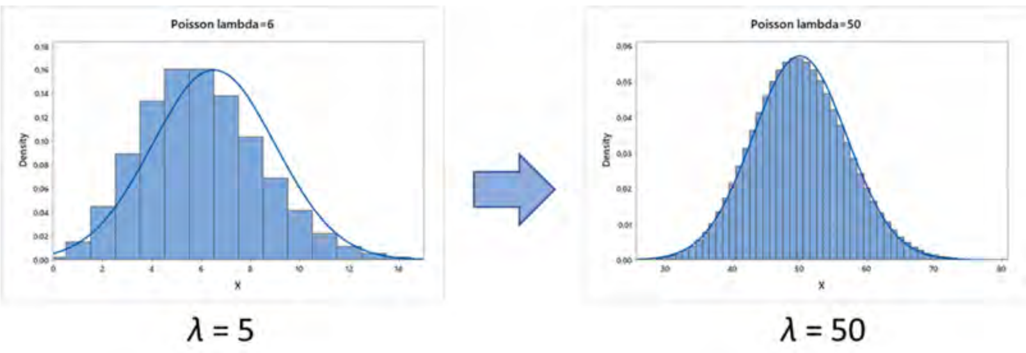


Figure 207 – CLT for Poisson distribution

7.2.3 Data transformation on non-Normal data

(Minitab: Stat > Quality Tools > Capability Analysis > Normal > Transform)

Many statistical analysis tools require data from Normally distributed populations such as individuals Control charts, Capability analysis, t-tests and analysis of variance (ANOVA). As mentioned already in section [7.2.1] you can try to transform non-Normal data to make it approximately Normal. Minitab offers the methods to transform non-Normal data and use it with any analysis that assumes that the data follow a Normal distribution. In this section we will discuss the Box-Cox and the Johnson transformation.

Box-Cox transformation
The Box-Cox transformation tries to transform a non-Normal dataset into a fairly Normal distributed dataset. The Box-Cox transformation is easy to understand but is very limited and often does not determine a suitable transformation. It is also only available for data that are positive.

The transformation function used is: $y = x^{\lambda}\ \{-5 < \lambda < +5\ ; if\ \lambda = 0\ then\ y = Ln(x)\}$

The λ with the best fit is selected. The original data are Lognormal distributed if the transformation y = Ln(x) gives the best fit.

Johnson transformation
If the Box-Cox algorithm does not determine a suitable transformation, then try a Johnson transformation. The Johnson transformation functions are more complicated, but the method is very powerful for determining an appropriate transformation. For Johnson transformations, data does not necessarily have to be positive.

Some Minitab tools already include the option to transform the data, like Capability analysis, which is shown in Figure 208.

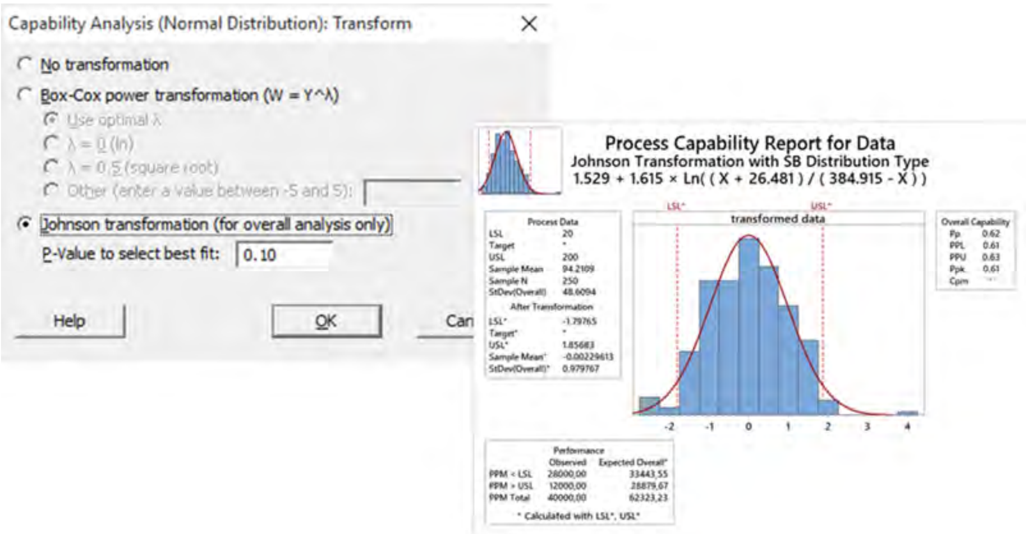


Figure 208 – Capability analysis using Johnson transformation

7.3 Measurement Systems

Metrology is the ‘science of measurement’, and includes a number of theoretical and practical aspects of the measurement process. It is important to ensure that data which are used in an improvement project are valid and reliable. For this purpose, it is necessary that use a reliable measurement system which, moreover, has sufficient resolution. This is one of the key elements of a Lean Six Sigma project because conclusions based on unreliable data are unreliable themselves. Therefore, much attention is given in the Measure-phase of a DMAIC project to the evaluation of the measurement system.

7.3.1 Measurement System Analysis (MSA)

Measurement method

There are many different measurement tools. One example is the so-called ‘Go / No Go Gage' (Figure 209) which is used to assess whether an item meets a certain specification or tolerance. The Gage has two possible outcomes: OK (approval) or NOK (rejection). The use of this type of Gages is based on the principle of Poka Yoke, because the outcome is not open to interpretation. Standard ‘Go / No Go Gages' can be purchased from various suppliers, but sometimes such Gage is tailormade to evaluate a specific component or assembly. Another example of a measurement system is the caliper, shown in Figure 210.

Figure 209 – Go/No Go Gages

Figure 210 – Measurement System: Caliper

In addition to the measurement tool itself, also the measurement method or measurement process is of great importance for carrying out a proper measurement. When you perform a number of consecutive measurements you do not necessarily always get the same value. For example, step on a scale to measure your weight. You will probably get a slightly different value each time. This measurement variation is part of the measurement system. ‘How important is this variation?’ and ‘Is this variation small enough to draw conclusions about the performance?’ In the following sections we will discuss the measurement system as a whole, consisting both of the measuring instrument and the measurement process.

Measurement System Analysis (MSA)
Every measurement instrument shows variation. Besides the variation of the instrument, there are other sources of variation, for example:

- Operators performing the measurements.
- Operating procedures.
- Data collection forms.
- Tools and aids that are used.
- The way and frequency samples are taken from the line.
- Calibration technique.
- Environment (temperature, moisture, vibration, light, etc.).
- . . .

The ideal measurement system produces the true value every time. However, . . . we all know nothing is perfect! Just like any other process, the collection of data and performing measurements on the product is a process in itself. Obtaining data and doing measurements will demonstrate variability and produce defects.

We will review how a 'Measurement System Analysis' (MSA) is performed on the measurement system. The MSA tells you how precise the measurement tool is (the equipment) and how large the impact of the measurement process is (e.g. operator and procedure). An MSA evaluates the test method, measuring instruments and the entire process of obtaining measurements in order to quantify measurement accuracy and variability. This is important for making decisions about a product or process.

The process variation that we observe by reading the measurement data on the instrument is always larger than the actual process variation. This is because we have to take the variation caused by the Measurement System (Gage) into account. The 'Observed variation' is also called the 'Total variation'. The actual 'Process variation' is also called 'Part-to-Part variation'.

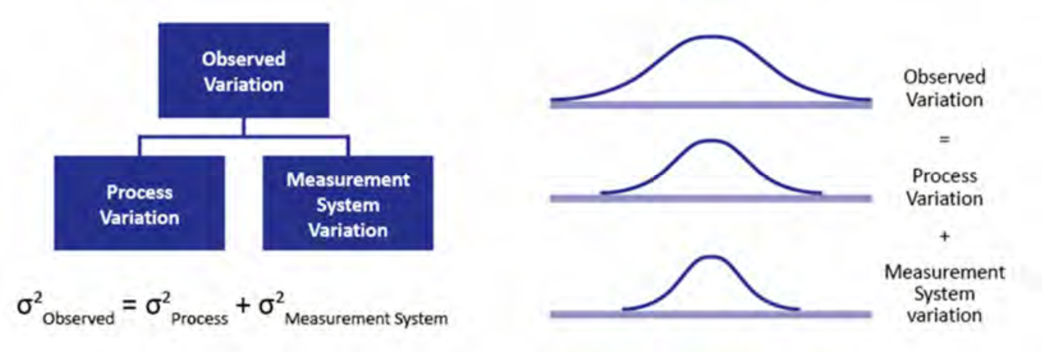


Figure 211 – Observed variation and Measurement system variation

To minimize measurement system variation, it is important to identify and understand the factors of influence. Measurement system errors can be characterized into the following three categories:

1. Accuracy: How big is the systematic error?
    a. Bias:
       The difference between the measured average and the true value.
    b. Linearity:
       Equal accuracy over the entire range of the instrument.

2. Precision: How big is the measurement variation?
    a. Repeatability:
       The amount of variation that is caused by the measuring instrument itself.
    b. Reproducibility:
       The amount of variation that is caused by the measurement procedure, operator, etc.
    c. Uniformity:
       Extent to which measurement variation is constant (uniform) over the whole range of the measurement scale.

3. Stability: Is the measurement system stable over time?

If you ask how good a measurement system is, they might tell you 'It has been calibrated recently, so it is perfect'. Keep in mind that calibration of the system is only one aspect of a good measurement system. A calibrated system is no guarantee for Accuracy, Precision or for Stability. An MSA is always done in combination with the objects to be measured.

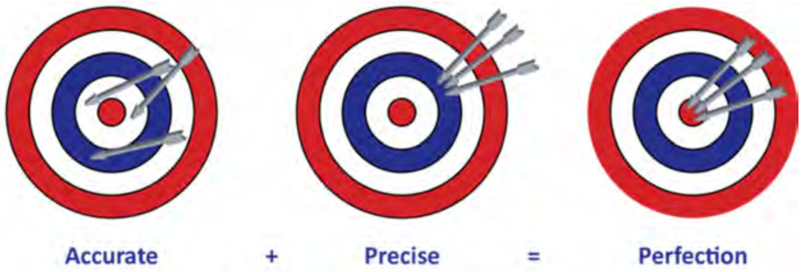


Figure 212 – Measurement System Variation

1 – Accuracy

The accuracy of a measurement system is also called the systematic difference between the measured average and the true value or Bias. Bias effects include:

Employee Bias:

Several employees get different measurement averages for the same object. Also, different observations or retrieving data from different database systems will cause this type of error. An effective measurement instruction, training and clear definitions will limit the extent of Employee Bias.

Instrument Bias:

Several instruments get different measurement averages for the same object. This can be minimized by performing calibration of the Gage. Realize, however, that the Bias after the calibration process will be determined by the reference value that is used for the calibration process. The reference must be traceable to SI units (French: Système international d'unités, SI) to minimize instrument bias caused by calibration.

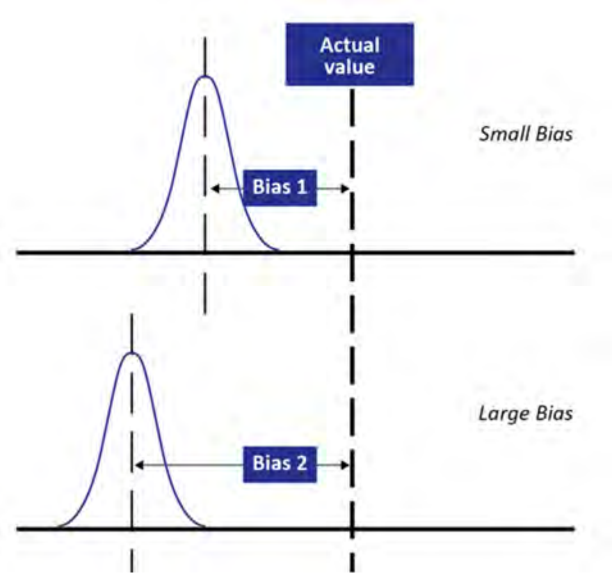


Figure 213 – Measurement System Accuracy (Bias)

Linearity:
The measurement system might give a different Bias at different locations of the measurement scale. Especially mechanic measurement systems or measurements related to temperature and pressure might demonstrate this type of measurement error.

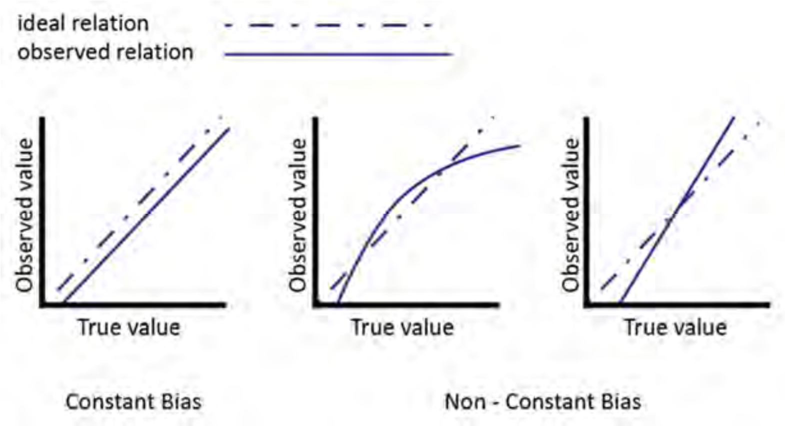


Figure 214 – Measurement system Accuracy (Linearity)

2 – Precision (Repeatability & Reproducibility)

Precision is the total amount of variation of the measurement system. This includes variation caused by the measurement instrument and the measurement process. The amount of Precision variability can be determined by a Measurement System Analysis (Gage R&R), where the two Rs stand for Repeatability and Reproducibility.

$$\sigma^2_{Measurement\ \ System} = \sigma^2_{Repeatability} + \sigma^2_{Reproducibility}$$

Repeatability:

Repeatability is the proportion of the variation that is caused by the measuring instrument itself, also called 'test-retest error'. It is the variation which occurs when repeated measurements are taken on the same object without changing the circumstances (e.g. same employee, same samples, same set-up, same measurement instrument, short time period, etc.).

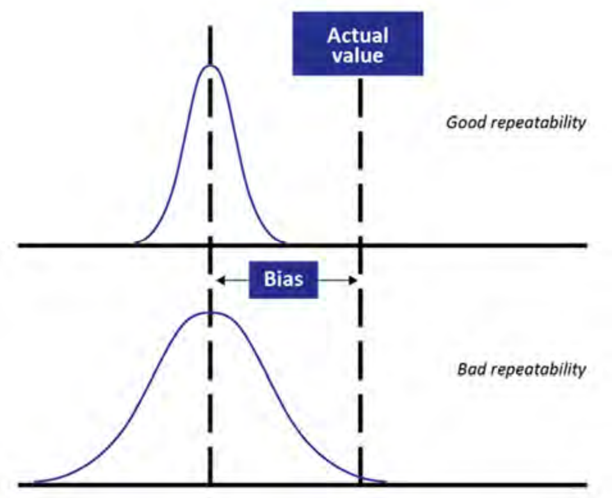


Figure 215 – Measurement system precision (Repeatability)

Reproducibility:
Reproducibility is the variation caused by the measurement procedure. This is the variation that occurs when repeated measurements are made of the same object under different conditions (e.g. different operators or employee, different set-ups, different test units, different environmental conditions, long time period).

The reproducibility is the sum of two variance components: the Operator and the Operator × Part interaction.

$$\sigma^2_{Reproducibility} = \sigma^2_{Operator} + \sigma^2_{Operator \times Part}$$

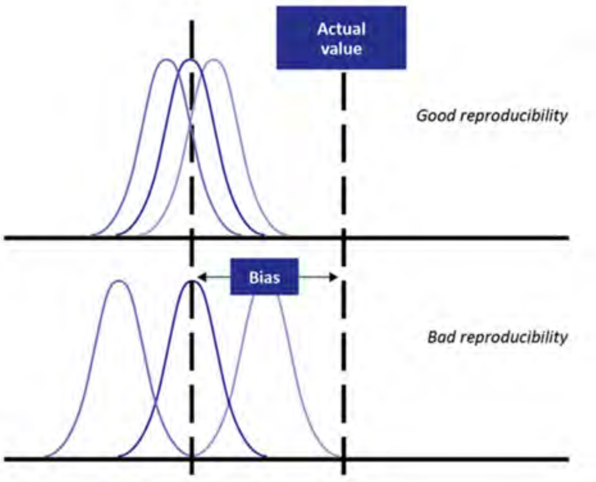


Figure 216 – Measurement system precision (Reproducibility)

Uniformity:
Extent to which measurement variation is constant (uniform) over the whole range of the instrument.

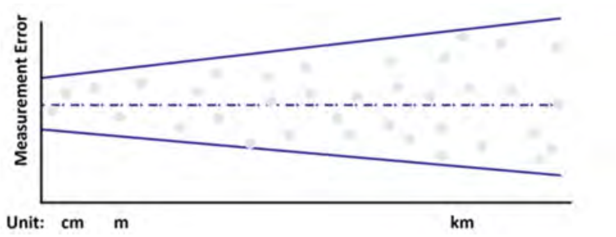


Figure 217 – Measurement system precision (Uniformity)

(Minitab: Stat > Quality Tools > Gage Study > Create Gage R&R Study Worksheet)

The Accuracy can be determined by a calibration study. The Precision or Measurement System variation can be determined by a Gage R&R measurement system analysis. The Green and Black Belts define which study should be performed and create the study worksheet. A common standard for a Gage R&R study (%-R&R), is to use 10 parts, measured by 3 different persons, 2 times each, providing a total of 60 results. Of course, different numbers can be used as well, but the term 'number of operators x number of parts measured' should be higher than 15.

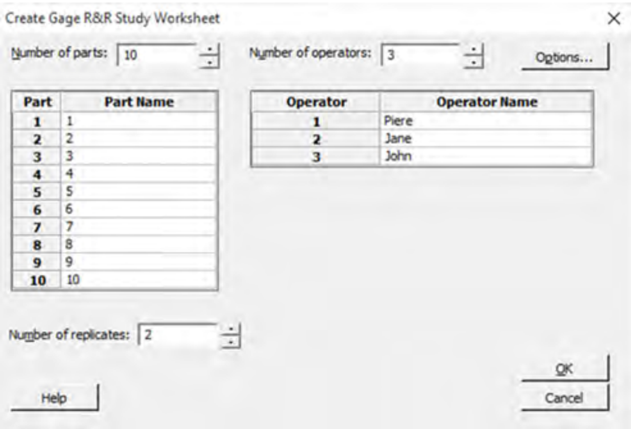


Figure 218 – Create Gage R&R Worksheet

There are four different indices that quantify the capability of a Gage:

- %-Tolerances - %-P/T (P/T Ratio)
- %-Study Variation - %-R&R (Ratio of Variations)
- %-Contribution - Ratio of Sum of Squares
- Number of Distinct Categories - Discrimination Index

Minitab is able to create Gage study designs and calculate each of these four indices. In the following Minitab output these indices are represented.

(Minitab: Stat > Quality Tools > Gage Study > Gage R&R Study (Crossed))

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0002014	0.58
Repeatability	0.0001929	0.56
Reproducibility	0.0000084	0.02
Operators	0.0000084	0.02
Part-To-Part	0.0344544	99.42
Total Variation	0.0346558	100.00

‘%Contribution’

‘%Study Variation’ or ‘%R&R’

‘%Tolerance’ or ‘%P/T’

Process tolerance = 6

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.014190	0.08514	7.62	1.42
Repeatability	0.013889	0.08334	7.46	1.39
Reproducibility	0.002905	0.01743	1.56	0.29
Operators	0.002905	0.01743	1.56	0.29
Part-To-Part	0.185619	1.11371	99.71	18.56
Total Variation	0.186161	1.11696	100.00	18.62

Number of Distinct Categories = 18 — Discrimination

This second part of the Table shows the %Study Variation, which is used most often to validate a measurement system. The Table shows that 99.71% (=1.113714/1.116966) of the total observed variation consists of Part-to-Part variation. The Gage variation represents 7.62% (=0.08514/1.116966) of the total observed variation. This consists of Repeatability; 7.46% (=0.08334/1.116966) and Reproducibility; 1.56% (=0.01743/1.116966). Reproducibility consists of Operators, 1.56% (=0.01743/1.116966), and also Part x Operator interaction, but only if it is significant. In our example it is not significant. %Study variation is demonstrated by the red bars in Figure 219. N.B.: the sum of these variations does not add up to 100%, caused by the fact that the variations are expressed in standard deviation. Expressed in variance instead, the sum does add up to 100%.

The right column of the Table shows the %Tolerance, also called the P/T ratio. Under the Option-button you have the possibility to enter either the known tolerance range (Upper spec – Lower spec), the lower specification limit, or the upper specification limit. %Tolerance is demonstrated by the yellow bars in Figure 219.

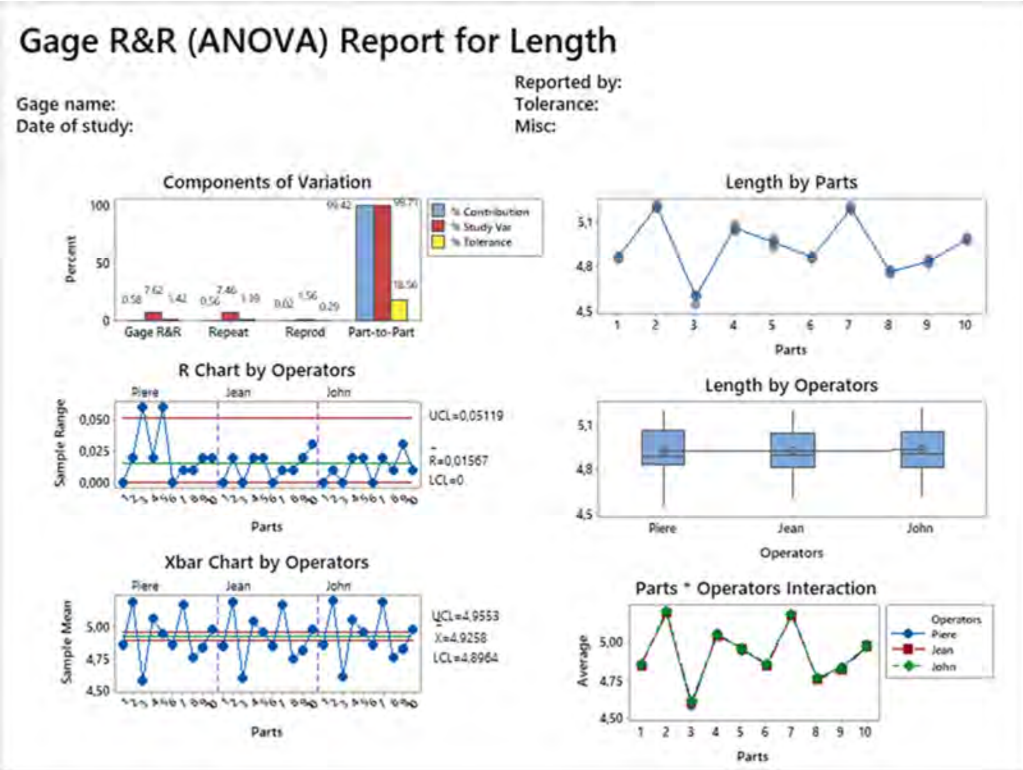


Figure 219 – Graphical representation Gage R&R

The Automotive Industry Action Group (AIAG) has set standards for Gage acceptance. The lower the percentage of the study outcome, the better the measurement system. In the example that we reviewed before, we can see that a Study Variation for Total Gage R&R of 7.62% is classified as an 'Ideal' measurement system, as its value is below 10%.

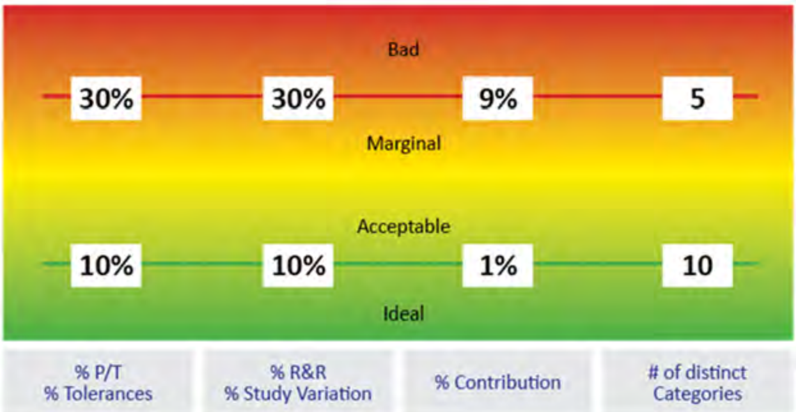


Figure 220 – AIAG Gage acceptance standards

7.3.2 Attribute Agreement analysis

(Minitab: Stat > Quality Tools > Attribute Agreement Analysis)

In section [6.3.1] we explained the difference between quantitative data and qualitative or attribute data. Both Categorical and Ordinal data are Attribute data. Examples are performance rating (e.g. Scale 1 to 5) and classification of quality (e.g. 'Good' or 'Bad'). While the Continuous Gage R&R is applied to Continuous data, the Attribute Agreement Analysis is applied to assess the agreement of Attribute data. The measurements are 'Subjective' ratings by people rather than direct physical measurements.

In situations when we are dealing with Attribute measurement systems, the quality characteristics are often difficult to assess. The Attribute Agreement Analysis is conducted in almost identical fashion to those for Continuous data. The results are used to assess the reproducibility (how well do appraisers agree with each other), as well as repeatability (how consistent do they agree with themselves). To obtain meaningful classifications, more than one appraiser should classify the response measure. If the appraisers agree, the possibility exists that the ratings are accurate. If the appraisers disagree, rating usefulness is limited.

When setting up an Attribute Agreement Analysis, you need to be aware that for Attribute Agreement Analysis more data will be needed than for Continuous Gage R&R, because attribute data has less resolution than continuous data. As a rule of thumb, you will need at least 50 objects to be assessed, at least 2 times by each appraiser.

Minitab offers the optional ability to include the 'known standard' of the attribute in the analysis. This is a separate column of data that can be selected which includes the 'correct answer'. This option can be used to train or certify new employees or to assess the bias of employees. For this it will be necessary to have a set of samples with 'known' ratings (training set or calibration set), defined for instance by a group of experts. To analyze the results, we have to take a look at the next elements:

- Within Appraiser:
  Shows the consistency of the appraisers between the trials as a percentage score. The Within Appraiser Table is not displayed if each appraiser conducted a single trial.
- Between Appraisers:
  Shows the consistency between the appraisers as a percentage score.
- Appraisers versus standard:
  If the 'known standard' is incorporated in the analysis, we will be able to evaluate the performance of the appraisers versus standard.
- All Appraisers versus standard:
  As before, but then for all Appraisers.

Kappa statistics are commonly used in attribute agreement analysis. The Kappa index indicates the degree of agreement of the nominal or ordinal assessments made by multiple appraisers when evaluating the same samples. For example, 45 patients are examined by two different doctors for a particular disease. How often will the doctor's diagnosis of the condition (positive or negative) agree? Kappa values range from -1 to +1. The higher the value of Kappa, the stronger the agreement. The Kappa index equals 0 if there is no agreement among the appraisers other than what would be expected by chance.

We will explain the Attribute Agreement Analysis with an example: Assume we have three teachers who are evaluating essays for a student exam. Based on a number of criteria, they classify the student as a 'Pass' or as a 'Fail'. We will evaluate if there is a significant difference between the evaluations of the three teachers. We will also include a 'known standard', which contains the 'expert decision' for passing or failing the exam. Each teacher (appraiser) will evaluate each essay twice.

A summary of the Minitab results is shown below. This demonstrates that the consistency within the appraisers is ok (minimum of 80%). The consistency between the appraisers is not good (they agree with themselves in 28 or 29 of the cases, but only for 15 cases they agree with each other). The results against the standard are a bit low for appraiser 1 and 3 (in particular appraiser 1).

Within Appraisers

```
Appraiser # Inspected # Matched Percent 95% CI
 1             30          28       93.33 (77.93; 99.18)
 2             30          28       93.33 (77.93; 99.18)
 3             30          29       96.67 (82.78; 99.92)
# Matched: Appraiser agrees with him/herself across trials.
```

Between Appraisers

```
# Inspected # Matched Percent 95% CI
     30          15       50.00 (31.30; 68.70)
# Matched: All appraisers' assessments agree with each other.
```

Each Appraiser vs Standard

```
Appraiser # Inspected # Matched Percent 95% CI
 1              30          22      73.33 (54.11; 87.72)
 2              30          28      93.33 (77.93; 99.18)
 3              30          24      80.00 (61.43; 92.29)
# Matched: Appraiser's assessment across trials agrees with the known standard.
```

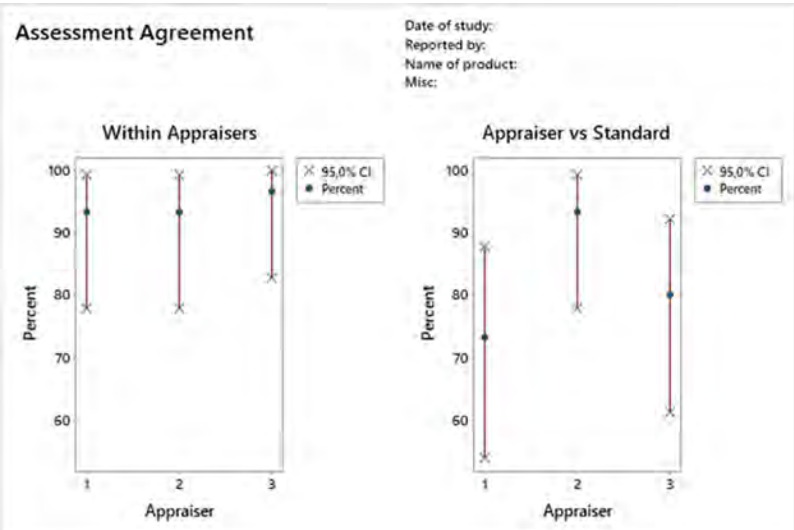


Figure 221 – Attribute Agreement Analysis

7.4 Hypothesis Testing and Confidence Intervals

The objective of Six Sigma is to reduce the variation of the CTQ by identifying the root causes of the variation and eliminate the root causes or reduce their influences. To identify and verify the root causes, we have at our disposal different statistical methods. Most of them are using Hypothesis testing. Hypothesis tests are used to test statements about a population. Confidence Intervals are used to quantify the confidence of the estimates of the population parameters.

7.4.1 Hypothesis testing

Hypothesis testing is used to investigate if a statement is 'True' or 'False'. For example, if we want to investigate if a certain factor has an influence on the process, we start by defining the null hypothesis (H_0) and the alternative hypothesis (H_A). There is a special way of formulating the hypotheses, which is often compared with a lawsuit where a suspect is still innocent until the opposite is proven. The starting point in hypothesis testing therefore is always that we assume there is no influence, even when we suspect that there actually is an influence. The null hypothesis is always defined as 'there is no influence of factor X' or 'there is no difference between machine A and machine B', etc. The alternative hypothesis then describes the difference. This, however, is an assumption that must be investigated and proven.

In 1933, Neymann and Pearson published the Statistical testing Theory. In 1934, Sir Karl Raimund Popper stated that a scientific hypothesis should be formulated in such a way that testable statements can be derived and that these statements should be assumed to be true until they are proven untrue by test results. The theory of testing hypotheses has been around a while and are tried and tested and not 'flavor of the month'.

For many people, defining the hypothesis is confusing in the beginning so let's illustrate it with an example. Suppose we are examining two vaccines that are both believed to protect against corona. The null hypothesis should be defined as 'Vaccine A has the same protection against corona as vaccine B'. Keep in mind that 'A person is innocent until proven guilty'.

- H_O: vaccine A offers as much protection against corona as vaccine B.
- H_A: vaccine A offers better protection against corona than vaccine B.

The next step is to test this hypothesis. To this end, we collect information from people who have received one of the two vaccines. These are two samples with data on the health of the patients. We then perform a statistical test to investigate whether there is a statistically significant difference between the two samples. Based on this test, we then (just like a judge) make a ruling on the assumption. However, it may be that 'the judge' is wrong. Even if there is hard evidence and the suspect is found guilty, it could be that the person is not guilty at all. Once in a while such stories make the news. In statistical terms, we will call this conclusion a 'Type-I error'. Another possibility is that a person who is declared not guilty is actually guilty. The acquittal of a guilty person is referred to in statistical terms as a 'Type-II error'. Of course we want the chance of these kinds of errors to be as small as possible and we do our very best to do so. In any case, it helps to have as much evidence as possible. In statistics, this means more samples and more data. But no matter how much evidence we have, it is important to realize that 100% certainty is not possible within statistics.

The ‘Type-I Error’ is the situation that we reject the null hypothesis although we should not. The significance level, or alpha level ‘*α*’, is the probability of rejecting the null hypothesis when the null hypothesis is actually true. The ‘Type-II error’ is the situation that we accept the null hypothesis when this hypothesis is not true. The probability of this error is called Beta or ‘*β*’.

- Type-I error: Supporting the alternative hypothesis when the null hypothesis is true.
- Type-II error: Not supporting the alternative hypothesis when the alternative hypothesis is true.

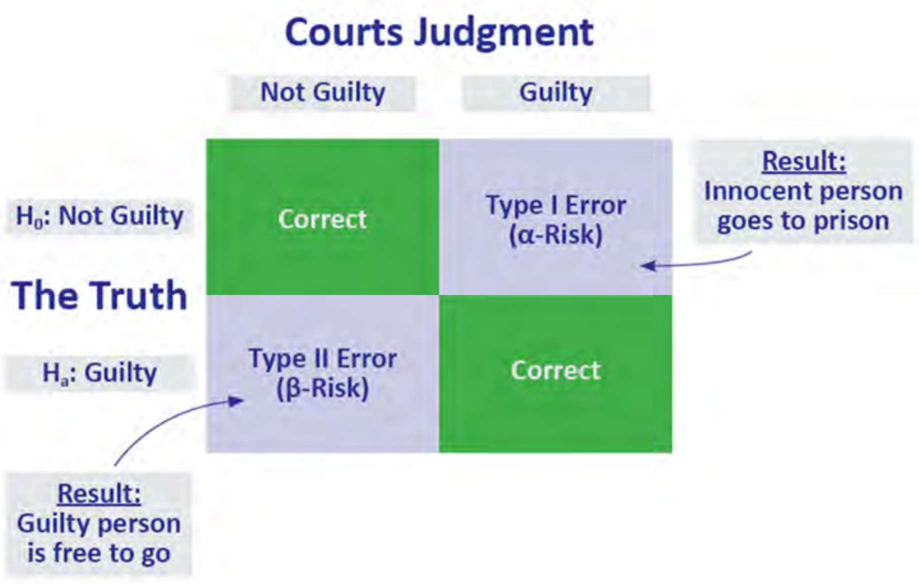


Figure 222 – Type I and Type II error

***p*-Value**

p-values are used to determine the statistical significance of the outcome of a hypothesis test. Understanding the meaning of the *p*-value is therefore very important for hypothesis testing. In medical publications for instance you will usually find statements based on the result of hypothesis tests presented, along with the associated *p*-values. In fact, *p*-values often determine what studies get published and what projects get funding.

In statistical significance testing, the *p*-value is the probability of obtaining a test outcome at least as extreme to the one that was actually observed, assuming that the null hypothesis is true.

The primary purpose of a hypothesis test is to decide if the results of a study, based on a small sample, provide enough evidence against the null hypothesis. This allows us to judge that it is reasonable to believe that, in a larger target population, the null hypothesis H_0 can be rejected. The *p*-value should always be indicated when performing a hypothesis test, as the *p*-value provides a continuous measure of the evidence against H_0. The *p*-value is simply a measure of the strength of evidence against the null hypothesis. The lower the *p*-value, the more evidence we have that H_0 is not true. A study with a $p = 0.231$ has much less evidence against H_0 than a study with a $p = 0.032$. The latter result indicates that the observed result would be highly unlikely, assuming that the null hypothesis is true.

But when is there enough evidence to reject the null hypothesis? Statisticians have defined a formal approach in evaluating the results of a hypothesis test. An artificial cut point is chosen which is called the 'Significance level'. A result of a test is called statistically significant if the p-value is less than the significance level and this leads to the rejection of the null hypothesis. Researchers often reject the null hypothesis when the *p*-value turns out to be less than a significance level alpha of 0.05 or 0.01 although there is no real scientific reason for choosing these values.

Interpreting a *p*-value can be confusing. The best way to learn how to do this is memorizing the following phrase:

If p is low, H_O must go

This means, having set up your hypothesis test assuming that the null hypothesis is true, if the result of the test indicates an unlikely outcome, then you should reject the null hypothesis and accept the alternative hypothesis. So, when the *p*-value is lower than the alpha risk (usually set at 0.05), you have to reject the H_0 and support H_A. For instance, if $p = 0.029$ you have to reject the null hypothesis, because '*p* is low' (0.029 is lower than 0.05) so 'H_0 must go'!

However, if the result of the test indicates a likely outcome then you should fail to reject the null hypothesis and cannot accept the alternative hypothesis. For instance, if you have an alpha level of 0.05 and $p = 0.302$ then there is not enough evidence to reject the H_0, because in this case '*p* is NOT low' (0.302 is NOT lower than 0.05) so 'H_0 must NOT go'! You should note that you cannot accept the null hypothesis, but only find evidence against it.

Many common statistical tests, such as Chi-square tests or Student's t-tests, produce test statistics that can be interpreted using *p*-values. Within statistical software like Minitab you will find *p*-values everywhere for normality testing, regression, design of experiments etc. Each time you can apply the same semantics over and over again. If you test the normality of a set of data, the null hypothesis would be: 'The data are normally distributed', while the alternative hypothesis would be: 'The data are not normally distributed'. When we find a *p*-value that is lower than our alpha, we have to reject the null hypothesis and support the alternative hypothesis.

7.4.2 Confidence Intervals

When you fit a parameter to a model, the accuracy or precision can be expressed as a Confidence Interval, a Prediction Interval or a Tolerance Interval. The three are quite distinct. In this section we will first explain the Confidence Interval and second explain the Prediction Interval and Tolerance Interval.

Confidence Interval (CI)

Statistics such as the average ($\overline{X}$) and standard deviation (*s*) of the sample are only estimates, not the actual values of the population parameters! From sample to sample these estimates will differ. A so-called 'Confidence Interval' (CI) indicates how reliable our estimate is. Unless we investigate the entire population, we have to accept that we can never be 100% sure about our estimates.

Instead of assuming a statistic is absolutely accurate, Confidence Intervals can be used to provide a range within which the true process statistic is likely to be with a known level of confidence. The confidence level defines how sure we are of conclusions that are drawn. Often a 95% level of confidence is used, but we can choose other levels. If we want to be more confident, we would need to increase the sample size.

Assume we want to draw a sample to calculate a 95% Confidence Interval for a population parameter. Then there is a 95% probability that the Confidence Interval will contain the actual value of the parameter. In other words: when we draw a large number of samples, about 95% of the calculated Confidence Intervals will contain the actual value of the parameter. It does not mean that the parameter's actual value has a probability of 95% of lying within the Confidence Interval.

Alpha levels are related to Confidence Intervals. You can choose the alpha level yourself. To define the alpha level, you have to subtract your Confidence Interval from 1. For example, if you want to be 95% confident that your analysis is correct, the alpha level would be 1 – 0.95 = 0.05 which is 5%, assuming that you had a one tailed test. For two-tailed tests you have to divide the alpha level by 2. In this example, the two tailed alpha would be 5% / 2 = 2.5%, as shown in Figure 223.

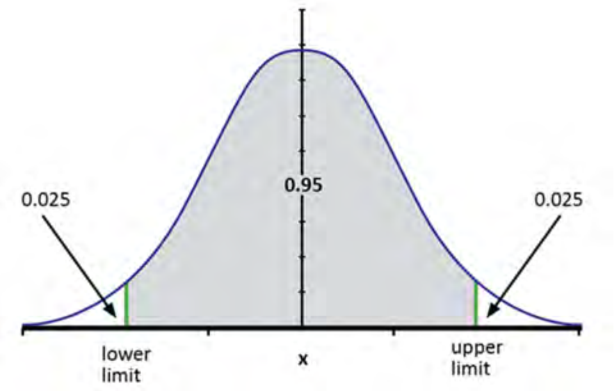


Figure 223 – Confidence Interval – Alpha levels

Sample size calculation for Confidence Intervals has been discussed in paragraph [7.1.2]. Calculation of the Confidence Interval width for continuous and discrete distributions will be covered in section [7.5].

Prediction interval (PI)
(Minitab: Stat > Regression > Fitted Line Plot > Options)

As explained above, the Confidence Interval is the range that is likely to contain the mean response, while the prediction interval is the range that is likely to contain the response value of a single new observation (the next data point sampled) with a specified probability. Assume, you collect a sample of data and calculate the 95% prediction interval. Then you take the next value sample from the population. If you do this many times, you'd expect the next value to lie within that prediction interval in 95% of the samples.

There are many methods to compute a prediction interval, but the simplest method is actually the non-parametric method which makes no assumptions about the population. The probability that the next value sampled will fall within the range of the n values previously sampled, is given by (n-1)/(n+1). For instance, if n = 3 then the chance of the next measure falling within the range of the first three measures is 2/4 = 50%. Likewise, the likelihood of the 40th measurement falling into the range of the previous 39 measurements is 95%. This can be calculated as: probability = (n-1)/(n+1) = 38/40 = 0.95. This means that the range of a sample of size 39 is a 95% prediction interval for any continuous distribution.

The prediction interval is always wider than the corresponding Confidence Interval. This is because of the added uncertainty involved in predicting a single response versus the mean response. In other words, the prediction interval accounts for both the uncertainty in knowing the value of the population mean plus data scatter. The 95% Confidence Interval of a certain regression equation is represented by the green dotted lines in Figure 224, while the 95% prediction interval is represented by the purple dotted lines in Figure 224.

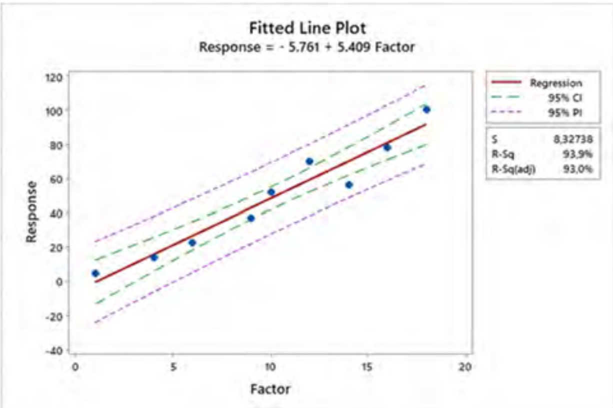
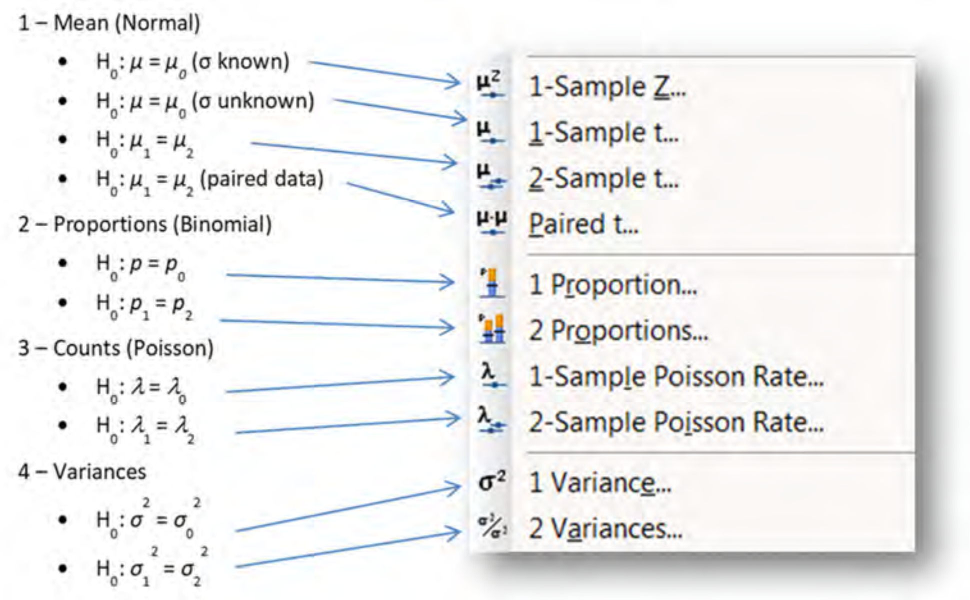


Figure 224 – Confidence Interval versus Prediction Interval

Tolerance Interval (TI)
A tolerance interval is a range that is likely to contain a specified proportion of the population. The tolerance interval is specified two different percentages. For example, if we want to be 90% sure that the interval contains 99% of the values, we have to use a tolerance interval. The first percentage expresses how sure you want to be, and the second percentage expresses what fraction of the values the interval should contain.

7.5 Tests for means, proportions and variances

In the following sections we will review the most common hypothesis tests. There are many different tests to investigate the difference between population means (μ); difference in variances (σ); difference in proportion (p) and difference in counts (λ). Also the ANOVA-technique is reviewed.



The Minitab Assistant will help you choose the proper test. This is shown in Figure 225.

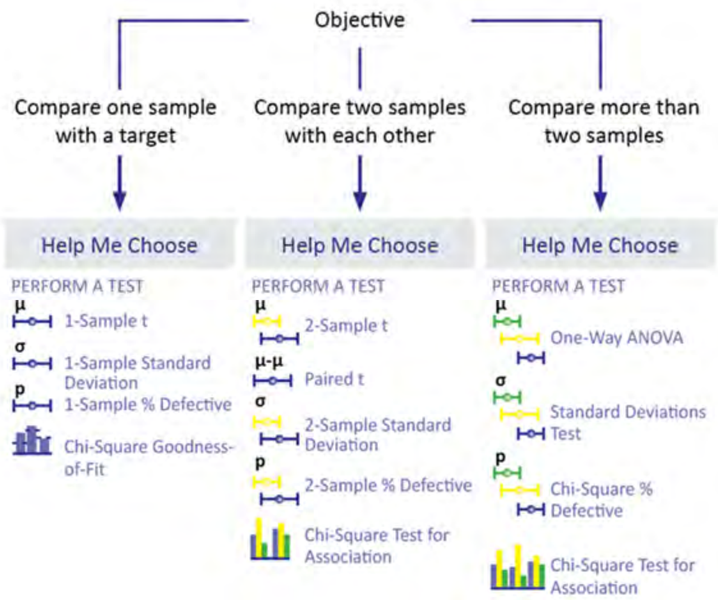


Figure 225 – Hypothesis test selection

7.5.1 Tests for means

1-Sample *Z*-test

The 1-Sample *Z*-test is used to compare the average of one sample against a specific target when the population standard deviation (σ) is known or very well estimated.

Example: Measurements were made on the volume of bottles of Cola. We want to test whether the population's average volume is statistically different from 300 [ml]. We know that the distribution of volume has historically been close to normal with $\sigma = 3.0$ [ml]. Since σ is known, we will test the Hypothesis using the 1 sample *Z*-test.

- H_O: $\mu_0 = 300$ (Volume mean is 300 [ml])
- H_A: $\mu_0 \neq 300$ (Volume mean is not 300 [ml])

We take a sample of 100 measurements and find a mean $\bar{x}$ of 299.169 [ml]. The test statistic *Z* in the 1-sample *Z* test is standard normal distributed and is calculated using the following equation:

$$Z = \frac{(\bar{X} - \mu_0)}{\sigma/\sqrt{n}} = \frac{(299.169 - 300)}{3.0/\sqrt{100}} = -2.77$$

To obtain $(1 - \alpha) = 95\%$ of the normal distributed population, we have to take *Z*-values of ±1.96 (Appendix C.1). If $|Z| > 1.96$ the null hypothesis will be rejected. Because $|Z| = 2.77$ is greater than 1.96 we have to reject the null hypothesis. So, the conclusion is that the average volume of the bottles is unequal to 300 [ml].

The significance of a test result is defined as the probability of finding a result that deviates more from the expected result than from the actual result. In Appendix C.1. we find the left tail probability of 0.0028 for a *Z*-value of -2.77. Because we have made a two-sided test, we have to multiply this value by 2 to determine a *p*-value of 0.006.

The 95% Confidence Interval can be calculated using the following equation:

$$CI = \bar{x} \pm Z_{0.975} \times \frac{\sigma}{\sqrt{n}} = 299.169 \pm 1.96 \times \frac{3.0}{\sqrt{100}} = (298.581, 299.757)$$

Because this Confidence Interval does not contain the $\mu_0 = 300$ value, we can also conclude that we have to reject the null hypothesis.

1-Sample Z-test – Using Minitab
(Minitab: Stat > Basic Statistics > 1-sample Z)

Using Minitab, we will find the following results:

```
One-Sample Z: Volume
Test of μ = 300 vs ≠ 300
The assumed standard deviation = 3

Variable    N     Mean   StDev  SE Mean        95% CI              Z      P
Volume    100  299.169   3.246    0.300  (298.581, 299.757)  -2.77  0.006
```

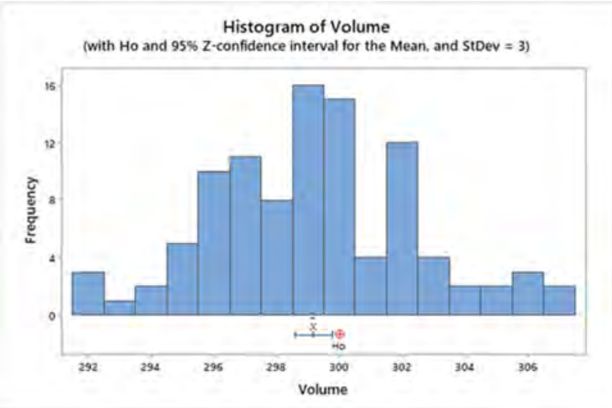


Figure 226 – Confidence Interval for 1-Sample Z-test

Conclusion:

- The *p*-value is lower than 0.05, indicating that we can reject H_O and support H_A.
- The hypothesized value of 300 [ml] falls outside the 95% CI for the population mean.

1-Sample *t*-test
The 1-Sample *t*-test is used to compare the average of one sample against a specific target when σ is unknown. Let's use the same data as we used in the 1-Sample *Z*-test. The only difference between the *Z*-test and *t*-test is that the *t*-statistic estimates standard error by using the sample standard deviation, while the *Z*-statistic utilizes the historical population's standard deviation.

Example: We will again collect measurements on the volume of bottles of Cola and test whether the population's average volume is statistically different from 300 [ml]. We take a sample of 100 measurements and find a mean of 299.169 [ml] and a standard deviation $s = 3.246$. We will test the hypothesis using the 1 sample *t*-test.

- H_O: $\mu_0 = 300$ (Volume mean is 300 [ml])
- H_A: $\mu_0 \neq 300$ (Volume mean is not 300 [ml])

The test statistic *t* in the 1-sample *t* test is calculated using the following equation:

$$t = \frac{(\bar{X} - \mu_0)}{s/\sqrt{n}} = \frac{(299.169 - 300)}{3.246/\sqrt{100}} = -2.56$$

To obtain $(1 - \alpha) = 95\%$ of the normal distributed population, we have to take a critical *t*-value of 1.984. This can be found in Appendix C.2 for $\alpha = 0.05/2 = 0.025$ and $df = 99$. If $|t| > 1.984$ the null hypothesis will be rejected. Because $|t| = 2.56$ is greater than 1.984 we have to reject the null hypothesis. So, the conclusion is that the average volume of the bottles is unequal to 300 [ml].

In Appendix C.2. we find the right tail probability of 0.006 for a *t*-value of 2.56 and $df = 99$. Because we have made a two-sided test, we have to multiply this value by 2 to determine a *p*-value of 0.012.

The 95% Confidence Interval for population mean μ can be calculated using the following equation:

$$CI = \bar{x} \pm t_{0.975,99} \times \frac{s}{\sqrt{n}} = 299.169 \pm 1.984 \times \frac{3.246}{\sqrt{100}} = (298.525, 299.813)$$

Because the Confidence Interval does not contain $\mu_0 = 300$, we can also conclude that we have to reject the null hypothesis.

1-Sample *t*-test – Using Minitab

(Minitab: Stat > Basic Statistics > 1-sample t)

Using Minitab, we will find the following results:

One-Sample T: Volume

Test of μ = 300 vs ≠ 300

Variable	N	Mean	StDev	SE Mean	95% CI	T	P
Volume	100	299.169	3.246	0.325	(298.525, 299.813)	-2.56	0.012

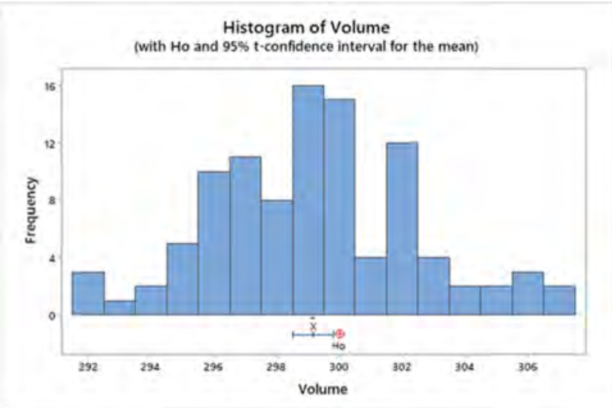


Figure 227 – Confidence Interval for 1-Sample t-test

Conclusion:

- The *p*-value is less than 0.05, indicating that we can reject H_O and support H_A.
- The hypothesized value of 300 [ml] falls outside the 95% Confidence Interval for the population mean.

2-Sample *t*-test

The 2-Sample *t*-test is used to compare two means with each other. The 2-Sample *t*-test is used to perform a Hypothesis test and compute a Confidence Interval of the difference between two population means.

Example: Two women, named Jane and Lucy, are entering customer orders into the ERP system. Jane has more years of experience than Lucy and we expect her to work faster, meaning lower processing times. We will investigate this by timing 15 orders for each of them and perform a hypothesis test.

Jane	Lucy
38	41
41	42
40	41
37	39
35	43
41	41
40	44
38	43
38	42
42	40
41	47
39	46
43	40
42	36
39	43

- H_O: $\mu_{Jane} = \mu_{Lucy}$ (There is no difference between Lucy and Jane)
- H_A: $\mu_{Jane} < \mu_{Lucy}$ (Jane processes orders faster than Jane)

Since we are testing in one direction ($\mu_{Jane} < \mu_{Lucy}$) we will perform a one-sided test, with a 5% level of significance (α= 0.05). When we can assume equal variances of the two samples, the common variance can be estimated by the pooled variance s_p^2. The hypothesized difference between the two population means is δ_0, which in this example is 0 (H_0: no difference between Lucy and Jane). The pooled variance s_p^2, the standard deviation estimates *s* and the test statistic *t* can be determined using the following equations:

$$s_p = \sqrt{\frac{(n_1-1)s_1{}^2+(n_2-1)s_2{}^2}{(n_1+n_2-2)}} = \sqrt{\frac{65.60+103.74}{28}} = 2.459$$

$$s = s_p \cdot \sqrt{\frac{1}{n_1}+\frac{1}{n_2}} = 2.459 \cdot \sqrt{\frac{1}{15}+\frac{1}{15}} = 0.898$$

The student (*t*) distributed test statistic *t* is:

$$t = \frac{(\bar{x}_1-\bar{x}_2)-\delta_0}{s} = \frac{(39.60-41.87)-0}{0.898} = -2.52$$

In Appendix C2. we find a left tail *p*-value of 0.01 for a *t*-value = -2.52 and *df* = 28.

2-Sample *t*-test – Using Minitab
(Minitab: Stat > Basic Statistics > 2-sample t)

Using Minitab, we will find the following results:

Two-Sample T-Test and CI: Jane, Lucy

```
       N   Mean  StDev  SE Mean
Jane  15  39.60   2.16     0.56
Lucy  15  41.87   2.72      1.1

Difference = μ (Jane) - μ (Lucy)
Estimate for difference:  -2.267
95% upper bound for difference:  -0.739
T-Test of difference = 0 (vs <): T-Value = -2.52  P-Value = 0.009  DF = 28
Both use Pooled StDev = 2.4592
```

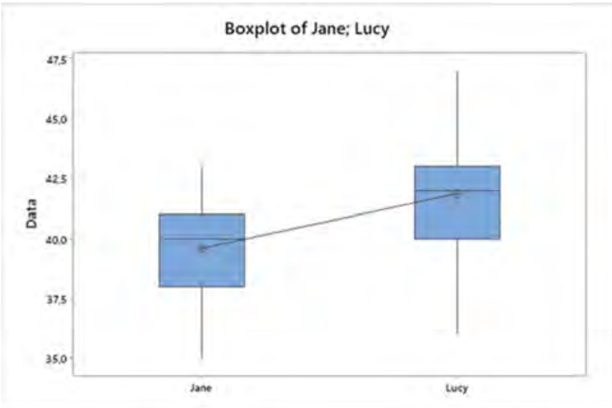


Figure 228 – Box plot of Jane and Lucy

Conclusion:

- Since the *p*-value is 0.009, we will reject H_0.
- We conclude that the average processing time of Jane is faster than the average processing time of Lucy, at the 0.05 level of significance.

Paired *t*-test
The Paired *t*-test is used to compare two samples in cases where each value in one sample has a natural partner in the other. A paired *t*-test evaluates the difference between paired values in two samples, filtering out the variation of values within each sample.

Example: Over the course of 10 consecutive days, John and George are running a track of 100 meters. They recorded their times, which is shown in the table below. Because we observed that the weather conditions differed greatly during these 10 days of running, we would like to eliminate the influence of the weather in our analysis. We can do this by calculating the difference in time between John and George for every single day.

Day	John	George	Difference
1	14.72	16.10	-1.38
2	13.53	14.13	-0.60
3	15.66	15.89	-0.23
4	14.91	15.45	-0.54
5	13.43	14.73	-1.30
6	14.10	15.15	-1.05
7	15.38	14.77	0.61
8	13.71	14.12	-0.41
9	15.84	15.96	-0.12
10	14.59	14.44	0.15

We will apply a Paired *t*-test to examine the following hypotheses:

- H_O: $\mu_1 - \mu_2 = 0$ (The difference of John – George is 0; there is no difference)
- H_A: $\mu_2 - \mu_2 \neq 0$ (The difference between John – George is not 0; there is a difference)

The test statistic *t* can be calculated using the following equation, where $\bar{d}$ is the average Difference. The sample standard deviation s_d of the paired sample differences can be calculated, which is 0.633.

$$t = \frac{\bar{d}}{s_d/\sqrt{n}} = \frac{-0.487}{0.633/\sqrt{10}} = -2.43$$

When $\alpha = 0.05$ the critical values for *t* can be found in Appendix C2. The null hypothesis will be rejected if $|t| > t_{[0.975;9]} = 2.262$. Because $|t| = 2.43$ is greater than 2.26 we may conclude that the means of John and Georg are significantly different. From the Appendix C.2 we can estimate the left tail probability of -2.43. This probability is between $p = 0.01$ and $p = 0.025$. Because the test is two-sided, the significance (p-value) of the found value -2.43 is greater than 0.02 but less than 0.05. So, the null hypothesis can be rejected.

The 95% Confidence Interval can be calculated by using the following equation:

$$CI = \bar{d} \pm t_{0.0975,9} \times \frac{s_d}{\sqrt{n}} = -0.487 \pm 2.262 \times \frac{0.633}{\sqrt{10}} = (-0.940, -0.034)$$

Because the Confidence Interval does not contain 0, we can also conclude that the null hypothesis can be rejected.

Paired *t*-test – Using Minitab
(Minitab: Stat > Basic Statistics > Paired t)

Using Minitab, we will find the following results:

Paired T-Test and CI: John, George

```
Paired T for John - George

             N    Mean  StDev  SE Mean
John        10  14.587  0.878    0.278
George      10  15.074  0.750    0.237
Difference  10  -0.487  0.633    0.200

95% CI for mean difference: (-0.940, -0.034)
T-Test of mean difference = 0 (vs ≠ 0): T-Value = -2.43  P-Value = 0.038
```

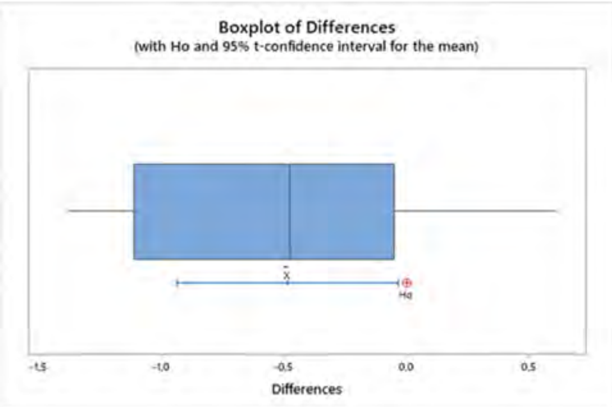


Figure 229 – Hypothesis test using Paired t-test

Conclusion:

- The Paired *t*-test results in a *p*-value of 0.038, which does provide us with enough evidence that we can conclude that both means differ at the 0.05 level of significance. The mean of the paired differences is smaller than zero.

7.5.2 Tests for variances

Test for Equal Variances

The Test for Equal Variance is used to test if two populations' variances (or standard deviations) are equal or not. The test for equal variances is also important to support the ANOVA technique (see section [7.5.3]).

For each test, the null hypothesis states that the two variances are equal. Sometimes the null hypothesis for testing equal variance is written as $H_0: \sigma_1^2 / \sigma_2^2 = 1$, which is the same. Therefore, this test is also called 'Ratio of Variances'.

Example: A study is made to investigate the difference in recovery time after medical treatment between men and women. The collected data is listed below.

- $H_0: \sigma_1^2 = \sigma_2^2$
- $H_A: \sigma_1^2 \neq \sigma_2^2$

Men	Women
14	27
16	12
17	23
18	12
17	21
18	18
18	21
20	14
23	28
19	14
15	
20	

The sample of 12 men gives a sample mean of 18.0 days and a variance s^2_{men} of 5.90 days. The sample of 10 women gives a sample mean of 19.0 days and a variance s^2_{women} of 35.33 days. Is the variance in recovery time significantly different for women and men?

Using the F-distribution gives that F[9,11] = 5.99:

$$F_{(n-1;m-1)} = \frac{s^2_{Women}}{s^2_{Men}} = \frac{35.33}{5.90} = 5.99$$

We use Appendix C.4 to compare the calculated F-value of 5.99 to the critical value of the F[9,11]-distribution. Appendix C.4 gives us a value of 4.63 for F[9,11] with *p*-value of 0.01. This means that the two-sided *p*-value is equal to 0.02. Because 5.99 > 4.63, we can conclude that 5.99 has a *p*-value < 0.02.

Conclusion:

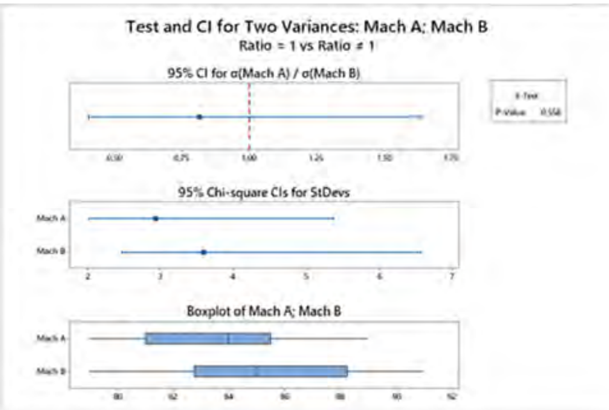
- If we use an alpha level of 0.05, we can conclude that the variance in recovery time is larger for women then for men.

Test for Equal Variances – Using Minitab
In this example we will explain how to use Minitab to ‘Test for Equal Variances’. The test can be accessed in Minitab under the hypothesis menu and under the ANOVA menu. There are a number of techniques to test the equality of variances:

- Levene’s test: for 2 or more samples that are not Normally but Continuously distributed.
- Bonett’s test: for 2 or more samples that are not Normally but Continuously distributed.
- F-test: for 2 samples that are Normally distributed.
- Bartlett’s test: for 3 or more samples that are Normally distributed.

Minitab provides both Bonett’s and Levene’s test results for a 2-variance test. Bonett’s test is generally more powerful than Levene’s test, except for small samples (<20) or highly skewed distributions or heavy tailed distributions (those exhibiting highly negative Kurtosis). Minitab will not automatically check for Normality. If you assume the distributions are normally distributed, you have to check the box to include this assumption in the test. Minitab will select automatically between F-test and Bartlett’s test.

The above text will be illustrated with an example. Assume a lumber distributor who wants to compare the variation of beam lengths that are cut by two different sawmills. The distributor measures the length of the beams [cm] from each sawmill to determine whether the consistency of the beam lengths differs.



Machine A	Machine B
89	84
81	86
84	83
84	91
87	86
79	79
85	82
81	89
83	83
84	88

Figure 230 – Hypothesis test for equal variance

Conclusion:
- We found a *p*-value of 0.558, meaning we will not reject H_0.
  Statistically, both machines have the same variability.

7.5.3 Analysis of Variance (ANOVA)

(Minitab: Stat > ANOVA > One Way)

A One-way ANOVA test is used to compare two or more sample means with each other. For comparing two means, the 2-sample t-test can be used as well as the ANOVA. The calculation method of the ANOVA technique is different, but the approach and interpretation of *p*-values is the same.

In ANOVA a balanced design has an equal number of observations for all possible combinations of factor levels. An unbalanced design has an unequal number of observations.

- One-Way ANOVA: hypothesis that the means of two or more populations are equal (1 factor)
- Balanced ANOVA: hypothesis that the means of two or more populations are equal (>1 factor)

Example: assume we have three machines (A, B and C) to produce fabric at a given length. Question: is there a significant difference between these machines?

A	B	C
75	76	78
74	76	79
76	75	78
75	79	76
77	75	77
76	78	78
73	77	79

Table 30 – Fabric length per machine

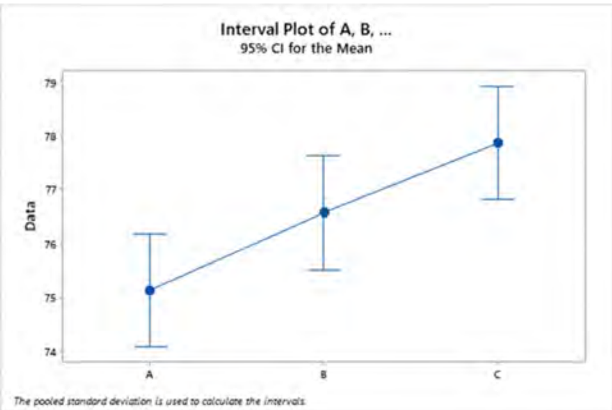
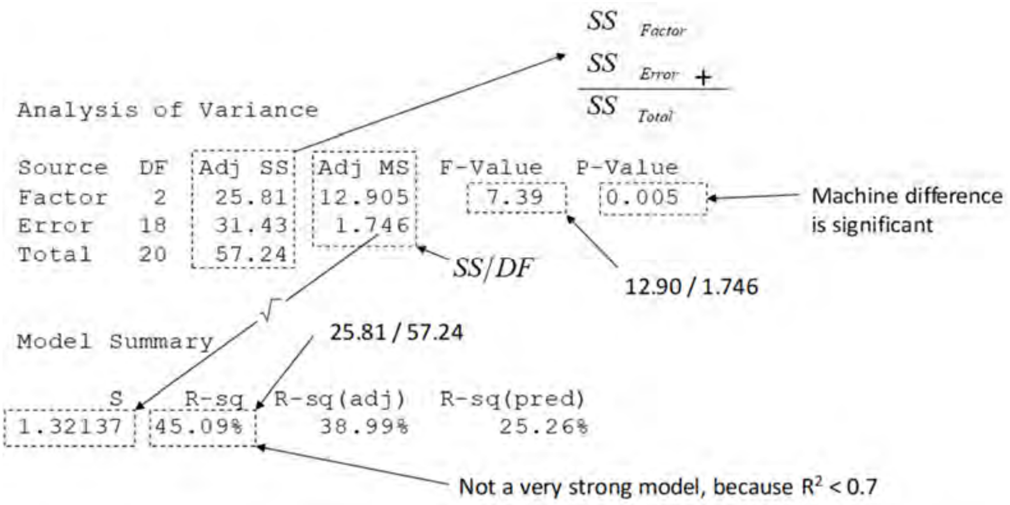


Figure 231 – Interval plot One way ANOVA

We will use a One-Way ANOVA to analyze the data. Minitab provides us an interval plot (Figure 231) and an ANOVA Table. The interval plot displays the means and Confidence Intervals for each of the three machines. These Confidence Intervals can be used to assess the practical significance of the differences.

We will now explain how to interpret the ANOVA Table.



The *p*-value of 0.005 indicates that there is sufficient evidence that not all three machine-means are equal when alpha is set at 0.05. The *R*-sq of 45.09% indicates that this model is not very good. A good model has a *R*-sq greater than 70%. So, we have to be careful with drawing conclusions.

In this simple example with samples of equal length, the calculations are as follows:

The s^2_{Within} can be calculated by:

$$s^2_{Within} = \frac{s^2_A + s^2_B + s^2_C}{3} = 1.746$$

$s^2_M = 1.846$ is the variance of the averages $\bar{x}_A, \bar{x}_B, \bar{x}_C$ of the three samples.

We have to multiply the variance of the averages with the sample size, in this case 7, per sample to get a good estimate $s^2_{Between}$ for the population variance if there is no difference between the three machines.

The $s^2_{Between}$ can be calculated by $s^2_{Between} = s^2_M \text{ X } 7 = 12.90$.

If there is no difference between the machines, then S^2_{Within} and $S^2_{Between}$ are expect to be equal.

In this case the ratio $S^2_{Between} / S^2_{Within}$ follows a F-distribution with [2,18] degrees of freedom.

In our example:

$$F[2,18] = \frac{S^2_{Between}}{S^2_{Within}} = \frac{12.90}{1.746} = 7.39$$

Because the *p*-value is 0.005 we may conclude that at least two means are unequal.

Conditions for applying ANOVA:

1. The sample must be randomly taken (all units in population have the same probability of being selected).
2. The samples must be mutually independent. If sample parameters are not dependent on parameters of other samples, then the samples are mutually independent.
3. Variances of all factor-level combinations have to be equal.
4. The residuals must be normally distributed.

Kruskal Wallis

Kruskal Wallis analysis can be used when the above conditions for ANOVA have not been met. This tests whether two or more independent samples came from populations with identical medians. The Kruskal Wallis test does not require the residuals to be normal distributed, but instead uses the rank of the data values, rather than the actual data values, for the analysis.

7.5.4 Tests for proportions

1-Proportion test

The 1-Proportion test is used to test the proportion of one sample outcome against an assumed proportion in a population. This is also called a '1-sample proportion test'.

Example: We select a sample of 500 (very cheap) pens out of a box. We expect a defective percentage of 1.0% (meaning $p_0 = 0.01$). We find 13 defective pens in the sample, although we would expect only 500 x 0.01 = 5 defective pens. Thus, we have found more than what we expected. Is this difference significant enough to reject the assumption $p_0 = 0.01$?

- H_O: $p = p_0$ (The number of defectives is not different to what we would expect)
- H_A: $p > p_0$ (The number of defectives is greater than what we expect)

To test these hypotheses the exact method and approximation methods can be used. The Poisson approximation can be used when $n \geq 20$ and $p \leq 0.05$, or if $n \geq 100$ and $np \leq 10$. The normal approximation can be used when both $x = np$ and $n(1 - p)$ are greater than 5 (some sources advice >10). In this example we will use the normal approximation method. The equation to calculate the test statistic Z is shown below, where $\hat{p}$ is the estimate of the proportion, based on the sample:

$$Z = \frac{\hat{p} - p_0}{\sqrt{p_0(1 - p_0)/n}}$$

$$\hat{p} = {}^{13}/_{500} = 0.026$$

The critical value for a right tailed test is given by $Z_{0.95} = 1.645$ (see Appendix C.1). Filling in the data gives:

$$Z = \frac{\hat{p} - p_0}{\sqrt{p_0(1 - p_0)/n}} = \frac{0.026 - 0.010}{\sqrt{0.010(1 - 0.010)/500}} = 3.60$$

This value is greater than the critical value 1.645, so the null hypothesis is rejected. The significance (*p*-value) of this 3.60 value is 0.000.

The 95% Confidence Interval can be calculated by using the following equations. The value for $Z_{(1-0.05/2)}$ can be found in Appendix C.1, and is 1.96.

$$CI = \hat{p} \pm Z_{(1-\alpha/2)} \times \sqrt{\frac{\hat{p} \times (1 - \hat{p})}{n}} = 0.026 \pm 1.96 \times \sqrt{\frac{0.026 \times (1 - 0.026)}{500}} = (0.01205, 0.03995)$$

1-Proportion test – Using Minitab
(Minitab: Stat > Basic Statistics > 1 Proportion)

Using Minitab, we will find the following results:

Minitab offers the possibility to choose between the 'Exact' approach or the 'Normal approximation'. When we choose the 'Normal approximation', we find the same results as we found using the equations on the previous page. The 'Exact' calculation uses the binomial distribution and gives us a slightly different result.

Test and CI for One Proportion

```
Sample    X    N  Sample p        95% CI
1        13  500  0.026000  (0.012051, 0.039949)

Using the normal approximation.
```

Conclusion:

- There is enough evidence to reject the H_O and conclude that the %-defective differs from 1.0% at the 0.05 level of significance. The 95% Confidence Interval shows that the true %-defective is expected to be between 1.20% and 4.0%.

2-Proportion test

The 2-Proportion test is used to compare two Binomial proportions in order to answer whether the two proportions are equal or not. Two statistical tests can be used. The first one is the 'Fisher exact test', the second test is using a normal approximation. The normal approximation can be used for large sample sizes and is used in the following example.

Example: Two machines are minting Euros. A Black Belt wants to know whether both minting machines produce an equal percentage of non-conforming coins. The Black Belt selects from both machines 1,000 coins. In one sample 8 non-conforming coins are found and in the other sample 20. The Black Belt performs a 2-proportion test on this result to verify if there is a difference between both minting machines:

- H_0: $p_1 = p_2$ (There is no difference between both machines)
- H_A: $p_1 \neq p_2$ (There is difference between both machines)

The significance level of the test is $\alpha = 0.05$.

When the hypothesized difference is zero, we can use the pooled estimate $\hat{p}_0$ for the test. The following equation can be used to calculate the test statistic Z:

$$Z = \frac{\hat{p}_1 - \hat{p}_2}{\sqrt{\hat{p}_0(1-\hat{p}_0) \times (\frac{1}{n_1} + \frac{1}{n_2})}} = \frac{0.008 - 0.020}{\sqrt{0.014(1-0.014) \times (\frac{1}{1{,}000} + \frac{1}{1{,}000})}} = \frac{-0.012}{0.00525} = -2.28$$

where

$$\hat{p}_0 = \frac{x_1 + x_2}{n_1 + n_2} = \frac{8 + 20}{1.000 + 1.000} = 0{,}014$$

Because $-2.28 < Z_{[0.025]} = -1.96$ we must reject the null hypothesis.

In Appendix C.1 we find for -2.28 a left tailed p-value of 0.0113. Because we have made a two-sided test, we have to multiply this value by 2 to determine a two tailed p-value of 0.0226.

The 95% Confidence Interval can be calculated by using the following equation:

$$CI = (\hat{p}_1 - \hat{p}_2) \pm Z_{0.975} \times \sqrt{\hat{p}_0(1-\hat{p}_0) \times (\frac{1}{n_1} + \frac{1}{n_2})} =$$

$$= (\frac{8}{1{,}000} - \frac{20}{1{,}000}) \pm 1.96 \times \sqrt{0.014(1-0.014) \times \left(\frac{1}{1{,}000} + \frac{1}{1{,}000}\right)} = (-0.0223, -0.0017)$$

2-Proportion test – Using Minitab
(Minitab: Stat > Basic Statistics > 2 Proportion)

Using Minitab, we will find the following results:

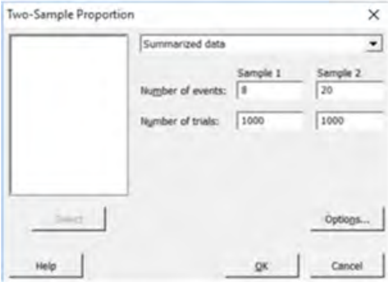


Figure 232 – Hypothesis test for 2 Proportion

Test and CI for Two Proportions

```
Sample    X     N  Sample p
1         3  1000  0.008000
2        10  1000  0.020000

Difference = p (1) - p (2)
Estimate for difference:  -0.012
95% CI for difference:  (-0.0222849, -0.00171514)
Test for difference = 0 (vs ≠ 0):  Z = -2.28  P-Value = 0.022

Fisher's exact test: P-Value = 0.034
```

Conclusion:

- Since the *p*-value is 0.022 for the normal approximation and 0.034 for the Fisher exact test, we will reject H_0.
- The two minting machines perform different at the 0.05 level of significance.

1-Sample Poisson rate

The 1-Sample Poisson rate test can be used for the number of events per interval (e.g. time, area, volume). The test is often used to test if a certain count of events is greater or less than a hypothesized rate. This test is very useful for transactional processes to verify quality. Again, we can use two different statistical tests, an exact one and one that is using a normal approximation. The normal approximation can be used when the total number of events is greater than 10 and is used in the following example.

Example: An insurance company has an internal quality standard that states that there should be no more than 4 complaints per month for a certain type of insurance policy. During an audit the auditor verifies if the organization has met this standard for a period of 12 months. Assume equal workload per month.

- Observed number of complaints: 59 complaints in 12 months
- Target complaint rate: 4 complaints per month

The hypothesis tests are defined as:

- H_O: $\lambda = \lambda_0$ (number of complaints found is 4 per month)
- H_A: $\lambda > \lambda_0$ (number of complaints found is greater 4 per month)

The significance level of the test is α = 0.05. The rate of occurrence is:

$$\hat{\lambda} = \frac{59}{12} = 4.917$$

The following equation can be used to calculate the test statistic *Z*:

$$Z = \sqrt{\frac{n}{\lambda_0 t}} \cdot (\hat{\lambda}t - \lambda_0 t) = \sqrt{\frac{12}{4 \times 1}}(4.917 \times 1 - 4 \times 1) = 1.59$$

where:

λ_0 = hypothesized value of the population rate parameter.
$\hat{\lambda}$ = observed value of the sample rate statistic.
t = length of observation.
n = sample size.

In Appendix C.1. we find a *p*-value of 0.0559 for a *Z*-value of 1.59. Because we have made a right tailed test, we cannot reject the null hypothesis.

The 95% Confidence Interval can be calculated by using the following equation:

$$CI = \frac{\hat{\lambda} \pm Z_{\alpha/2}\sqrt{\frac{\hat{\lambda}}{n}}}{t} = \frac{4.917 \pm 1.96\sqrt{\frac{4.917}{12}}}{1} = (3.662, 6.171)$$

1-Sample Poisson rate – Using Minitab
(Minitab: Stat > Basic Statistics > 1-sample Poisson rate)

Using Minitab, we will find the following results:

Press 'Options' and choose: Normal approximation.

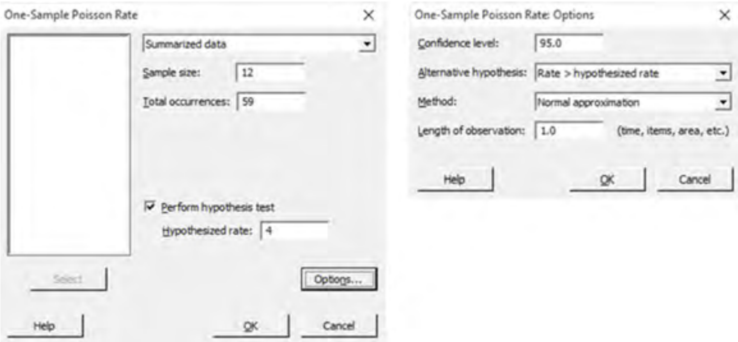


Figure 233 – Hypothesis test for 1-Sample Poisson rate

Test and CI for One-Sample Poisson Rate

```
Test of rate = 4 vs rate > 4

                Total            Rate of
Sample  Occurrences   N  Occurrence         95% CI          Z-Value  P-Value
     1           59  12     4.91667  (3.66210, 6.17123)       1.59    0.056

"Length" of observation = 1.
```

Conclusion:

- There is not enough evidence to conclude that the complaint rate is greater than 4 at the 0.05 level of significance, because $p = 0.056 > 0.05$.
- The Confidence Interval quantifies that we can be 95% confident that the true complaint rate is between 3.66 and 6.17.

2-Sample Poisson rate

The 2-Sample Poisson rate test compares two samples from Poisson processes and calculates Confidence Intervals for the difference between two populations.

Example: Two departments (A and B) from the same company manufacture 82" LCD displays. Each display was inspected and the number of dead pixels was counted for the past year. To decide whether there is a difference between the dead pixel rates between the departments, we can perform a '2-Sample Poisson Rate' test.

Department	Number of displays produced	Dead pixels
A	3,680	127
B	2,750	43

Table 31 – Example of 2-Sample Poisson rate test

The hypothesis tests are defined as:

- H_O: $\lambda_1 = \lambda_2$ (Dead pixel rate A = Dead pixel rate B)
- H_A: $\lambda_1 \neq \lambda_2$ (Dead pixel rate A ≠ Dead pixel rate B)

Rate of occurrence A: $\hat{\lambda}_1 = \frac{127}{3{,}680} = 0.0345$ and Rate of occurrence B: $\hat{\lambda}_2 = \frac{43}{2{,}750} = 0.0156$

Because we test a difference of zero between both samples, we can use the pooled rate:

$$\hat{\lambda} = \frac{n_1\hat{\lambda}_1 + n_2\hat{\lambda}_2}{n_1 + n_2} = \frac{3{,}680 \times 0.0345 + 2{,}750 \times 0.0156}{3{,}680 + 2{,}750} = \frac{127 + 43}{3{,}680 + 2{,}750} = 0.0264$$

The pooled-rate procedure is based on the following *Z*-statistic, which is approximately distributed as a standard normal distribution under the null hypothesis.

$$Z = \frac{(\hat{\lambda}_1 - \hat{\lambda}_2)}{\sqrt{\hat{\lambda}(\frac{1}{n_1} + \frac{1}{n_2})}} = \frac{(0.0345 - 0.0156)}{\sqrt{0.0264 \times (\frac{1}{3{,}680} + \frac{1}{2{,}750})}} = 4.61$$

The *p*-value of this *Z* = 4.61 is far below 0.05: *p* = 0.0000

The 95% Confidence Interval can be calculated by using the following equation:

$$CI = \hat{\lambda}_1 - \hat{\lambda}_2 \pm Z_{\alpha/2}\sqrt{\hat{\lambda}(\frac{1}{n_1} + \frac{1}{n_2})} =$$

$$= 0.0345 - 0.0156 \pm 1.96\sqrt{0.0264 \times (\frac{1}{3{,}680} + \frac{1}{2{,}750})} = (0.0109, 0.0269)$$

2-Sample Poisson rate – Using Minitab
(Minitab: Stat > Basic Statistics > 2-sample Poisson rate)

Using Minitab, we will find the following results:

Press 'Options' and choose the pooled estimate of the rate, to test a difference of 0 between the two samples.

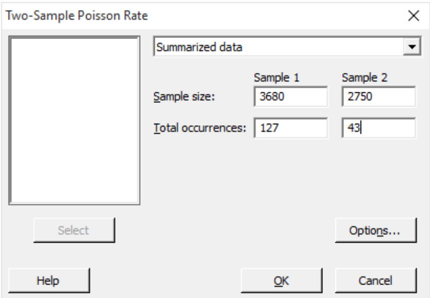


Figure 234 – Hypothesis test for 2-Sample % defective

Test and CI for Two-Sample Poisson Rates

```
               Total            Rate of
Sample   Occurrences      N   Occurrence
1                127   3680    0.0345109
2                 43   2750    0.0156364

Difference = rate(1) - rate(2)
Estimate for difference: 0.0188745
95% CI for difference: (0.0112674, 0.0264816)
Test for difference = 0 (vs ≠ 0): Z = 4.61 P-Value = 0.000
Exact Test: P-Value = 0.000
```

N.B.: The Confidence Interval in Minitab is different, because the pooled rate is not used to calculate this interval.

Conclusion:

- The *p*-value is lower than 0.05, so we should reject H_0. We can conclude that the dead pixel rate differs at the 0.05 level of significance.
- The Confidence Interval quantifies the uncertainty associated with estimating the difference from sample data. We can be 95% confident that the true difference is between 0.011 and 0.027.

7.5.5 Chi-square test

Contingency Tables
(Minitab: Stat > Tables > Cross Tabulation and Chi-Square)

A 'Contingency Table', also referred to as 'Cross Tabulation', is a table that displays the frequency distribution of variables. In this section we will review how to use Chi-square to test the relationship between Nominal variables for significance. We will do this by reviewing a diet and health study. The question we try to answer whether there is a significant relationship between type of diet and certain diseases. (N.B.: The numbers listed in Table 32 are fictitious and not based on an actual study).

- H_0: no relation between diet and health
- H_A: there is a relation between diet and health

The 'Observed frequencies' for the number of diseases within a certain diet group is listed in Table 32. A precondition of this Chi-square test is that each subject contributes data to only one cell. Therefore, the sum of all cell frequencies in the Table should equal to the number of subjects in the experiment.

The first step is to compute the 'Expected frequencies' based on the assumption that there is no relationship (null hypothesis). These 'Expected frequencies' are computed from the Totals for each row (T_i) and column (T_j) by using the following equation. An example is given for the expected frequency for healthy people and Gluten-free diet. Table 32 shows the expected frequencies between parentheses.

$$E_{i,j} = \frac{T_i \times T_j}{Total}$$

$$E_{Gluten,Healthy} = \frac{582 \times 1{,}654}{1{,}825} = 527.5$$

Diet	Healthy	Heart Disease	Cancer	Diabetes	Total
Gluten-free diet	523	18	6	35	582
	(527.5)	(14.0)	(10.5)	(30.0)	
Cookie diet	752	12	15	32	811
	(735.0)	(19.6)	(14.7)	(41.8)	
Vegan diet	379	14	12	27	432
	(391.5)	(10.4)	(7.8)	(22.3)	
Total	1,654	44	33	94	1,825

Table 32 – Observed and Expected Frequencies for Diet and Health Study

The significance test is conducted by computing Chi-square. The individual values are listed in the Table below. The sum of these individual values adds up to a Chi-square of 14.44.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} = 14.44$$

Diet	Healthy	Heart Disease	Cancer	Diabetes	Total
Gluten-free diet	0.04	1.12	1.94	0.84	
Cookie diet	0.39	2.92	0.01	2.29	
Vegan diet	0.40	1.23	2.25	1.01	
Total					14.44

Table 33 – Chi-square for Diet and Health Study

The number of degrees of freedom is equal to (r-1) x (c-1), where r is the number of rows and c is the number of columns. For this example, the degrees of freedom is (3-1) x (4-1) = 6.

The Chi-square distribution Table (Appendix C.3) can be used to determine that the probability value for a Chi-square of 14.44 with 6 degrees of freedom is equal to 0.025. Therefore, the null hypothesis can be rejected and the alternative hypothesis can be accepted. There is a relationship between diet and health.

Goodness-of-Fit

(Minitab: Stat > Tables > Chi-Square Goodness-of-Fit Test)

The Chi-square 'Goodness-of-Fit' tests whether a dataset follows a multinomial distribution with certain proportions by calculating the Chi-square contribution for each category. This test can also be applied to continuous data by dividing both the dataset and the expected response into bins and then comparing the frequency of observed data with the expected frequency within each bin. We will illustrate the Hypothesis test with an example using Minitab.

Example: When continuously rolling a dice, the outcome of a fair dice would follow a uniform distribution because all six outcomes have equal probability. The expected probability is 16.7% for each outcome. We would like to test if the dice is fair. We will test this by rolling the dice 100 times and apply the 'Chi-square Goodness-of-Fit test' to determine whether the results follow the expected distribution.

- H_O: $p_1 = p_2 = p_3 = p_4 = p_5 = p_6$ (The dice is fair: each outcome has the same probability)
- H_A: $p_i \neq p_j$ (The dice is unfair: at least one outcome has a different probability)

Chi-Square Goodness-of-Fit Test for Categorical Variable: dice

Category	Observed	Test Proportion	Expected	Contribution to Chi-Sq
1	13	0.166667	16.6667	0.80667
2	26	0.166667	16.6667	5.22667
3	19	0.166667	16.6667	0.32667
4	13	0.166667	16.6667	0.80667
5	9	0.166667	16.6667	3.52667
6	20	0.166667	16.6667	0.66667

N	N*	DF	Chi-Sq	P-Value
100	0	5	11.36	0.045

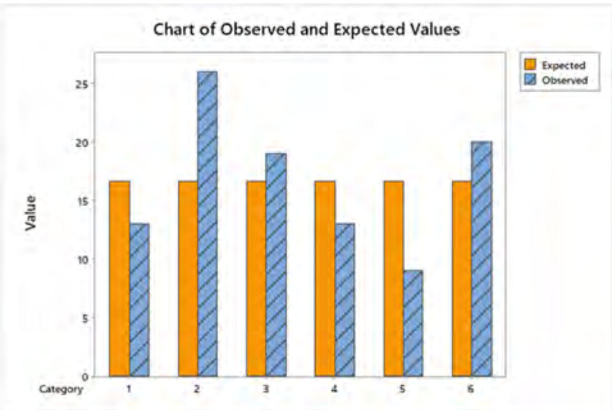


Figure 235 – Hypothesis test for Chi-square Goodness of Fit

Conclusion:

- Because $p = 0.045$ we can conclude that the proportions differ from the expected proportions (at the 0.05 level of significance).
- The p-value is low, meaning we can reject H_0. We assume that the dice is an 'unfair dice'.

7.5.6 Non-parametric tests

Non-parametric tests can be used when no assumption can be made about the distribution of the population. These tests are also known as distribution-free tests. For example, many tests rely on the assumption that the population follows a normal distribution with parameters μ and σ. Non-parametric tests do not make this assumption so they are useful when your data are strongly non-normal and resistant to transformation. For example, salary data are heavily skewed to the right, with many people earning modest salaries and fewer people earning larger salaries.

Non-parametric tests are often based on testing the median instead of the mean. The hypotheses are defined as:

- H_0: $\eta_1 = \eta_2$ (population medians are the same)
- H_A: $\eta_1 \neq \eta_2$ (population medians are not the same)

The following three non-parametric tests are commonly used:

Mann-Whitney test
(Minitab: Stat > Nonparametrics > Mann-Whitney)

Mann-Whitney test (also called Wilcoxon rank-sum test or Wilcoxon–Mann–Whitney test) is a 2-sample rank test that can be used to test the equality of medians of two populations. It is nearly as efficient as the 2-Sample *t*-test on normal distributions. All observations from both groups need to be independent of each other and the distributions of both groups need to be equally shaped.

Kruskal-Wallis test
(Minitab: Stat > Nonparametrics > Kruskal-Wallis)

Kruskal-Wallis test can be used to test the equality of medians from two or more populations. An assumption for this test is that the samples from the different populations are independent random samples from continuous distributions, with the distributions having the same shape. The Kruskal-Wallis test is more powerful than Mood's median test for data from many distributions, including data from the normal distribution, but is less robust against outliers.

Mood's median test
(Minitab: Stat > Nonparametrics > Mood's Median Test)

Mood's median test can be used to test the equality of medians from two or more populations. An assumption of Mood's median test is that the data from each population come from independent random samples and the population distributions have the same shape. Mood's median test is more robust against outliers and errors in data than the Kruskal-Wallis test.

7.6 Correlation and regression

'Correlation and Regression' is an approach for analyzing data and summarizing their main characteristics. This includes descriptive statistics and visualization of data. In this section we will review a number of additional techniques that are typically used in the Analyze phase of the DMAIC approach. Black Belts are expected to calculate and analyze the correlation coefficient, to determine its statistical significance (*p*-value) and to recognize the difference between correlation and causation.

7.6.1 Correlation coefficient

(Minitab: Stat > Basic Statistics > Correlation)

Correlation Analysis studies the degree of correlation between two continuous variables. The Pearson Correlation Coefficient is used to measure the strength of the linear relationship between two variables. The correlation coefficient assumes a value between -1 and +1.

- '-1' Depicts complete inverse (negative) dependence.
- '0' Depicts complete independence.
- '+1' Depicts complete direct (positive) dependence.

The equation to calculate the Pearson Correlation Coefficient between variables x and y is:

$$r = \frac{\sum_i (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_i (x_i - \overline{x})^2} \times \sqrt{\sum_i (y_i - \overline{y})^2}}$$

The following general rules can be applied to determine the strength of a correlation:

- Strong: Correlation Coefficient $|R| > 0.8$
- Moderate: Correlation Coefficient $0.5 < |R| < 0.8$
- Weak: Correlation Coefficient $|R| < 0.5$

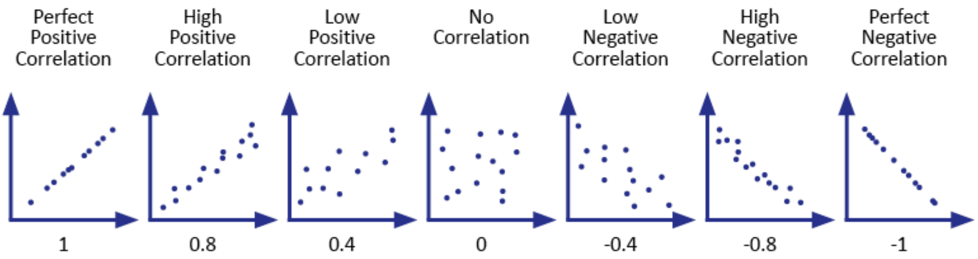


Figure 236 – Pearson Correlation Coefficients

Warning: Correlation does not imply causation. It should be noted that Correlation does not necessarily mean that there is a cause and effect relation. Practically, a well-designed experiment should be performed where the joint variation of two measurements are observed while keeping all other variables the same. Such an experiment could indicate causation, but it would need an explanation in the form of a physical relation or theory.

7.6.2 Regression analysis

Regression analysis is a statistical method for estimating the relationships between variables, containing several different techniques for modeling and analyzing the relationships. In regression analysis, the 'Outcome' or 'Response' is the dependent variable *Y* that changes as a result of one or more independent variables X_i, also called 'Factor' or 'Predictor variable'. The predictor variables can be both continuous and categorical. Simple Linear Regression investigates the relation between one response and one predictor. Multiple Linear Regression Investigates the relationship between one response and more than one predictor.

Table 34 gives an overview of different regression methods. This paragraph explains Linear regression and Polynomial regression. Logistic regression is explained in section [7.6.3].

Method	Response(s)	Single Predictor (optionally prefixed Simple)	Multiple Predictor(s) (usually prefixed Multiple)	Assumed relationship
Simple Linear Regression	Single Continuous	Single Continuous	Multiple Continuous	Linear
Polynomial Regression	Single Continuous	Single Continuous	Multiple Continuous	Non-Linear (including 2nd or higher order term)
Exponential Regression	Single Continuous	Single Continuous	Multiple Continuous	Exponential (including an e^x term)
Poisson Regression	Poisson distributed count	Single Continuous	Multiple Continuous	Linear with log(response)
Binomial Regression	Single Categorical with a series of Bernoulli trial outcomes	Single Continuous or Categorical	Multiple Continuous or Categorical	Linear with log(response)
Binary Logistic Regression	Single Categorical with two possible outcomes	Single Continuous or Categorical	Multiple Continuous or Categorical	Linear with log(response)
Nominal Logistic Regression	Single Categorical with three of more possible Nominal outcomes	Single Continuous or Categorical	Multiple Continuous or Categorical	Linear with log(response)
Ordinal Logistic Regression	Single Categorical with three of more possible Ordinal outcomes	Single Continuous or Categorical	Multiple Continuous or Categorical	Linear with log(response)

Table 34 – Regression methods

Simple Linear Regression
(Minitab: Stat > Regression > Fitted Line Plot > Linear)

Simple linear regression generates an equation that describes the linear (statistical) relationship between a continuous response variable and one predictor variable.

$$Y = a + bx$$

Example: assume your hobby is gardening and you are interested in the relationship between growth of plants (height) and time (weeks). Over a period of time you collect the data as listed in Table 35.

Week	2	4	6	8	10	12	14	16	18
Height [cm]	4	14	27	36	45	62	67	83	94

Table 35 – Growth of plants

Performing a linear regression analysis, using Minitab, results in the following table and graph:

Regression Analysis: Height versus Week

```
Analysis of Variance
Source      DF   Adj SS   Adj MS  F-Value  P-Value
Regression   1  7548.82  7548.82  1501.90    0.000
  Week       1  7548.82  7548.82  1501.90    0.000
Error        7    35.18     5.03
Total        8  7584.00

Model Summary
      S    R-sq  R-sq(adj)  R-sq(pred)
2.24192  99.54%     99.47%      99.32%

Coefficients
Term       Coef  SE Coef  T-Value  P-Value   VIF
Constant  -8.08     1.63    -4.96    0.002
Week      5.608    0.145    38.75    0.000  1.00

Regression Equation
Height = -8.08 + 5.608 Week
```

We will explain how to interpret the output, starting at the bottom of the output Table. The regression equation is listed at the bottom of the Table. We can use this equation to predict the output 'Height', by filling in a certain value for 'Week'.

$$Height = -8.08 + 5.608 \times Week$$

The regression equation is also graphically represented by a simple, linearly fitted line plot in Figure 237.

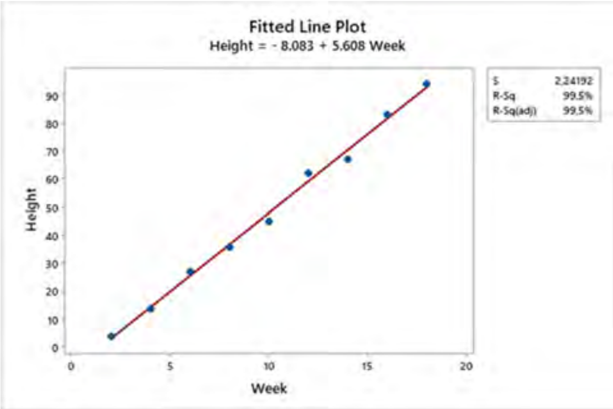


Figure 237 – Linear Regression analysis plot

Regression generally uses the ordinary least squares method, which derives the equation by minimizing the sum of the squared residuals. The total sum of squares is equal to the sum of the regression sum of squares and the error sum of squares:

$$SS_{Total} = SS_{Regression} + SS_{Error} = 7{,}548.82 + 35.18 = 7{,}584$$

By comparing the regression sum of squares to the total sum of squares, you can determine the proportion of the total variation that is explained by the regression model *R*-sq value, also known as R^2 or the coefficient of determination:

$$R_{sq} = \frac{SS_{Regression}}{SS_{Total}} = \frac{7{,}548.82}{7{,}584.00} = 0.995 = 99.5\%$$

The *R*-sq value is the fraction of the variability (not variation) in the data that is explained by the regression model. An *R*-sq value of 99.5% means that the model explains 99.5% of the variability (total sum of squares) in the response. The larger the *R*-sq value, the better the relationship is explained. An *R*-sq value of 99.5% means that the regression equation is very strong. However, a high *R*-sq value isn't necessarily good and a low *R*-sq value isn't necessarily bad. The answer to the question 'how high should R-squared be', depends on the decision-making situation. A low *R*-sq could mean that other predictors are present which are not incorporated in the equation, but it could also mean that measurement variation was too high. Some say that no regression model with an *R*-sq smaller than 0.7 should be interpreted. However, although a low *R*-sq indicates small effect size, it doesn't mean it's bad or useless. Even small effect sizes can have scientific or clinical significance. Remember that when you find a low *R*-sq, you should look for additional predictors, improve the measurement system and be careful with drawing conclusions.

In addition, you should know that it is better to look at the adjusted *R*-sq rather than *R*-sq, because *R*-sq will always be maximal if all predictors are in the model, even if some predictors are not significant. The adjusted *R*-sq is adjusted for the number of predictors in the model. The adjusted *R*-sq will only increase if a new added predictor improves the model more than would be expected by chance. It will decrease when the predictor improves the model less than expected by chance.

A measure that describes the relationship between explained variance and unexplained variance is the *F*-statistic or *F*-ratio. The following ratio follows a *F*-distribution when there is no regression:

$$\frac{SS_{predictor}\ /DF_{predictor}}{SS_{error}\ /DF_{error}} = \frac{S^2_{predicto\ r}}{S^2_{error}} \cong F_{[DF_{predictor}\ ;DF_{error}\ ]}$$

When we fill in the values from the regression analysis Table, we get:

$$F[1,7] = \frac{7{,}548.82}{5.03} = 1{,}501.90$$

Appendix C.4 gives for $\alpha = 0.05$ a $F_{[1;7]} = 5.59$ for F[1,7]. Because F = 1,501.90 > 5.59, we can conclude that that the regression is significant. We are using a right tailed test, because F is expected to increase when regression is present.

Multiple Linear Regression
(Minitab: Stat > Regression > Regression > Fit Regression Model)

In Multiple linear regression analysis, there are several independent variables rather than one, as is shown in the following equation. In this equation we have k independent variables. Ɛ is the error.

$$Y = \beta_0 + \beta_1 x_1 + \beta_1 x_2 + \cdots + \beta_k + \varepsilon$$

For example, Peter a real estate agent, might want to know the influence of multiple variables on the price of houses. During a brainstorm session with his colleague they define the following number of variables: size of the house [m^2], number of bedrooms [n], distance to school [km_1], distance to supermarket [km_2] and the condition of the house [rating of 1 to 10]. Based on the available data on the market, he performs Multiple regression analysis. Based on this model, Peter might learn that the number of bedrooms is a better predictor for price than the size of the house.

Peter may also detect a certain error of his estimates, telling him the model is not complete yet. This is because at least one important factor is missing in his model. He assumes that the location of the house is a variable that is significant. In order to improve his model and to reduce the error, he will add this variable to the model.

Multicollinearity
In regression, Multicollinearity refers to predictors that are correlated with other predictors. To measure Multicollinearity, you can examine the correlation structure of the predictor variables. You can also review the 'Variance Inflation Factor' (VIF), which measures how much the variance of an estimated regression coefficient increases if your predictors are correlated. If the VIF = 1, there is no Multicollinearity but if the VIF is > 1, predictors may be moderately correlated. When the VIF is 5 – 10, the regression coefficients are poorly estimated (Source: Minitab).

One way to solve severe Multicollinearity is by removing highly correlated predictors from the model because they supply redundant information. Another way is to apply 'Principal Component Analysis' (PCA) to transform the set of predictors into an orthogonal (uncorrelated) set of components. PCA is outside the scope of this book.

For example, an economist wants to predict how much a person is spending on a new car. The economist initially includes 'Income', 'IQ', 'Age' and the 'Vacation costs' as predictor variables in his regression model. The regression analysis shows that the variables 'Income' and 'Vacation costs' are strongly correlated and have a VIF greater than 5. Therefore, the economist considers removing one of the factors from his model.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-4574	1783	-2.56	0.022	
Income	0.5104	0.0806	6.33	0.000	11.04
IQ	8.9	20.3	0.44	0.667	1.65
Age	0.0	56.1	0.00	1.000	2.24
Vacation costs	0.27	1.79	0.15	0.880	9.08

Polynomial Regression

(Minitab: Stat > Regression > Fitted Line Plot > Quadratic)

Polynomial regression generates an equation that describes the (statistical) relationship between a continuous response variable and one or more predictor variables. Polynomial regression is used when it is not possible to adequately model the relationship using linear parameters. An example of a polynomial of degree 2 with only two predictors is:

$$Y = 2 + x_1 + 3x_2 - x_1x_2 + x_1^2 + 5x_2^2$$

Polynomial regression with one predictor can be visualized with a fitted line plot using a quadratic or cubic regression model that displays the relationship and regression equation.

Example: Assume your hobby is gardening. We will investigate the relation between the amount of water that we give a tomato plant each week (Predictor) and the weight of the tomato (Response). A polynomial regression analysis of 'Weight' versus 'Water' is performed and the regression equation appears to be:

$$\text{Weight} = -190.3 + 24.84 \cdot \text{Water} - 0.4094 \cdot \text{Water}^2$$

This can be graphically represented using a quadratic fitted line plot:

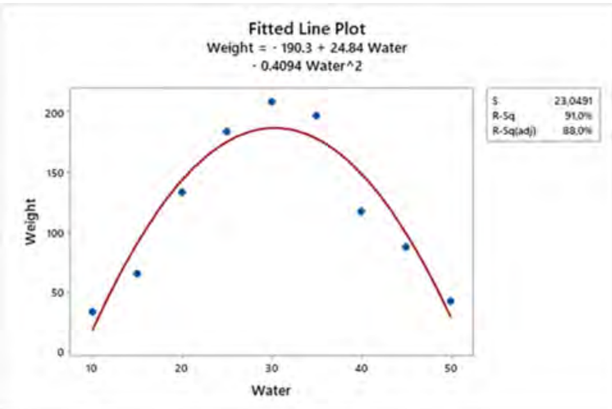


Figure 238 – Polynomial Regression analysis plot

7.6.3 Logistic Regression analysis

(Minitab: Stat > Regression > Binary Logistic Regression)

Within Linear regression analysis, as explained in section [7.6.2], both the independent variables and the dependent variable (response) are continuous. Within Logistic regression analysis, the dependent variable is an attributes value and can be Binary, Ordinal or Nominal. Based on this we have to choose Binary logistic regression, Ordinal logistic regression or Nominal logistic regression. In this section we will explain 'Binary logistic regression'. This technique is used to analyze data where the dependent variable is a 'Binary' response variable. A binary variable is categorical and only has two possible values. Examples of this are Passed or Failed, Chosen or Not chosen, Presence or Absence, Alive or Dead, etc. Logistic regression is widely used in several fields, especially in medical and social science research. When applying Binary logistic regression, we often take a look at the 'Odds Ratio' (OR). The Odds ratio compares the odds (probabilities) of two events. The odds of the events are calculated by dividing the probability the event occurs (*p*) by the probability that the event does not occur (1 – *p*). In logistic regression, Odds ratios compare the odds of each level of a categorical response variable to quantify how each predictor affects the probabilities of each response level.

$$Odds\ ratio = \frac{p}{1-p}$$

Binary logistic regression analysis using Minitab supports analyzing a combination of multiple continuous predictors and multiple categorical predictors on a single 'Binary' response. For example: Assume you are a marketing manager for a bookshop and interested in the effect of two predictors upon sales. The first predictor is the 'Age' of the bookshop visitors. The second predictor is the 'Customer Type', which is characterized by 'New Customer' or 'Existing Customer'. Because the outcome 'Sales' is categorized into two distinct values 'Sale' and 'No Sale', Binary logistic regression analysis is suitable to analyze the collected data. In Minitab we enter the continuous predictor, 'Age', and the categorical predictor, 'Customer Type'. As with regression, the session Window provides a model that we can use to predict the result.

```
Link function                 Logit
Categorical predictor coding  (1, 0)
Rows used                     151

Response Information
Variable  Value     Count
Sales     Sale         78  (Event)
          No Sale      73
          Total       151

Deviance Table
Source           DF  Adj Dev  Adj Mean  Chi-Square  P-Value
Regression        2   15.631     7.815       15.63    0.000
  Age             1    4.512     4.512        4.51    0.034
  Customer Type   1   13.497    13.497       13.50    0.000
Error           148  193.534     1.308
Total           150  209.165

Model Summary
Deviance   Deviance
    R-Sq  R-Sq(adj)     AIC
   7.47%      6.52%  199.53

Coefficients
Term              Coef  SE Coef   VIF
Constant         1.917    0.705
Age            -0.0252   0.0121  1.07
Customer Type
  New           -1.281    0.360  1.07
```

The Deviance Table displays the likelihood ratio test *p*-values for the coefficients. The low *p*-value for both 'Age' and 'Customer Type' indicates that both predictors have a significant influence on the outcome 'Sales'. The value of deviance R^2 is pretty low and indicates a low fit of the model and that we therefore have to be very careful about drawing conclusions.

Black Belts ought to be able to apply 'Link function' to the resultant regression equation to provide the probability of a given event based on the input variables. The logit link function provides an estimate of the Odds Ratios. The default link function is the 'Logit', which is the inverse of the cumulative logistic distribution function. The coefficients of this Link function can be found in the coefficients Table. In this response model we need to use '+1' when it is a 'New Customer' and '-1' for an 'Existing Customer'. Other link functions are the 'Probit Function' and the 'Gompit Function', but detailed explanations of these functions are outside the scope of this book.

```
Coefficients
Term                Coef  SE Coef   VIF
Constant           1.917    0.705
Age              -0.0252   0.0121  1.07
Customer Type
  New             -1.281    0.360  1.07
```

$$Logit\ Response = 1.917 - (0.0252 \times Age) - (1.281 \times Type) + error$$

It requires a few additional steps in order to use the model, because the response in the equation is not the regular '*Y*' as within a normal response model. In this case we deal with the 'Logit Response model', which is the logit transformation of '*Y*'. In this example, the response is the natural logarithm of the probability of 'Sale' divided by the probability of 'No Sale':

$$Logit\ Response = Ln\left(\frac{p(Y)}{1-p(Y)}\right) = Ln\left(\frac{p(Sale)}{1-p(Sale)}\right) = Ln\left(\frac{p(Sale)}{p(No\,Sale)}\right)$$

Putting these two equations together gives us:

$$Ln\left(\frac{p(Y)}{1-p(Y)}\right) = 1.917 - (0.0252 \times Age) - (1.281 \times Type)$$

We will now explain how to use this equation in practice. Let's assume that the marketing manager is interested in the probability of a 'Sale' for a 27-year-old, New Customer ('+1') visiting our bookshop.

$$Ln\left(\frac{p(Y)}{1-p(Y)}\right) = 1.917 - (0.0252 \times 27) - (1.281 \times 1) = -0.044$$

$$e^{Ln\left(\frac{p(Y)}{1-p(Y)}\right)} = e^{-0.044}$$

$$\frac{p(Y)}{1-p(Y)} = 0.957$$

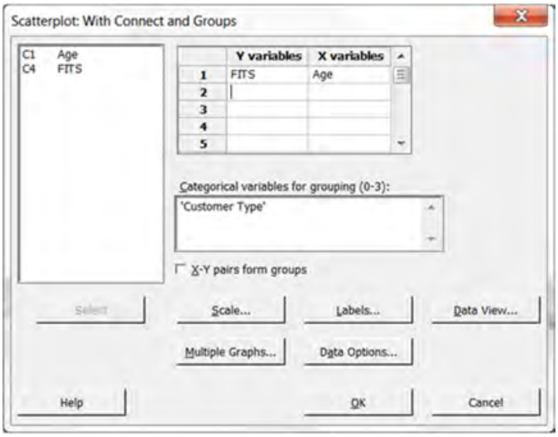
$$p(Y) = 0.957 \times (1 - p(Y)) = 0.957 - 0.957 \times p(Y)$$

$$p(Y) = \frac{0.957}{1.957} = 0.489$$

This tells us that there is a 49% chance that a 27-year-old, New customer will result in a Sale (i.e. a 51% chance of No Sale).

(Minitab: Graph > Scatterplot)

An easier way than working through all the maths is to produce a Scatter plot of event probabilities in Minitab, which is also a neat way of representing the regression equation graphically. This is the best logical way to graphically represent continuous inputs with discrete outputs. To draw the Scatter plot, we have to store the 'Fits (Event probabilities)' in Minitab by checking the box under the button 'Storage'. Minitab will then add a separate column with the event probabilities in the Data Window. These are the probabilities of the high value ('Sale' in this case) for each combination of factors. If we plot these values on a Scatter plot with Connect and Groups, we will see a visual depiction of the regression model.



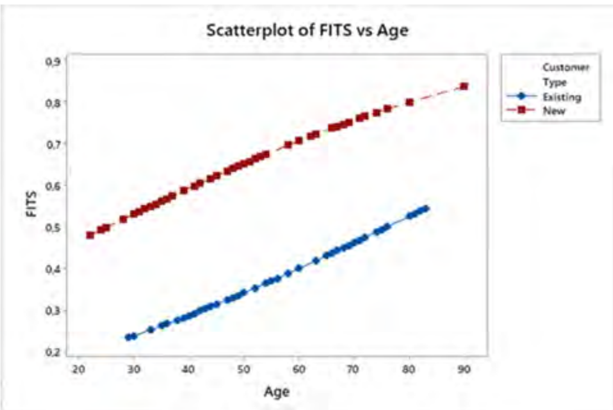


Figure 239 – Scatter plot of event probabilities

We can use the cross hairs to find where the vertical line at 27 for Age intersects the New Customer plotted line, which will give us a good estimate of the event probability of a 'Sale'. The reading says 48.4%, which is pretty close to what we calculated earlier.

We can derive some useful information from graphing the event probabilities. The Scatter plot tells us that the probability of a 'Sale' is significantly lower for New Customers. As customer age increases, so does the probability of a 'No Sale'.

When we would like to calculate the Odds ratio for this example, we can use the following equations for Customer Type on Sale or No Sale.

$$Odds\ A_{New} = \frac{p(Sale)}{1 - p(Sale)} \quad \& \quad Odds\ B_{Existing} = \frac{p(Sale)}{1 - p(Sale)}$$

$$Odds\ ratio = \frac{Odds\ A_{New}}{Odds\ B_{Existing}}$$

Or, using the logit function we can calculate the odds:

$$Ln\left(\frac{p(Y)}{1 - p(Y)}\right) = 1.917 - (0.0252 \times Age) - (1.281 \times Type)$$

$$\frac{p(Y)}{1 - p(Y)} = e^{1.917 - (0.0252 \times Age) - (1.281 \times Type)}$$

For each predictor variable in the logistic regression model, Minitab displays the Odds ratio and a Confidence Interval in the session window.

```
Odds Ratios for Categorical Predictors

Level A        Level B   Odds Ratio       95% CI
Customer Type
  New          Existing      0.2779   (0.1371, 0.5631)

Odds ratio for level A relative to level B
```

Given that our visitors have the same Age, the Odds ratio of 0.2779 can be interpreted as the odds of a New customer resulting in a ‘Sale’ being 28% of the odds of Existing customer resulting in a ‘Sale’.

7.6.4 Multivariate studies

Multivariate statistical analysis refers to a number of techniques for examining relationships among multiple variables at the same time. Multivariate studies are used to analyze data when multiple measurements on items or subjects are made. In this section we will explain two of the most commonly used multivariate techniques, 'Factor analysis' and 'Principal Component Analysis'.

Factor analysis
(Minitab: Stat > Multivariate > Factor Analysis)

Factor analysis is technique used to reduce the number of variables and detect relationships between variables. Researchers use this technique to combine a large number of variables to a smaller, more manageable number of factors. Factor analysis searches for patterns among variables and then clusters interrelated variables into a combined factor. For example, in a survey research factor analysis can be used to see if a set of questions can be grouped into one combined question.

Principal Component Analysis
(Minitab: Stat > Multivariate > Principal Components)

'Principal Component Analysis' (PCA) is also a technique used to reduce the number of variables. PCA is a tool that is used in exploratory data analysis and for making predictive models. PCA is a statistical process that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called 'Principal Components'. PCA can supply the user with a lower-dimensional picture. This is done using only the first few principal components so that the number of principal components is less than the number of original variables.

We will explain PCA by reviewing an example. Let's assume a researcher has collected the following data for 20 workers: Yearly income, IQ, Age, value of their car and the number of days per year doing sport. A part of the collected data is shown in Table 7.14. (N.B.: the data in this table is fictitious).

Income	IQ	Age	Car value	Sport days
€49,000	58	50	€22,000	35
€92,000	122	55	€47,000	35
€78,000	118	60	€36,000	29
€70,000	63	42	€34,000	39
€67,000	110	44	€33,000	37
…	…	…	…	…

Table 36 – PCA data (partly)

Before we perform the PCA, we will verify the amount of correlation between these variables. The correlation table below shows several high correlation coefficients. For instance, the Pearson correlation coefficient between Income and Car value is 0.984. Because we see several high correlation coefficients, it makes sense to apply a Principal Component Analysis to understand the underlying data structure.

	Income	IQ	Age	Car
IQ	0.593			
	0.006			
Age	0.715	0.568		
	0.000	0.009		
Car	0.984	0.600	0.707	
	0.000	0.005	0.000	
Sport days	0.165	-0.130	0.052	0.063
	0.486	0.585	0.828	0.793

The PCA transformation is defined in such a way that the first principal component has the largest possible variance. This first component then accounts for as much of the variability in the data as possible. Each succeeding component will then have the highest variance possible, under the constraint that it is orthogonal to the preceding components. The resulting vectors are an uncorrelated orthogonal basis set.

The following table represents the outcome of our Principal Component Analysis. The first principal component (PC1) has an 'Eigenvalue' (variance) of 3.1072 and accounts for 62.1% of the total variance. The second principal component (PC2) has an Eigenvalue of 1.0686 and accounts for 21.4% of the total variance. Together, the first two and the first three principal components represent 83.5% and 92.5%, respectively, of the total variability (see row Cumulative). Thus, most of the data structure can be captured in two, three or maybe four underlying dimensions. The remaining principal components account for a relatively small proportion of the variability and are probably irrelevant.

Eigenanalysis of the Correlation Matrix

Eigenvalue	3.1072	1.0686	0.4487	0.3656	0.0100
Proportion	0.621	0.214	0.090	0.073	0.002
Cumulative	0.621	0.835	0.925	0.998	1.000

Variable	PC1	PC2	PC3	PC4	PC5
Income	0.539	0.135	-0.295	0.297	0.718
IQ	0.432	-0.307	0.823	0.204	-0.013
Age	0.481	-0.006	-0.038	-0.876	-0.013
Car	0.538	0.041	-0.358	0.321	-0.692
Sport days	0.043	0.941	0.327	0.004	-0.077

The coefficients listed under PC1 show how to calculate the principal component scores:

$$PC1 = 0.539\ Income + 0.432\ IQ + 0.481\ Age + 0.538\ Cae + 0.043\ Sport\ days$$

Scree plot:
The graphical representation of the Eigenvalues is demonstrated in Figure 240, which is called a ‘Scree plot’. In this plot, we can see the five Eigenvalues for each of the five principal components.

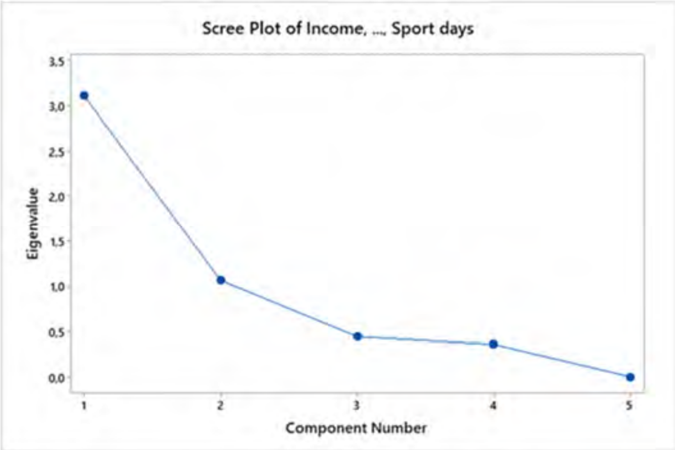


Figure 240 – PCA Scree plot

Loading plot:
A loading plot gives information about the contribution of the variables to the first and second Principle Components. A line is drawn from each loading to the (0,0) point. Income, Age, Car and IQ all have a large contribution to the first Principal Component, while the factor Sport days has the largest contribution to the second Principal Component.

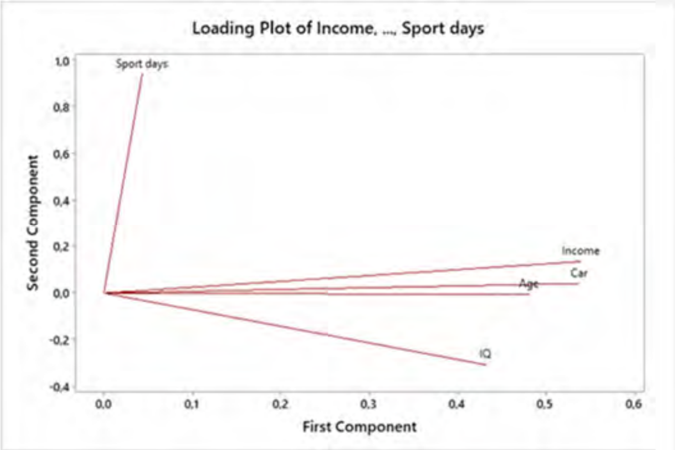


Figure 241 – PCA Loading plot

Outlier plot:
The final step is to check for outliers, because they can significantly influence our results. Points that fall above the Y-axis reference line (automatically calculated by Minitab) are outliers. In our census data there appear to be no outliers.

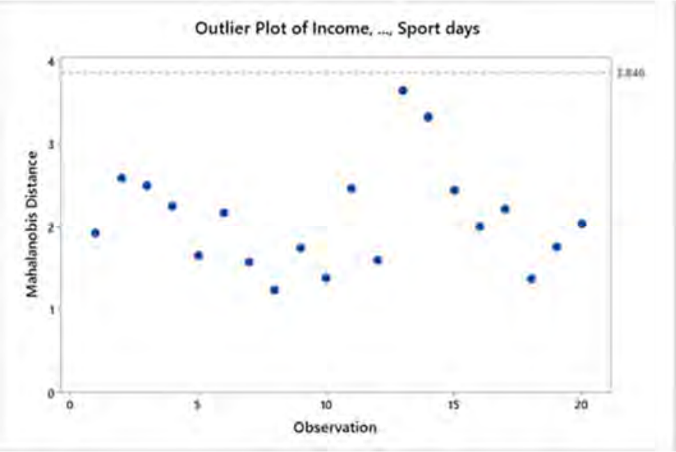


Figure 242 – PCA Outlier plot

7.7 Process Capability and Performance

When reviewing process capability, two somewhat contrasting concepts need to be considered: 'Process Capability' and 'Process Performance'. Process capability shows what the process can do and process performance is what the process is actually doing. The gap between these two concepts can be seen as an opportunity for improvement.

7.7.1 Process Capability

Process stability
(Minitab: Stat > Quality Tools > Run Chart)

Before undertaking a process capability study, it is essential that the process is stable. Additionally, we must know whether the process is producing normally distributed data. We perform three analyses:

- Stability: The first test is to identify if any special causes are acting on the process. Is the process stable? This is undertaken with a 'Run chart'.
- Normality: The second test is to identify whether the process is producing normal data. Is the process normal? This is completed with a normality test [7.2.1].
- Capability: Finally, it is then possible to determine if the process is capable. Is the process capable of meeting customer or business requirements? This is completed with a process capability analysis.

A run chart can be used to check stability. This is a simple graphic representation of the process data over time and can also be used to look for evidence of special cause variation in your process. The run chart provides information on non-random variation due to trends, oscillation, mixtures and clustering.

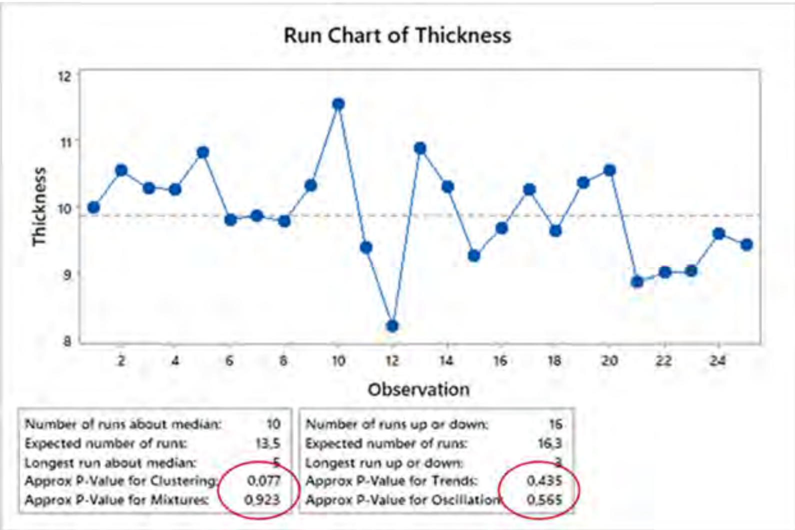


Figure 243 – Example of Run chart

A *p*-value lower than 0.05 indicates that the variation observed is due to special causes. Any special cause needs to be eliminated before attempting to undertake a capability analysis or capability improvement.

- Trends: the process mean is not stable.
- Oscillation: the process is affected by some cyclical special cause.
- Mixture: the data is from more than one process.
- Clustering: the sampling has not been randomized and is affected by rational subgroups.

A normality test is undertaken to check normality. If the data is normal then the process capability study can be undertaken. If the data is not normal then it may be possible to identify whether the data is from a known distribution (see section 7.2.1 on distribution identification). Finally, if the data does not match any known distribution it will be necessary to transform the data into a normal distribution using either a Box-Cox or a Johnson transformation. Non-normal process capability is not covered in detail within this text but Minitab helpfully offers both options.

Process capability versus Process performance
Process capability is the potential of a process to produce products or services within the design specifications. These design specifications are called 'Lower Specification Limit' (LSL) and 'Upper Specification Limit' (USL). The difference between the USL and the LSL, is called the process tolerance and is numerically equal to USL – LSL. Process capability assumes only common cause variation and not special cause variation. Process capability represents the best performance of the process itself. This is demonstrated when the process is operated in a state of statistical control. According to the AIAG, the process must first be brought into statistical control by detecting and acting upon special causes of variation. Then its performance is predictable and its capability to meet customer expectations can be assessed. This is the basis of Continuous Improvement [1.].

Process performance is defined as what the process is currently doing and is what the customer sees. Therefore, process performance is what typically concerns customers more than process capability. Process performance is based on the total variation of a process in the long term and assumes both common cause variation and special cause variation. Since a process is seldom perfectly stable, its Mean will drift in time and the standard deviation may vary in time too.

Figure 244 – Process Capability

In the Lean Six Sigma quality methodology, both process capability and process performance are reported to the organization as a sigma level. The higher the sigma level, the better the process is performing. A process capability analysis or process performance analysis can be done for the following purposes:

- To determine the baseline performance at the start of an improvement project.
- To demonstrate the improvements at the end of a project.
- To see the capability of a process to produce within specifications.
- To help product development select or change the process.
- To establish the interval between taking samples for process control.
- To define performance requirements for new equipment.
- To make choices between competing suppliers.

Process Capability indices
(Minitab: Stat > Quality Tools > Capability Analysis > Normal)

The 'Process Capability index' (C_p) has become the standard metric for defining what the process can do. The index C_p compares short-term process width to the maximum allowable variation as indicated by the tolerance. The index provides a metric of how well the process can satisfy the variability requirements if the process is perfectly stable. It does not take into account the location of the process. As already discussed in section 7.1, less process variation results in a higher quality level, which is equivalent to a higher C_p value.

The index can be calculated for two-sided (bilateral) tolerances using the following equation:

$$C_p = \frac{Specification\,width}{Process\,width} = \frac{USL - LSL}{6 \cdot \sigma_{within}}$$

Data that are used for calculating Process Capability is normally collected in rational subgroups. The subgroups are defined in such a way that only common cause variation is present within the subgroups. The C_p is based on the within-subgroup variation (σ_{within}), also called short-term variability. Rational subgrouping ensures that common cause variation is within subgroups and special cause variation is between subgroups.

In the 1980s, the process width 6σ was targeted to be equal to the tolerance range. This resulted in a minimal defect level of 0.27% (2,700 ppm; C_p = 1.0) if the process is centered. In reality, the defect level is always higher because a process is never perfectly centered. At that time this was considered a 'Reach out' quality level. In the 1990s, the automotive industry required that the process width 6σ be targeted to fit at least 1.33 times within the tolerance range. This means that the tolerance range has a width of 8σ. When centered, this is equivalent to a defect level of 0.0063% (63 ppm; C_p = 1.33). The C_p level of 1.33 is often mentioned in supplier contracts for key characteristics.

The Motorola's 'Six Sigma approach' introduced a Process width equal to half of the tolerance range. This means that the process fits 2 times within the tolerance range. When centered, this equals a defect level of 0.0000002% (0.002 ppm; C_p = 2.0). This has become a part of the theoretical meaning of 'Six Sigma performance'. The other part is a rule for the location of the process average. Even today, many companies have capability indices C_p less than 0.67 for important parameters.

Let’s assume four arbitrary processes are compared to the same specification requirements. The ‘Lower Specification Limit’ (LSL) of 10 and the ‘Upper Specification Limit’ (USL) of 30. Each of these four processes has a different standard deviation σ (respectively σ = 5.0, σ = 3.33, σ = 2.5 and σ = 1.67). The graph also shows the number of defects that fall outside the specification. Note that the processes are centered.

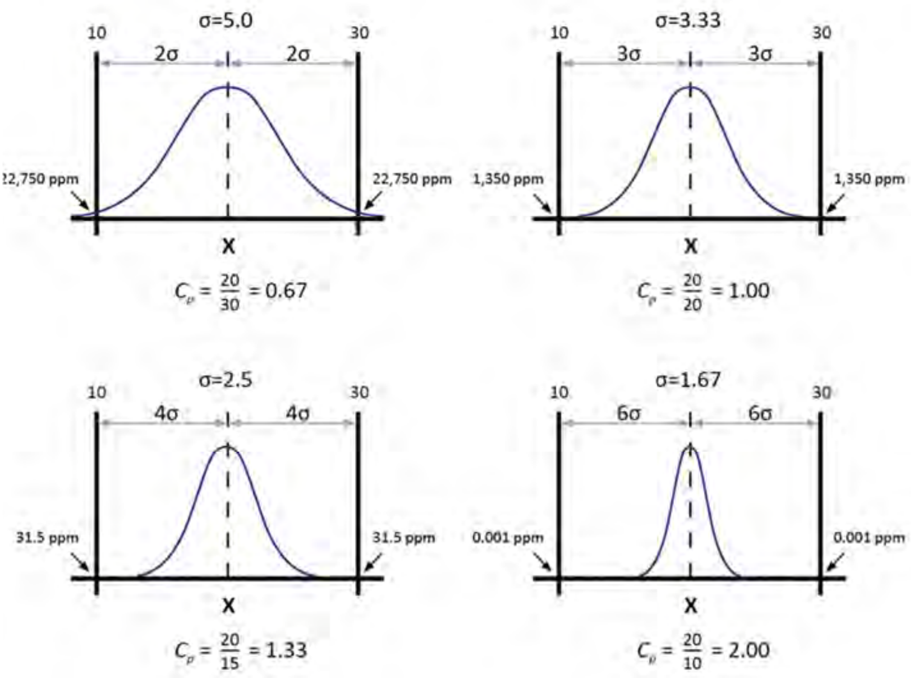


Figure 245 – Process Capability & Sigma levels

C_p is used as a basic introduction to the concept of process capability. Yet, it does not take into account any non-centering of the process relative to the specification limits of a parameter. The Process Capability index C_{pk} is defined as process capability, but corrected for non-centering. C_{pk} is a metric that takes into account both the spread and location. The index defines how close a process is running to its nearest specification limit, relative to the natural variability of the process. The larger the index, the higher the capability of the process to produce parts within the specification limits.

For bilateral tolerances, C_{pk} will always be less than or equal to C_p. C_{pk} will be equal to C_p only if the process is centered (Figure 247). C_{pk} and C_p should always be evaluated together, as a difference between C_p and C_{pk} indicates an opportunity for improvement by centering the process.

$C_{pk} = \min(C_{pL}, C_{pU})$, which is the smallest value of $C_{pL} = \frac{\bar{x}-LSL}{3\cdot\sigma_{Within}}$ and $C_{pU} = \frac{USL-\bar{x}}{3\cdot\sigma_{Within}}$

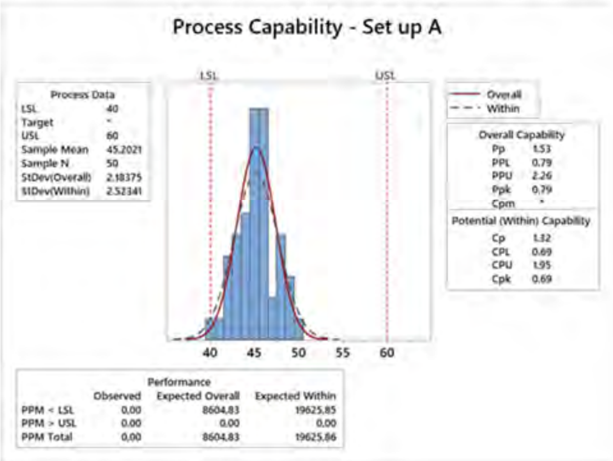


Figure 246 – Process Capability Set up A: C_p = 1.32, C_{pk} = 0.69

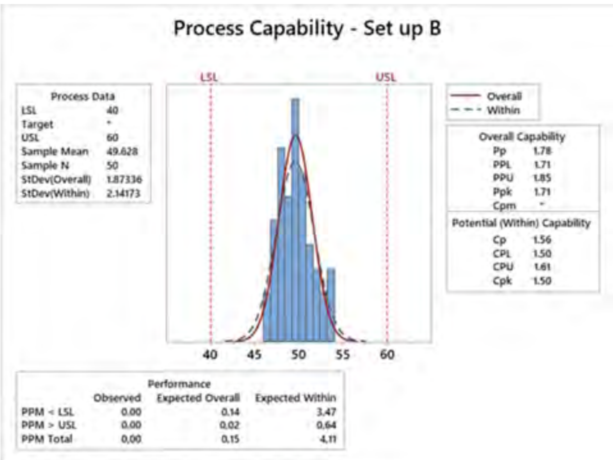


Figure 247 – Process Capability Set up B: C_p = 1.56, C_{pk} = 1.50

As a Green Belt or Black Belt, it is important to realize that centering the process is much easier than reducing process spread. Centering the process normally requires an adjustment of one parameter, whereas reducing process spread often requires a more comprehensive design of experimental techniques.

The relation between specification width, sigma level, defect rate and process capability when the process is perfectly centered is demonstrated in Table 37.

Sigma level	Specification width	ppm outside spec	Percent defective	Cp; Cpk
1	2σ	317,311	31.7%	0.33
2	4σ	45,500	4.55%	0.67
3	6σ	2,700	0.27%	1.00
4	8σ	63	0.0063%	1.33
5	10σ	0.57	0.00006%	1.67
6	12σ	0.002	0.0000002%	2.00

Table 37 – Six Sigma metrics (centered process)

7.7.2 Short-term and Long-term Capability

In the previous section we mentioned that a centered 'Six Sigma Process' equals a defect rate of 0.002ppm. Those who have read other books about Six Sigma might state that a Six Sigma performance equals a defect rate of 3.4ppm. So, what explains the difference? The reason is that in the past decades the initial mathematical Six Sigma philosophy has been adapted for process shifting and drifting over time. Many have adopted this paradigm of the 'Shifting $\bar{X}$ over time', while others call it 'deterioration of Six Sigma' (Bohte, 2000). Also, the statistician Donald J. Wheeler has dismissed the 1.5σ shift as 'Goofy' because of its arbitrary nature.

Shift Happens

Let's go to the source of the 1.5σ shift paradigm. In '*Six Sigma: The Breakthrough Management Strategy Revolutionizing The World's Top Corporations'* (2006), Harry and Schroeder wrote:

> *"By offsetting normal distribution by a 1.5σ on either side, the adjustment takes into account what happens to every process over many cycles of manufacturing… Simply put, accommodating shift and drift is our 'fudge factor,' or a way to allow for unexpected errors or movement over time. Using 1.5σ as a standard deviation gives us a strong advantage in improving quality not only in industrial process and designs, but in transactional processes as well. It allows us to design products and services that are relatively impervious, or 'robust', to natural, unavoidable sources of variation in processes, components and materials."*

There is a statistical reason for the 1.5σ shift. When Control charts are used to control a process and a process shifts a bit, it will last a while before the control chart will give an Out-of-control signal. The time between a shift and the signal depends on the size of sampled subgroups. When the subgroup size is 4, the expected shift (before detecting) is about 1.4σ to 1.6σ. When the size of the subgroups is larger, the expected shift will be less.

Because of this, the overall variation (long-term variation) will be greater than the within subgroup variation (short-term variation). This is visualized in Figure 248.

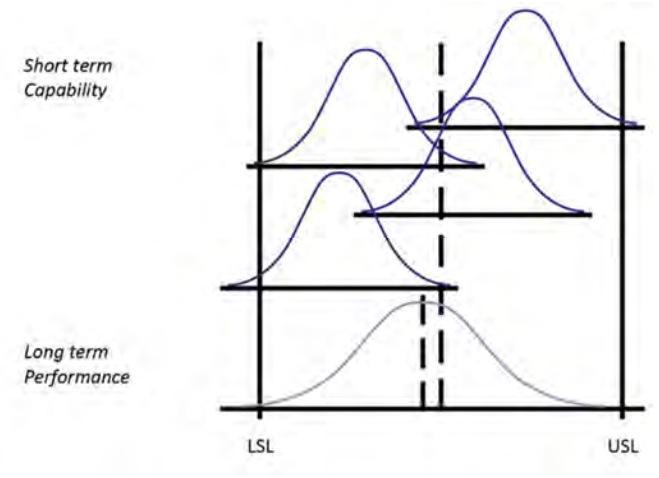


Figure 248 – Short term Capability and Long term Performance

The amount of shift is not the same for all processes. Assuming that a process has a tendency to drift towards 1.5σ over time means a distance between the $\bar{X}$ and the nearest specification limit is 4.5σ instead of 6.0σ. This is mathematically equivalent to a defect level of 3.4ppm at one side of the specification limits, as visualized in Figure 249. This is called a 'Six Sigma performance'.

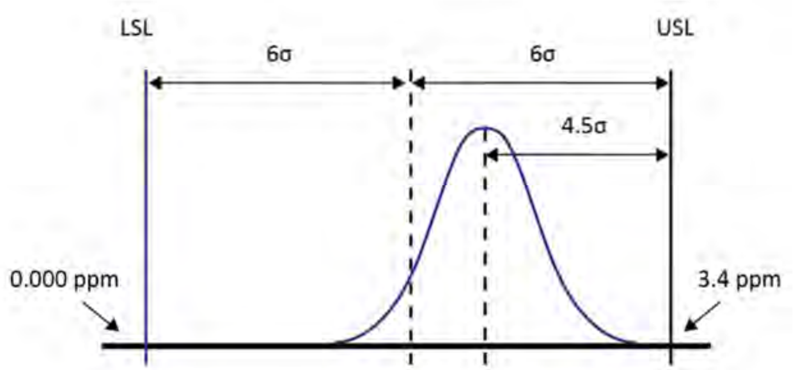


Figure 249 – Six Sigma performance including 1.5 sigma shift

7.7.3 Process Performance

Summarizing, a Six Sigma process is a process that first fits twice within the tolerance range ($C_p = 2$). Second, the mean has not drifted more than 1.5*σ* from the center. It is important to communicate clearly what data you have used for calculating process capability and process performance. If your analysis is based on common cause variation only, you should use Process capability indices (C_p and C_{pk}). If your analysis includes special cause variation or data over a longer period of time, you should use Process Performance indices (P_p and P_{pk}).

The performance indices P_p and P_{pk} are very comparable to the capability indices C_p and C_{pk}. The P_p index compares the process performance to the maximum allowable variation as indicated by the tolerance. This index provides a measure of how well the process meets the variability requirements. P_{pk} takes the process location as well as the performance into account. For bilateral tolerances P_{pk} will always be less than or equal to P_p. P_{pk} will be equal to P_p only if the process is centered [1.].

The equations are similar to the equations of Process Capability:

$$P_p = \frac{USL - LSL}{6 \cdot \sigma_{Overall}}$$

$P_{pk} = \min(P_{pL}, P_{pU})$, which is the lowest value of $P_{pL} = \frac{\bar{x} - LSL}{3 \cdot \sigma_{Overall}}$ and $P_{pU} = \frac{USL - \bar{x}}{3 \cdot \sigma_{Overall}}$

The relation between specification width, sigma level, defect rate and process performance is demonstrated in Table 38:

Sigma level	Specification width	ppm outside spec	Percent defective	Ppk (long term)
1	2σ	691,462	69%	-0.17
2	4σ	308,538	31%	0.17
3	6σ	66,807	6.7%	0.5
4	8σ	6,210	0.62%	0.83
5	10σ	233	0.023%	1.17
6	12σ	3.4	0.00034%	1.5

Table 38 – Six Sigma metrics, incorporating 1.5σ shift

The difference between Process Capability and Process Performance is demonstrated in Figure 250.

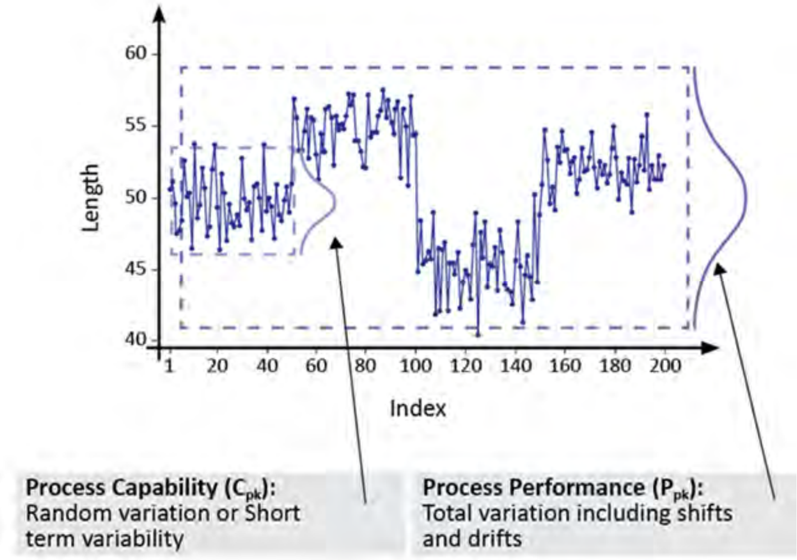


Figure 250 – Process Capability versus Process Performance

7.7.4 Process Capability for Attributes data

Continuous data typically provide more information and are more objective, however this is not always possible. Attribute data are easier to collect and thus are often used when continuous measurements are difficult to obtain. Especially in transactional processes there is a lot of attribute data. It is possible to perform a Capability analysis on attribute data. In the case of Binomial data, the process capability is defined as the average proportion of defective products. In the case of Poisson data, it is defined as the average number of defects per standard unit. Minitab offers both Binomial and Poisson analyses for attribute data.

Capability analysis (Binomial)
(Minitab: Stat > Quality Tools > Capability Analysis > Binomial)

The Binomial Capability analysis can be used to produce a process capability report when your data are from a Binomial distribution. As mentioned in section [7.2.2] Binomial distributions are usually associated with evaluating the number of defective items in a sample. For example, an assembly station uses a 'Go/No-Go' Gage to determine whether an assembly is 'OK' or 'NOK' (Defective). The operator records the total number of parts inspected and the number of Defective parts (source: Minitab).

In order to apply Binomial Capability analysis your data should meet the following criteria:

- Each item is the result of identical conditions.
- The outcomes of the items are independent of each other.
- Each item can result in one or two possible outcomes (Success or Failure).
- The probability of a Success or Failure is constant for each item.

Example: The number of people that shows up in time for their appointment at the Hospital is being recorded, as well those who do not show up or are more than five minutes late (Defective).

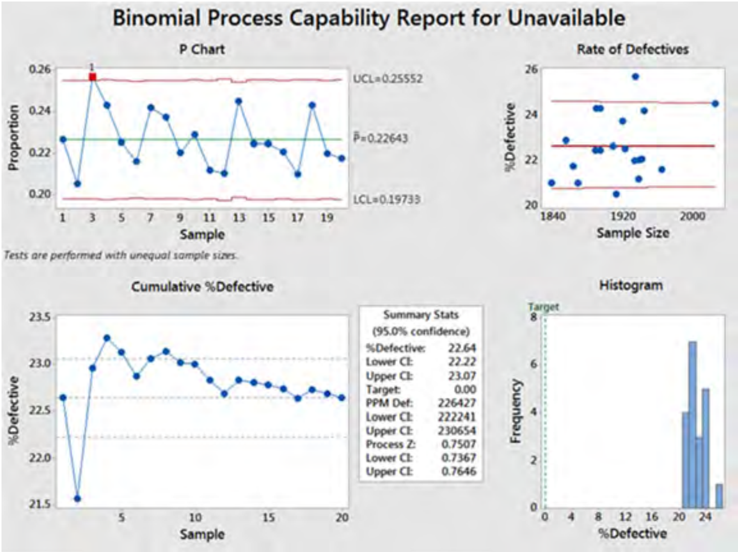


Figure 251 – Binomial Capability report for 'No Shows' at Hospital

Capability analysis (Poisson)
(Minitab: Stat > Quality Tools > Capability Analysis > Poisson)

The Poisson Capability analysis can be used to produce a process capability report when your data are from a Poisson distribution. Poisson data is usually associated with the number of defects observed in an item. As mentioned in section [7.2.2], the Poisson distribution is used for the number of events per interval (e.g. time, area, volume). This means the item occupies a specified amount of time or specified space. Often the size of the item varies so the size should be tracked as well (source: Minitab).

In order to apply Poisson Capability analysis, your data should meet the following criteria:

- The rate of Defects per unit of space or time is the same for each item.
- The number of Defects observed in the items is independent of each other.

Example: A cable manufacturer wants to record the number of damages in a cable. As the lengths for each cable varies, he also records the length of each cable sampled.

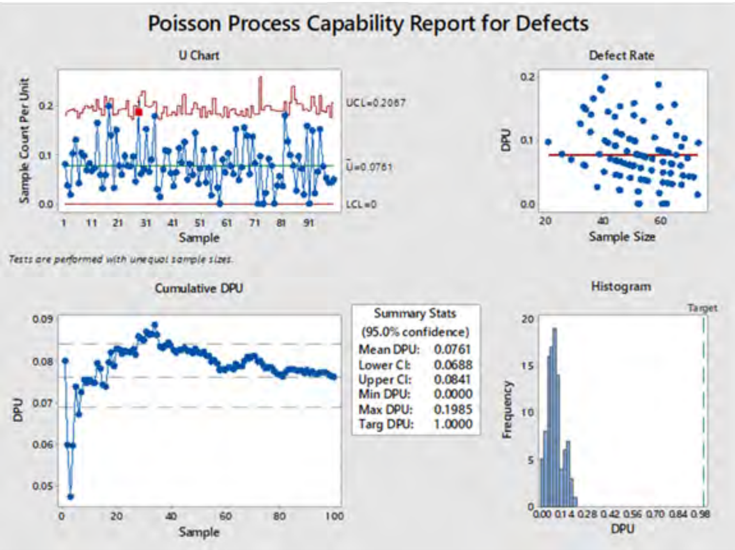


Figure 252 – Poisson Capability report for Cable manufacturer

Improve

7.8 Design of Experiments (DOE)

'Design of Experiments' (DOE) includes the design and evaluation of experiments. DOE is a systematic and highly efficient way to conduct experiments, to examine the influence of factors and factor interactions on the responses. The DOE approach is based on the pioneering work of Sir Ronald Fisher, who applied DOE in agriculture in the early 1920s. He improved the productivity of British farms by using the Full Factorial method. For this great contribution he was knighted.

7.8.1 Principles and terminology

One-Factor-At-a-Time
Some 'Classic Problem Solver' experts will tell you to change only one factor at a time. The traditional 'One-Factor-At-a-Time' (OFAT) approach is inferior to DOE because OFAT experiments usually require more time-consuming test runs and obtain only incomplete information regarding the process. OFAT does not reveal interactions between factors. OFAT, however, is an inferior but still commonly used alternative for the more complicated 'Designed Experiments'. Example, Statin medicines lowers the cholesterol level. Grapefruit does not have an effect on the cholesterol level. However, Grapefruit intensifies the effect of Statin. So, the two factors 'Grapefruit' and 'Statin' have an interaction effect on the response 'Cholesterol'.

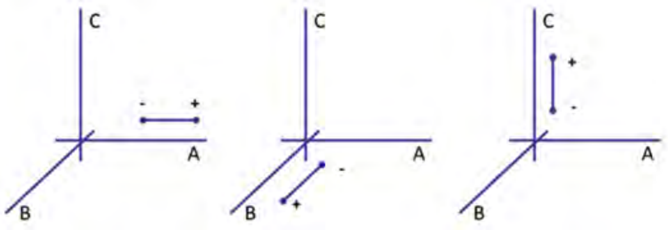


Figure 253 – Changing one factor at a time (OFAT)

Another example that OFAT is not arriving at the correct optimum in all cases, is demonstrated in Figure 254. Here we can vary the temperature and pressure to influence the yield of a reaction. OFAT will lead to a yield of 92%, while DOE lead to an optimum yield of 95%.

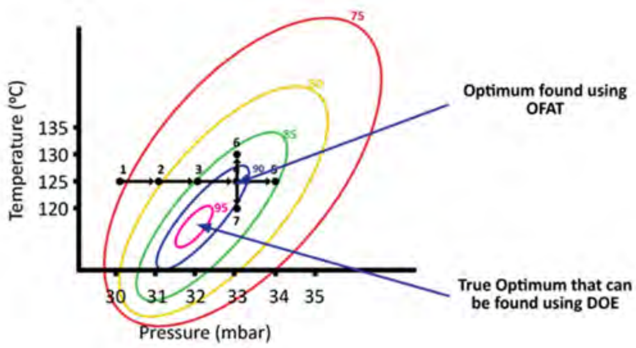


Figure 254 – OFAT versus DOE

Responses, Factors and Levels
DOE helps to really understand the investigated process. This will be achieved by determining the mathematical 'Transfer function' of the effect that multiple Factors have on the process Response. This includes the effect of Factor Interactions. Without DOE, interactions would remain undetected.

DOE allows you to vary Factor levels simultaneously, rather than one-at-a-time. This reduces the amount of trials that are needed to chart the complete Transfer function. This approach is very efficient in terms of time and cost. DOE determines which Factors have a significant influence on the Response and which Factors have not. DOE also determines the Factor settings that produce optimal process performance.

Assume you have two input variables (Factors A & B) that have an influence on the output (Response Y). Two variables give us four possible combinations, which form the corners of a 'Square plot'. The two Factor levels are displayed in coded values -1 and +1 (low and high).

This is what the Design matrix, to test all combinations, would look like:

Run	A	B	Y
1	-1	-1	y1
2	1	-1	y2
3	-1	1	y3
4	1	1	y4

Table 39 – Design matrix for Factors A and B

Let's assume 'Temperature' and 'Pressure' as Factors of influence on the Response 'Reaction Time'. Each combination (Run) has its own Response y_i.

Factor	Description	Low level	High level
A	Temperature	400°C	800°C
B	Pressure	1 bar	2 bar

Table 40 – Design matrix for Factors A and B

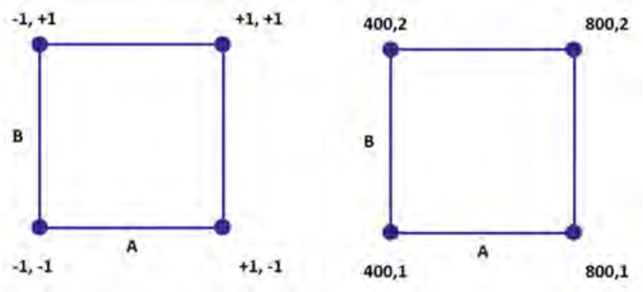
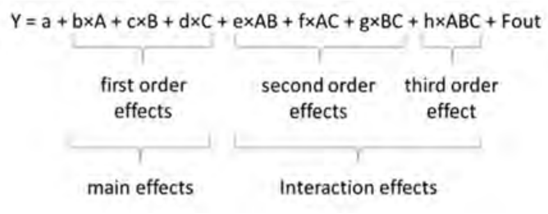


Figure 255 – Design matrix

Transfer function

A 'Transfer function' Y = f(X) is a mathematical representation and describes inputs and outputs of the 'Black box' model. Once quantified through Design of Experiments, the Transfer Function can be used to define and optimize the process.



Run Order

The Standard Order is the logical sequential order in which the design is composed or generated, while the Run Order is the sequence in which all of the experimental Runs are actually are conducted. When the Design is not randomized, the Run Order will be equal to the Standard Order. Normally the Design is randomized and the Run Order will be different to the Standard Order.

Randomization

To execute an experiment in a fully independent way, it is recommended to conduct the 'Runs' in random order. Randomization is used to reduce the effect of extraneous or uncontrollable conditions that can impact the results of an experiment. In Minitab the default setting of the randomization option is 'enabled'.

Balanced Designs

A Balanced Design is an experimental design within which all cells (combination of settings) have an equal number of measurements.

Residual Error

Performing a Residual Analysis is always the final step in a Design of Experiments. A Residual is the difference between the predicted value (fitted value) and the observed value (actual value). If we are to rely upon the model produced by the analysis then we need to see that the residuals are normally distributed, mutually independent and also independent of any factor/ level combination. When the Residual Error is exactly 0, the model fits the data perfectly.

Main Effects

The effect of a Factor is called the Main effect, which is the average response at level +1 minus the average response at level -1. The Main effects can be calculated as:

Main effect of A:

$$\frac{y_2 + y_4}{2} - \frac{y_1 + y_3}{2} = \frac{1}{2}(-y_1 + y_2 - y_3 + y_4)$$

Main effect of B:

$$\frac{y_3 + y_4}{2} - \frac{y_1 + y_2}{2} = \frac{1}{2}(-y_1 - y_2 + y_3 + y_4)$$

We will perform the test. As mentioned, this requires four test runs. Assume we have found the responses in Table 41:

Run	A Temp [°C]	B Pressure [bar]	Y Time [s]
1	400	1	2
2	800	1	4
3	400	2	1
4	800	2	6

Table 41 – Response matrix for Factors A and B

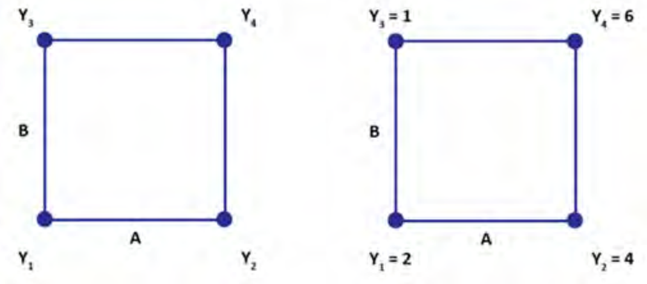


Figure 256 – Design matrix

The two Main effects can be calculated with the following equation:

Main Effect of Temperature:

$$\frac{y_2 + y_4}{2} - \frac{y_1 + y_3}{2} = \frac{1}{2}(-y_1 + y_2 - y_3 + y_4)$$

$$\frac{4+6}{2} - \frac{2+1}{2} = \frac{1}{2}(-2+4-1+6) = 3.5$$

Main Effect of Pressure:

$$\frac{y_3 + y_4}{2} - \frac{y_1 + y_2}{2} = \frac{1}{2}(-y_1 - y_2 + y_3 + y_4)$$

$$\frac{1+6}{2} - \frac{2+4}{2} = \frac{1}{2}(-2-4+1+6) = 0.5$$

The Main effects can be plotted as demonstrated in Figure 257.

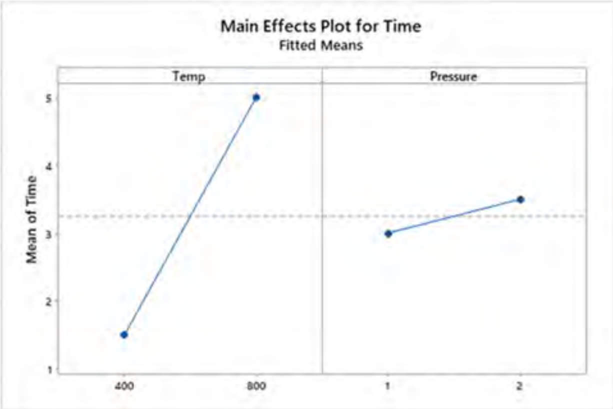


Figure 257 – Main Effects plot

Interaction Effects

As mentioned the big advantage of DOE above OFAT is the ability to determine the Interaction effect. The Interaction is the combined effect of A and B on the Response Y, which is called the A x B Interaction. The Interaction effect can be calculated as half the difference in effect of A on both B levels:

$$\frac{1}{2}\left[A_{B_{high}} - A_{B_{low}}\right] = \frac{1}{2}\left[(y_4 - y_3) - (y_2 - y_1)\right] = \frac{1}{2}(+y_1 - y_2 - y_3 + y_4)$$

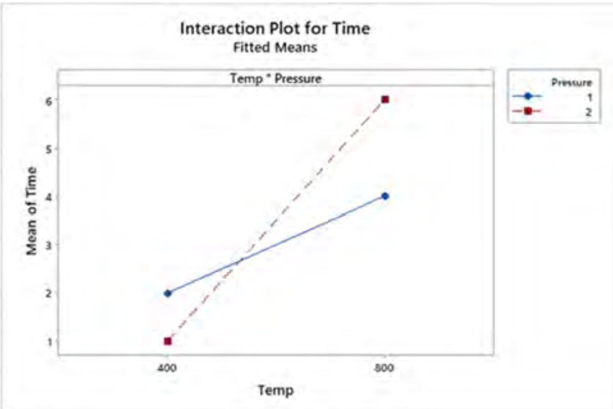


Figure 258 – Interaction Effects plot

Like Main effects, the interactions can be plotted. An interaction plot always shows two lines. Figure 259 demonstrates a number of examples. If the two lines are parallel – as shown in the middle graph – there is no interaction present. However, if the slopes of both lines are different to each other, as shown in the other four graphs, then there is interaction. A statistical analysis of the data should determine if this interaction is statistically significant.

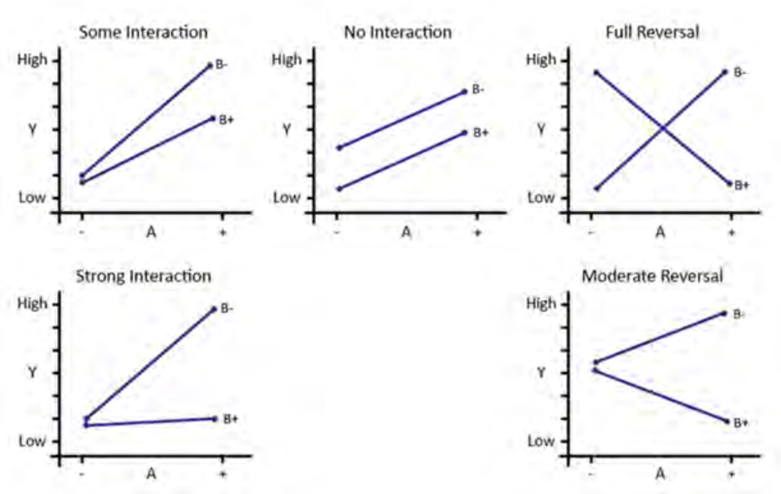


Figure 259 – Different types of interaction effects

Let's take a closer look at the interaction plot on the left side at the bottom. When Factor A is Low (A-), a change in B, from Low (B-) to High (B+), does not have much effect on the response Y. However, when Factor A is High (A+), the same change of Factor B from Low to High has a huge effect on the response Y. In other words, the effect that Factor B has depends on the setting of Factor A. This means that Factor A and B demonstrate an 'Interaction effect'.

Replicates and Repetitions

Replicates are multiple measurements taken from different experimental runs but at the same Factor settings (level). Repetitions, on the other hand, are multiple measurements taken during the same experimental run. The benefit of replicates is that they will increase the precision of your model. In some cases, including replicates or repetitions in the experiment may be costly. Consider the benefits of replicates or repetitions against the additional costs.

The choice between adding Replications or Repetitions into your experiment depends on how the data is collected. Treat as Replicates when different setups of the equipment are done within each Factor combination. Treat as Repetitions when all measurements were made without modifying the setup of the equipment within each Factor combination. It is necessary to randomize the design when repetitions are included to ensure that all experimental variability is taken into account. It is therefore important to instruct the person that is executing the experiment that replicate measurements should not be replaced by repetitions instead.

Curvature

The lines in Figure 260, demonstrates a linear interaction effect: 'the higher (or lower) you get, the better (or worse) . . .’ Most processes are not linear though. If we assume linearity, we will miss the process optimum as we only test on two levels (Low and High). By adding Centerpoints to the Design we can detect Curvature in the response model.

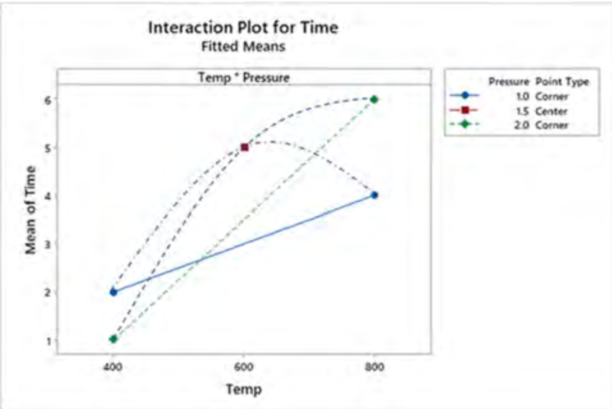


Figure 260 – Non-linearity (Curvature)

Centerpoints

Centerpoints are design points with the level of each Factor chosen halfway between the Low and High. Often the current process setting is chosen as Centerpoint. The more Centerpoints, the better the estimate of the Residual Error. Keep in mind that Centerpoints cannot be added if all Factors are of the type ‘Text’. At least one of the Factors needs to be type ‘Numeric’ in order to add a Centerpoint. If there is a combination of Text and Numeric Factors, there is no true center to the Design. These points are so-called ‘Pseudo Centerpoints’ in the Factorial Design.

Adding Repetitions, Replicates or Centerpoints to the Design will give you a better estimate of the Residual Error, because you add degrees of freedom. You may find it difficult to choose between adding Repetitions, Replicates or Centerpoints to the Design. Often you cannot do all of them, as experimenting costs time, resources and money. Adding Centerpoints is preferred above adding Replicates.

Planning experiments

Experiments cost time, resources and money. This is especially the case when (proto type) samples need to be prepared or acquired and when valuable production time and equipment is needed. Good preparation of experiments is important to receive the appropriate output. The following steps can be used:

1. Define problem and objective.
2. Define Response (Output Variables) & Specifications.
3. Identify potential Factors of influence (Input Variables).
4. Reduce the number of potential Factors of influence.
5. Identify and control Noise Factors.
6. Define Factor levels.
7. Determine how to measure Factors and Responses.
8. Determine how to collect data.
9. Plan and assign Resources.

Special attention should be paid to the preparation of samples. If measures can be taken prior to the test, like dimensions of the components used, it should be done before beginning the experiment. All parts and components need to be numbered and ordered. Operators should be instructed properly and equipment recipes should be prepared as well.

During the test it is very important to follow the plan properly and not to mix up parts or measurements. It is also important that unintended changes during the experiment and any other type of noise or disturbance are prevented. It is therefore recommended to ensure that you have a few separate samples available to set up equipment, to instruct operators and to fine-tune the recipe before the actual experiment is started.

7.8.2 Two-level Full Factorial experiments

Full Factorial experiments are DOEs and their designs consist of two or more Factors. Each of these Factors has discrete possible values or 'Levels'. These levels can take all possible values but with 2^k Full Factorial designs, each Factor has only two levels, Low and High, as we have demonstrated in the previous pages. This is the reason that we call these types of design 2^k Full Factorials, where 'k' is the number of Factors and 2^k the number of test runs. The corner points of the design are also called 'Cube points'.

In the previous example we demonstrated the Design matrix, showing 2^2 = 4 runs. You can imagine what would happen if we extend our design with additional Factors. Using the same approach we now can construct a Design matrix for a 2^3 Full Factorial design that contains 8 runs (Table 42) and a 2^4 Full Factorial design that contains 16 runs (Table 43).

Run	A	B	C	AB	AC	BC	ABC
1	-1	-1	-1	1	1	1	-1
2	1	-1	-1	-1	-1	1	1
3	-1	1	-1	-1	1	-1	1
4	1	1	-1	1	-1	-1	-1
5	-1	-1	1	1	-1	-1	1
6	1	-1	1	-1	1	-1	-1
7	-1	1	1	-1	-1	1	-1
8	1	1	1	1	1	1	1

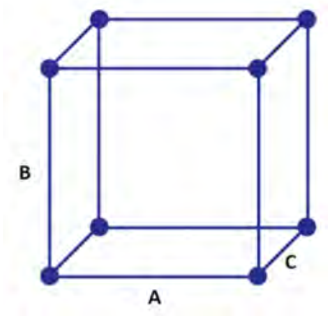


Table 42 – Design matrix Full Factorial 8 runs

Setting up and analyzing a Design of Experiment with two Factors can be done using Excel. However, if the number of Factors increases, it will become pretty complicated. Fortunately, we can use software like Minitab to support us in applying Design of Experiments for a large number of experiments. Nevertheless, you should still keep in mind that the number of runs will equal 2^k. So, pay attention when choosing the Factors that will be used in the design of the experiment.

A Contrast is a column in a Design with an equal number of '-1' and '+1' (sum = 0). The number of (orthogonal) Contrasts equals the number of Factor combinations (Runs) minus one. This is also the number of columns in a Factorial Design Table. For example, the Factorial Design Table 42 shows an experiment with eight Runs. This Design has seven Contrasts and seven columns. The Factorial Design Table 43 shows an experiment with sixteen Runs. This Design has fifteen Contrasts and fifteen columns.

Run	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	ABCD
1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1
3	-1	1	-1	-1	-1	1	1	-1	-1	1	1	1	-1	1	-1
4	1	1	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1	1	1
5	-1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	1	-1
6	1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	1	1
7	-1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	-1	1
8	1	1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	-1	-1
9	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	1	1	-1
10	1	-1	-1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1
11	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1
12	1	1	-1	1	1	-1	1	-1	1	-1	-1	1	-1	-1	-1
13	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	-1	1
14	1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	1	-1	-1
15	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	-1
16	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 43 – Design matrix Full Factorial 16 runs

Example: We would like to investigate the amount of Wear (in seconds) for a drilling process. Three potential factors of influence have been identified, the lubrication of the process, the speed of the drill and the material of the drill.

Step 1 – Create Factorial Design:
(Minitab: Stat > DOE > Factorial > Create Factorial Design)

The first step is to select a design type. A Full Factorial design is selected. We will use 2 replicates. Then we need to define the Factors and values for Low and High. The output of this step is a Worksheet that contains the test runs. When using 2 replicates there are 16 runs instead of 8. This is shown in Table 44.

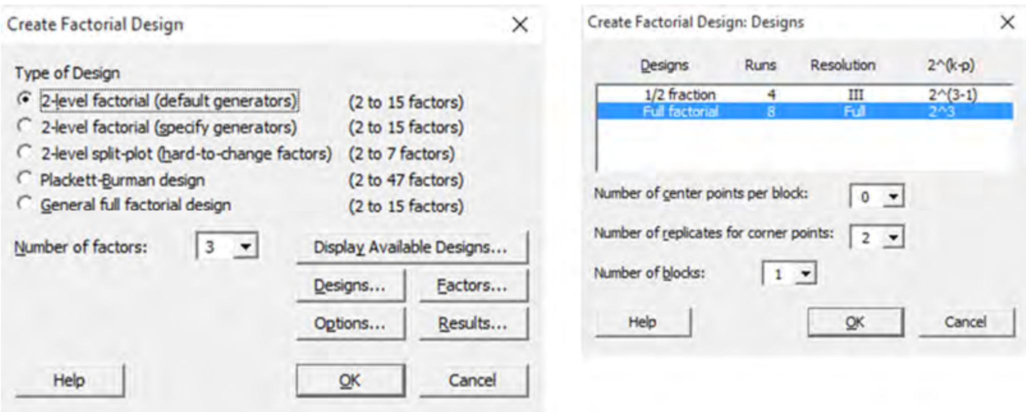


Figure 261 – Create Factorial Design

Step 2 – Perform the test:
The next step is to perform the test. We will add an additional column to the end of the Worksheet and fill in the test results for the response Y, 'Wear'.

Run	X1: Lube	X2: Speed	X3: Material	Y: Wear [s]
1	No	100	A	71
2	Yes	100	A	61
3	No	150	A	90
4	Yes	150	A	82
5	No	100	B	68
6	Yes	100	B	61
7	No	150	B	87
8	Yes	150	B	80
9	No	100	A	61
10	Yes	100	A	50
11	No	150	A	89
12	Yes	150	A	83
13	No	100	B	59
14	Yes	100	B	51
15	No	150	B	85
16	Yes	150	B	78

Table 44 – Full Factorial Design matrix and Response Y

Step 3 – Analyze Factorial Design:
(Minitab: Stat > DOE > Factorial > Analyze Factorial Design)

Now we will instruct Minitab to analyze the results. The analysis that Minitab performs is based on ANOVA. The Output session Window shows the output. The first *p*-value indicates that the regression model is significant. Also, the *R*-sq value is high: 99.50%. The ANOVA Table also indicates that the linear terms Lube and Speed are significant, and that Material is not significant. It also shows that the 2-Way interaction (Lube x Speed) is significant. N.B.: The *F*-value and *p*-value can only be calculated when Replicates are applied.

Factorial Regression: Wear versus Lube; Speed; Mat

```
Analysis of Variance
Source                  DF   Adj SS   Adj MS  F-Value  P-Value
Model                    7  1491.75   213.11   426.21    0.000
  Linear                 3  1444.75   481.58   963.17    0.000
    Lube                 1  1260.25  1260.25  2520.50    0.000
    Speed                1   182.25   182.25   364.50    0.000
    Mat                  1     2.25     2.25     4.50    0.067
  2-Way Interactions     3    44.75    14.92    29.83    0.000
    Lube*Speed           1    42.25    42.25    84.50    0.000
    Lube*Mat             1     2.25     2.25     4.50    0.067
    Speed*Mat            1     0.25     0.25     0.50    0.500
  3-Way Interactions     1     2.25     2.25     4.50    0.067
    Lube*Speed*Mat       1     2.25     2.25     4.50    0.067
Error                    8     4.00     0.50
Total                   15  1495.75
Model Summary
       S    R-sq  R-sq(adj)  R-sq(pred)
0.707107  99.73%     99.50%      98.93%
```

The degrees of freedom *df* in the ANOVA Table can be defined as follows:

• Total *df*: number of runs – 1	16 – 1 = 15
• For each Main Factor *df*: number of levels – 1	(2–1) = 1
• Model: Linear *df*: sum of the main factor degrees of freedom:	1 + 1 + 1 = 3
• For each 2-way interaction Factor *df*: product of number of levels – 1 for each main factor	(2–1) x (2-1) = 1
• Model: 2-Way Interactions *df* sum of the interaction's degrees of freedom:	1 + 1 + 1 = 3
• Model: 3-Way Interactions Factor *df*: product of degrees of freedom for all main factors	(2–1) x (2–1) x (2–1) = 1
• Model *df*: main factor *df* + 2-way interaction *df* + 3-way interaction *df*	3 + 3 + 1 = 7
• Error *df*: total *df* – model *df*	15 – 7 = 8

Step 4 – Remove terms that are not significant
In order to determine the 'Transfer function' or 'Regression equation' for this model, it is necessary to remove all terms that are not significant. This can be done manually or it can be reduced automatically using an algorithmic procedure, such as stepwise regression. Start the reduction by removing all insignificant terms one-by-one starting with the highest order of interaction term (in this example 'ABC') and then analyze the model again. Continue reducing all insignificant terms in the model one-by-one, starting from the lowest insignificant term. This process should be repeated until only statistically significant terms remain.

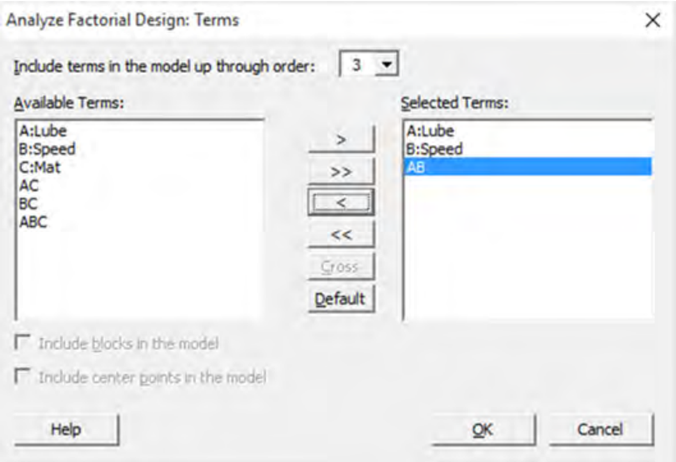


Figure 262 – Remove terms that are not significant

The Transfer function generated by Minitab, after removing all insignificant terms is:

```
Regression Equation in Uncoded Units
Wear = 85.50 + 17.00 Lube - 0.13500 Speed - 0.06500 Lube*Speed
```

This equation demonstrates the coefficients for the two linear Main effects, Lube and Speed, and the coefficient of the 2-way interaction of Lube and Speed. The response equation can be used to calculate the outcome for a certain Lube and Speed. For example, when applying lubrication (1) and a speed of 100, the outcome is:

$$Wear = 85.5 + 17.0 - 0.135 \times 100 - 0.065 \times 100 = 82.5$$

Step 5 – Factorial plots:
(Minitab: Stat > DOE > Factorial > Factorial Plots)

We will now create the plots for the significant Main effects and Interaction effect to visualize the data (Figure 263 and Figure 264).

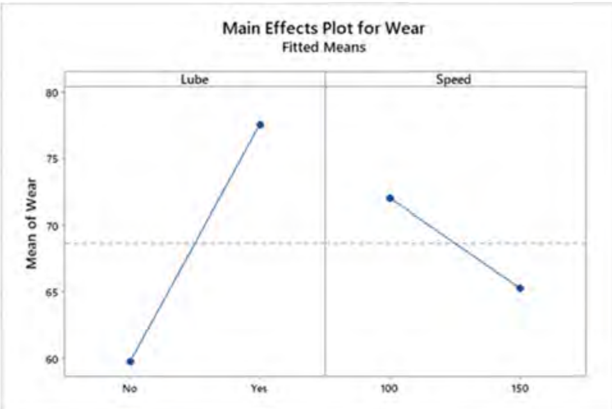


Figure 263 – Main effect plot

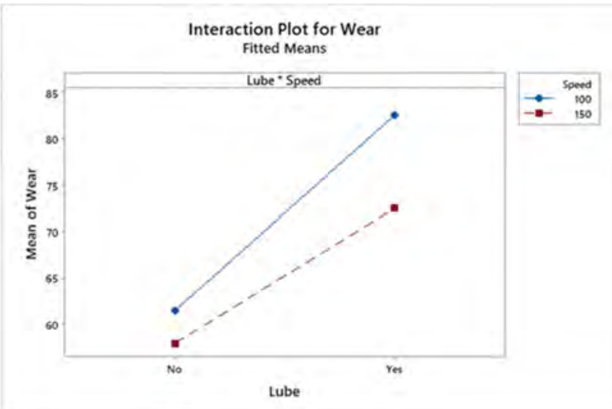


Figure 264 – Interaction effect plot

Step 6 – Residual Analysis:
(Minitab: Stat > DOE > Factorial > Analyze Factorial Design > Graphs)

The final step is the residual analysis to check that the ANOVA prerequisites are met. The residuals should be normally distributed and have equal variances. The top left graph shows that the normal distribution assumption cannot be rejected; the top right graph demonstrates equal variances. So, the prerequisites are met.

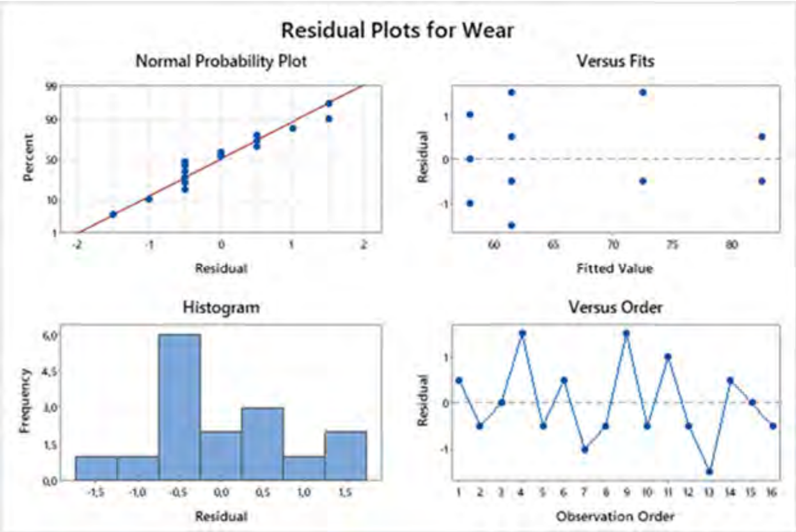


Figure 265 – Residual plots

Covariate
(Minitab: Stat > DOE > Factorial > Analyze Factorial Design > Covariates)

In Design of Experiments, the Covariate is typically used to analyze the effect of a measurable, but not controllable, noise Factor. A Covariate can be added to the model to reduce the Noise variation. For example, the ambient temperature can be added as a Covariate to a Design that takes several hours. The temperature is difficult to control, but it can be measured easily.

Blocking
(Minitab: Stat > DOE > Factorial > Create Factorial Design > Designs)

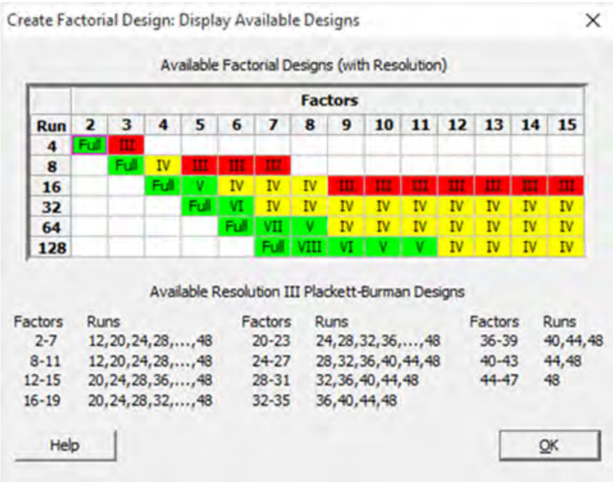
Although each measurement should be performed under identical conditions, this is not always possible. Factors that have an impact on the experiment and that can be determined, but not controlled, can be used as a 'Block' in the experiment. Observations done under the same experimental conditions are in the same Block. Examples of Factors that can be handled as a 'Block' include: material batches, different teams or shifts, maintenance or set up and different equipment. Minitab will try to put Blocks in the different Replicates.

7.8.3 Two-level Fractional Factorial experiments

As the number of Factors in a 2^k design increases, the number of runs necessary to perform a Full Factorial design increases exponentially. Fractional Factorial designs are a good choice when resources are limited or the number of Factors in the design is large, because they need fewer runs than the Full Factorial designs. Fractional Factorial designs are Design of Experiments consisting of a carefully chosen subset (fraction) of experimental runs of the Full Factorial design.

Resolution
(Minitab: Stat > DOE > Factorial > Create Factorial Design > Display Available Designs)

An important property of Fractional Factorial designs is the 'Resolution'. This is the ability to separate Main effects and low-order Interactions from one another. Minitab offers the resolutions as is shown in Figure 266 while designing a Fractional Factorial design. The most important Fractional designs are those of Resolution 'III', 'IV' and 'V'. Resolution 'III' designs should only be used for screening experiments in sequential experiments when you start with many input factors.


Create Factorial Design: Display Available Designs

Available Factorial Designs (with Resolution)

Run	Factors 2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	Full	III												
8		Full	IV	III	III	III								
16			Full	V	IV	IV	IV	III	III	III	III	III	III	III
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Available Resolution III Plackett-Burman Designs

Factors	Runs	Factors	Runs	Factors	Runs
2-7	12,20,24,28,...,48	20-23	24,28,32,36,...,48	36-39	40,44,48
8-11	12,20,24,28,...,48	24-27	28,32,36,40,44,48	40-43	44,48
12-15	20,24,28,36,...,48	28-31	32,36,40,44,48	44-47	48
16-19	20,24,28,32,...,48	32-35	36,40,44,48		

Figure 266 – Create Fractional Factorial Design

Resolution III

- No main effects are aliased with any other main effect.
- Main effects are aliased with 2-Factor interactions.
- 2-Factor interactions are aliased with each other. I + II = III

Resolution IV

- No main effects are aliased with any other main effect or 2-Factor interactions.
- 2-Factor interactions are aliased with each other. II + II = IV

Resolution V

- No main effects or 2-Factor interactions are aliased with any other main effect or 2-Factor interactions.
- 2-Factor interactions are aliased with 3-Factor interactions. II + III = V

We will explain this with an example by extending the Full Factorial case from the former section with two additional factors, 'Speed' and 'Power'. If we would apply a Full Factorial, we would need $2^4 = 16$ experimental runs. However, applying a Fractional Factorial design with resolution IV, results in 8 experimental runs. This is shown in Figure 266.

Run	X_1: Temperature [°C]	X_2: Pressure [bar]	X_3: Speed [rpm]	X_4: Power [W]	Y: Time [s]
1	400	1	2,000	500	…
2	800	1	2,000	750	…
3	400	2	2,000	750	…
4	800	2	2,000	500	…
5	400	1	2,500	750	…
6	800	1	2,500	500	…
7	400	2	2,500	500	…
8	800	2	2,500	750	…

Table 45 – Fractional Factorial Design matrix

Confounding / Aliasing
Less runs also means less information. Confounding occurs within a Fractional Factorial design when one or more effects cannot be estimated separately. This happens when the effect of one Factor is combined with that of another. We then say that both Factors are 'Confounded' with each other. This means that the effects of both Factors on the response cannot be separated in the results of the experiment. In Fractional Factorial designs, all Main effects are 'Confounded' with Interactions and Interactions are 'Confounded' with other Interactions. Aliasing and Confounding are synonyms. Both are so-called 'Lost Interactions' in a Design of Experiment. The lower the Resolution of a Design, the higher the aliasing issue. In our example the Alias Structure is:

I + ABCD
A + BCD
B + ACD
C + ABD
D + ABC
AB + CD
AC + BD
AD + BC

Confounding does not necessarily mean that there is a problem, as usually the higher order interactions have very little effect on the response. In most cases it is adequate to only investigate the 2-way interactions and neglect the higher-order interactions. Fractional Factorial design is very powerful, but requires caution in drawing conclusions. Aliasing is also a critical feature of Plackett-Burman and Taguchi Designs. These designs are outside the scope of this book though.

Folding
(Minitab: Stat > DOE > Factorial > Create Factorial Design > Options)

Suppose we want to separate the confounded effects of the AB and the CD interactions. 'Folding' is a way to reduce confounding. Folding the design will add additional tests to the design that will separate confounded interactions. Fractional Factorials can be 'Folded over' a certain Main Effect. 'Folding over' is just changing all signs of the original fraction and doing the experiment again. After this, the number of runs is doubled. A Block is added to the Design.

Run	A	B	C
1	-1	-1	1
2	1	-1	-1
3	-1	1	-1
4	1	1	1

Table 46 – Design matrix

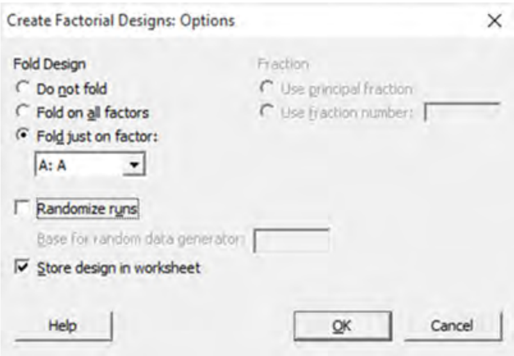


Figure 267 – Fold Design

Run	Block	A	B	C
1	1	-1	-1	1
2	1	1	-1	-1
3	1	-1	1	-1
4	1	1	1	1
5	2	1	1	-1
6	2	-1	1	1
7	2	1	-1	1
8	2	-1	-1	-1

Table 47 – Design after Folding over

7.8.4 Response Surface Modeling

Response Surface Modeling
(Minitab: Stat > DOE > Response Surface > Create Response Surface Design)

Full and Fractional Factorial designs are an efficient way of experimentation to lead us in the right direction, but if curvature is present, we need a higher order model to describe and analyze the not linear response. ‘Response Surface Modeling’ (RSM) is usually applied after Design Of Experiments with Centerpoints has shown the existence of curvature. So, usually there are no more than 2-4 factors left. RSM involves two efficient design families: ‘Central Composite Designs’ (CCD) and ‘Box-Behnken Designs’.

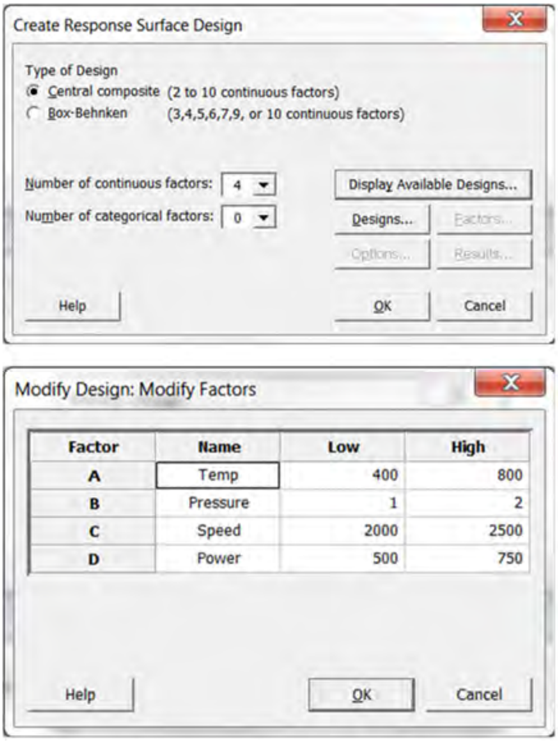


Figure 268 – Create Response Surface Design

Central Composite Design
(Minitab: … Response Surface > Create Response Surface Design > Display Available Designs)

The 'Central Composite Design' (CCD) is the most commonly used response surface experimental design. It consists of a Factorial or Fractional Factorial design with Centerpoints, augmented with a group of axial (or star) points that allow estimation of curvature.

Central Composite Designs are useful in sequential experiments. Each new design can build on previous Factorial experiments by adding axial points and/or Centerpoints. For example, you can first run an experiment based on a Factorial design to determine the significant factors of influence and then extend this design to a CCD by adding a Centerpoint and four axial points, as is shown in Figure 269. You can then use this response surface design to determine the optimal settings for the factors of influence. A Central Composite Design makes it possible to increase the efficiency in estimating the quadratic terms of a 2nd order model.

- The Cube points: -1 and 1
- The Axial points or Star points: – α and α
- The Centerpoint: 0,0

The α value, along with the number of Centerpoints determines whether a design can be orthogonally blocked and is rotatable.

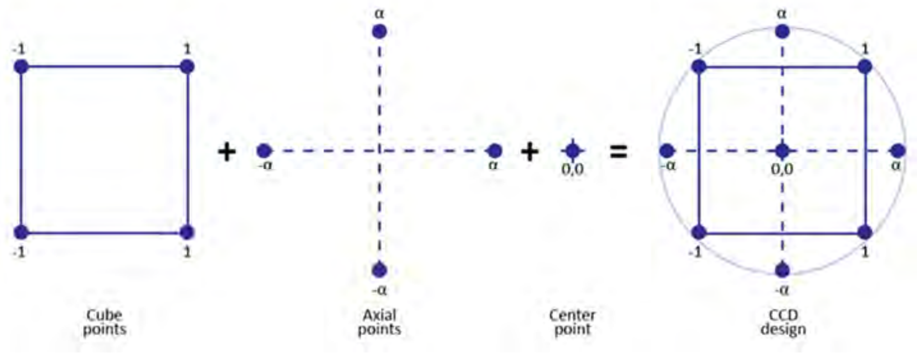


Figure 269 – Central Composite Design

The full CCD design for four factors and one Centerpoint contains 31 runs. Table 48 demonstrates the 12th till the 20th run. You can clearly see the difference in factor settings when comparing the Fractional Factorial design matrix and the CCD design matrix.

Run	X_1: Temperature [°C]	X_2: Pressure [bar]	X_3: Speed [rpm]	X_4: Power [W]	Y: Time [s]
…	…	…	…	…	…
12	800	2	2,000	750	…
13	400	1	2,500	750	…
14	800	1	2,500	750	…
15	400	2	2,500	750	…
16	800	2	2,500	750	…
17	200	1.5	2,250	625	…
18	1,000	1.5	2,250	625	…
19	600	0.5	2,250	625	…
20	600	2.5	2,250	625	…
…	…	…	…	…	…

Table 48 – CCD Design matrix

When designing a CCD, you have to take care that all points fall within the operational area. For instance, in our example it should be possible to set the Temperature at 1,000 and the Pressure at 1.5. If this is not possible, or settings fall outside the operational area, a CCD design might not be the best solution. If you want to stay within the safe area of the process, a Box-Behnken design is more suitable.

Box-Behnken Design

(Minitab: … Response Surface > Create Response Surface Design > Display Available Designs)

Box-Behnken designs are used when no sequential experiments are needed. That means you want to do only one experiment. Box-Behnken designs make efficient estimation of the 1st and 2nd order coefficients possible. Figure 270 demonstrates a 3-factor Box-Behnken design. The points on the ribs represent the runs of the experiment.

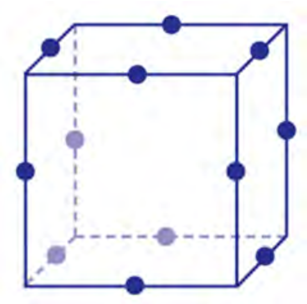


Figure 270 – Box-Behnken Design

Box-Behnken designs are very useful if you want to stay within the safe area of the process, because the points on the ribs remain exactly inside the circle of the square design or the sphere of the cube design. In this way, you are sure all runs can be carried out safely. Box-Behnken designs ensure that not all factors are set on their extreme levels at the same time. Because Box-Behnken designs have less design points, they are less expensive than Central Composite Designs with the same number of factors.

Contour plot

(Minitab: Stat > DOE > Response Surface > Analyze Response Surface Design)

A RSM can be analyzed and then be used to generate a contour plot for a single pair of variables, while certain fixed values can be entered for the remaining independent variables.

(Minitab: Stat > DOE > Response Surface > Contour Plot)

Figure 271 demonstrates a contour plot for the two variables Temperature and Pressure for a given value of 2,250 for Speed and 625 for Power. The contour plot shows that the minimum value for the response 'Time' is found in the center. The crosshairs can be used to determine accurate values for the independent variables Temperature, Pressure and dependent variable Time. An alternative for the Contour plot is the Surface plot, which works in a similar way. The Contour plot and Surface plot are visualization tools and not really analytical tools. They cannot be used for more than two variables.

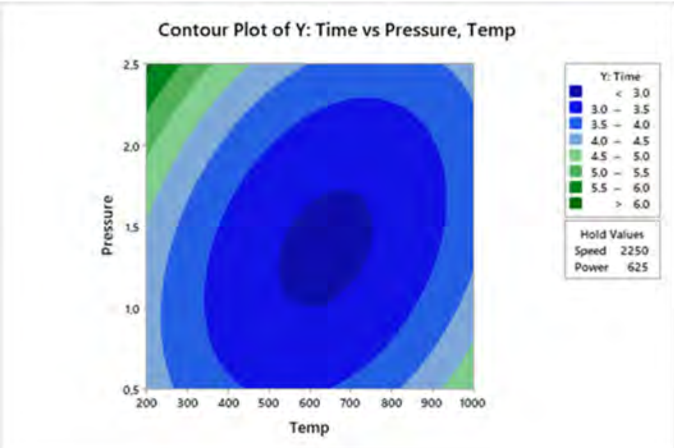


Figure 271 – Contour plot

Response Optimizer
(Minitab: Stat > DOE > Response Surface > Response Optimizer)

An alternative tool that can be used to find the optimal setting of variables is the Response Optimizer. The Response Optimizer identifies the combination of input variable settings that jointly optimize the response. It can be used for one single response, but it can also be used to optimize a set of responses using 'Composite Desirability' (D). Composite Desirability evaluates how the settings optimize a set of responses overall using weighting factors. The optimization plot offers interactively changing input variable settings, to perform sensitivity analyses and possibly improve upon the initial solution.

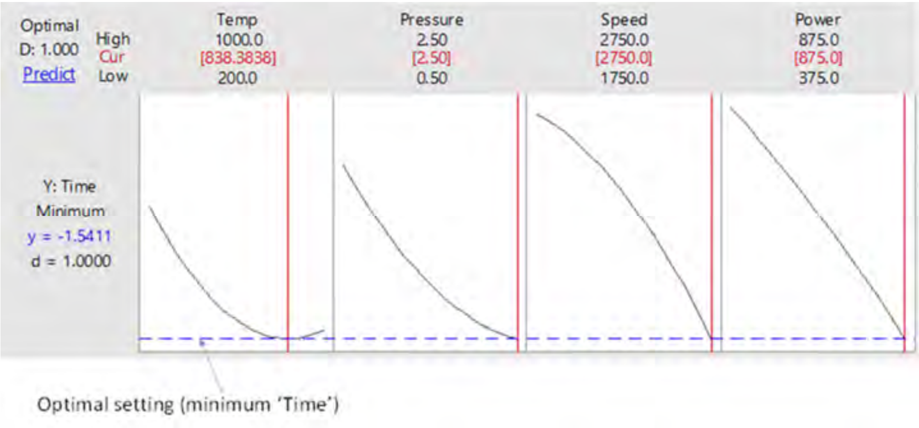


Figure 272 – Response optimizer

Evolutionary Operation
'Evolutionary Operation' (EVOP) is a process-optimization technique. The initial idea is that the operational process should not be disrupted by experimentation. EVOP consists of a number of sequential experiments, each with a very small change to the standard process settings. Because these deviations in the process settings are not large enough to result in non-conforming products, experimentation can be done during normal production. At the same time, the settings are large enough to collect data that will help to analyze the process and to define the optimum process setting. EVOP was introduced by G.E.P. Box and K.B. Wilson in the 1950s.

"Essentially, all models are wrong, but some are useful."

George E.P. Box

The 'Path of Steepest Ascent' (or the Path of Steepest Descent) defines the most likely path of increasing (or decreasing) response values based on a Full or Fractional Factorial design. Figure 273 demonstrates the Path of Steepest Ascent whereby the experimenter proceeds sequentially along the path of maximum decrease in the predicted response (from a cost of '92' to the lower value of '80'). This process is repeated until the optimum settings of the input variables are found. At all times, the intention of EVOP is that products produced during the experiments are still meeting their specification and that they can be delivered to the next process step or sold to the customer. The lines of equal response (Figure 273) are called 'Equi-response lines', 'Equipotentials' or 'Isotherms', which are similar to altitude lines on a map.

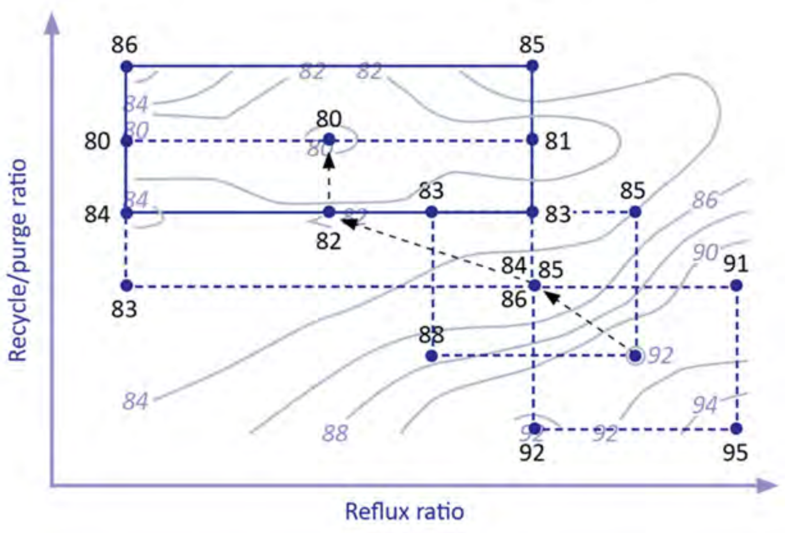


Figure 273 – Path of Steepest Ascent

The 'Step size' is determined by the experimenter based on process knowledge or other practical considerations. Experiments are conducted along the Path of Steepest Ascent (or Decent) until the optimum is reached or the output is sufficiently good. Then a new first-order model may be fit and a new path is determined. If necessary, replicates at the Centerpoint can be used to estimate the experimental error and to allow for checking the adequacy of the first-order model. This procedure of evolutionary experimentation continues until the experimenter will arrive in the vicinity of the optimum. This is usually indicated by lack of fit of the first-order model. At that time, additional experiments should be conducted based on a second-order model to obtain a more precise estimate of the optimum.

Example: John is Six Sigma Black Belt, working in a petrochemical plant. He is asked to reduce the cost per ton for a certain product. It is not an option to stop production to do experiments. Therefore, he chooses the EVOP method, taking samples from regular production batches without disturbing production.

John investigates the influence of two input variables: the 'Reflux ratio' of the distillation column and the 'Recycle/Purge ratio'. His first experiment is a Two-level Full Factorial with one Centerpoint. John sets the Centerpoint at the current process setting (6.9; 7.75). John also takes into account a 'Step size' of '0.2' for the Reflux ratio and 0.5 for the Recycle/Purge ration. He then defines the four Cube points of the Factorial design relative to the Centerpoint. Because the levels of the input variables are very close to each other and the Centerpoint, the measurements are repeated several times in a cycle (not randomized to prevent mistakes):

Example of a cycle: (0,0) => (1,1) => (1,-1) => (-1,-1) => (-1,1)

After several cycles the effects of the settings on the output can be quantified accurately. The experiment results in the responses (Costs per Ton), listed in the following Table and in Figure 274.

Reflux Ratio X_1	Recycle/Purge Ratio X_2	Costs per Ton Y
6.7	7.5	92
7.1	7.5	95
6.7	8.0	86
7.1	8.0	91
6.9	7.75	92

Table 49 – Costs per Ton

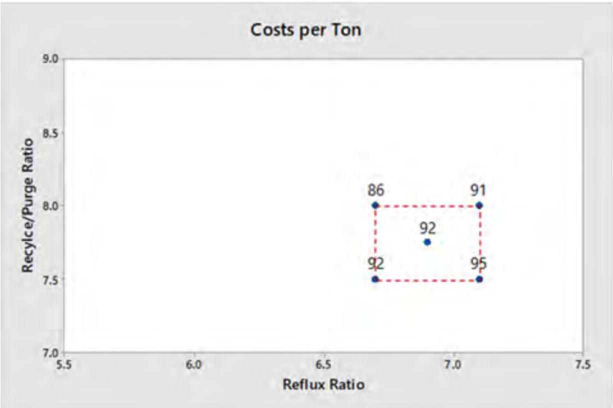


Figure 274 – EVOP first phase

For the first test we will only take into account the first order terms of the Transfer function, so we will not include any interactions. The Transfer function then is as follows:
(using x_1 for the Reflux ratio, x_2 for the Recycle/Purge ratio and 'y' for the response 'Costs per Ton'):

```
Regression Equation in Coded Units

Y = 91.2 + 2.0 X1 - 2.5 X2
```

To define the Centerpoint for the next experiment, John decides to use the path of the steepest ascent. To move away from the design center along the path of steepest ascent, John would move 2.0 coded units in the x_1 direction for every -2.5 coded units in the x_2 direction. The path of steepest ascent passes through the point (6.9; 7.75) and has a slope of -2,5/2,0 (in coded units).

Equation (in coded units): $\Delta x_2 = (-2.5/2.0) \cdot \Delta x_1$

To lower the cost John has to reduce the Reflux ratio and decides to use -0.2 as the basic Step size for the Reflux ratio (in coded units: -1), and uses the following equation to define the settings for the Centerpoint of the next experiment:

$$\Delta x_2 = (-2.5/2.0) \cdot \Delta x_1 = -1.25 \times -1 = 1.25 \text{ (in coded units)}$$

$$\Delta x_2 = 1.25 \times 0.25 = 0.31 \text{ (in uncoded units)}$$

The Centerpoint for the next experiment is set at $x_1 = 6.9 – 0.2 = 6.7$ and $x_2 = 7.75 + 0.31 = 8.06$ (for practical purposes this is rounded off to 8.0 for the next experiments).

John continues to compute points along the path of steepest ascent, until he observes an increase of the response 'Costs per Ton'. After four experiments, John observes that he is relatively close to the optimum point. The next step is to use a model that incorporates curvature to approximate the response. In most cases, a second-order model with Centerpoint is adequate. This fitted model can be used to find the optimum set of operating conditions for the x's and to characterize the nature of the Response surface.

Control

7.9 Statistical Process Control (SPC)

The objective of the Control phase is that solutions that have been implemented to improve the process performance will be embedded in the process and organization, to assure that improvements will sustain after the project has been closed. This is a critical element to make an improvement project successful.

In the previous chapters we already explained a number of tools and techniques that can be used in the Control phase of a Six Sigma breakthrough project. All the techniques that we discussed in CIMM Level-I, II and III such as 5S, Standardized Work, Poka Yoke and the Control plan are very useful for process control. Figure 162 presents an overview of all the techniques that can be used in this phase. One tool listed here has not been explained yet, which is 'Statistical Process Control' (SPC). This is an important tool for sustaining improvements made at all levels.

The concept of 'Statistical Process Control' (SPC) was introduced by Walter Shewhart in 1924 at Western Electric. Before that, products were tested and removed if defective. Shewhart used simple control charts for early detection of process variation. Deming was a student of Walter Shewhart. In the 1930s, SPC became popular in the UK and later in the United States. After World War II, Japan started the 'Quality revolution' and Deming taught them to use SPC to control and improve their processes [4.].

SPC helps to detect special cause variation. Special cause variation is variation that cannot be explained by common causes alone. Often this type of variation is very large when compared to common cause variation and is caused by problems that can be identified and often eliminated. SPC can be applied in different phases of a project and also at different maturity levels. SPC can be applied in the Define phase to identify new improvement opportunities. It can be applied in the Analyze phase to investigate the influence of certain Factors on the response. SPC is also an important tool in the Control phase at the end of an improvement project to ensure that results will be sustained.

A mistake that is often made by using SPC charts is that the control limits on the SPC chart are used as specification limits. Although control limits and specification limits might look similar, there is a difference. Specification limits are set by the customer. Products outside these limits do not meet requirements and are not OK. Process Control limits, however, are calculated with the data from the process itself, normally based on a Capability study. Control limits are set in such a way that almost all of the process variation falls within these limits, but there is no relation to the specification limits. Knowing whether the process meets customer demands is extremely important indeed, but specification limits do not belong on a Control chart. If they are, the Control chart simply becomes an inspection tool and can no longer be considered a Control chart. The Control limits are normally set at ± 3 Sigma, which is equivalent to 99.73% of the data falling within the two Control limits.

7.9.1 Control charts

There are different SPC charts available. The chart you need to apply depends on the type of data that you want to analyze or control. In the following sections we will review four charts that are most commonly used:

- Xbar-R chart: for monitoring the means and ranges of subgroups of continuous data.
- I-MR chart: for monitoring individual data points and moving ranges for continuous data.
- P & NP chart: for monitoring defective items (Attribute data).
- C & U chart: for monitoring the number of defects per unit (Attribute data).

The Flow chart shown in Figure 275 can be applied to select the proper SPC chart.

"Failure to use control charts to analyze data
is one of the best ways known to mankind
to increase costs, Waste effort and lower morale."

Dr. Donald J. Wheeler

At the end of this section we will also briefly discuss a number of special Control charts:

- Individuals Moving Range and Range (I-MR-R/S) chart.
- Moving Average (MA) chart.
- Exponential Weighted Moving Average (EWMA) chart.
- Cumulative Sum (CUSUM) chart.
- Zone chart.
- Short-run SPC chart.

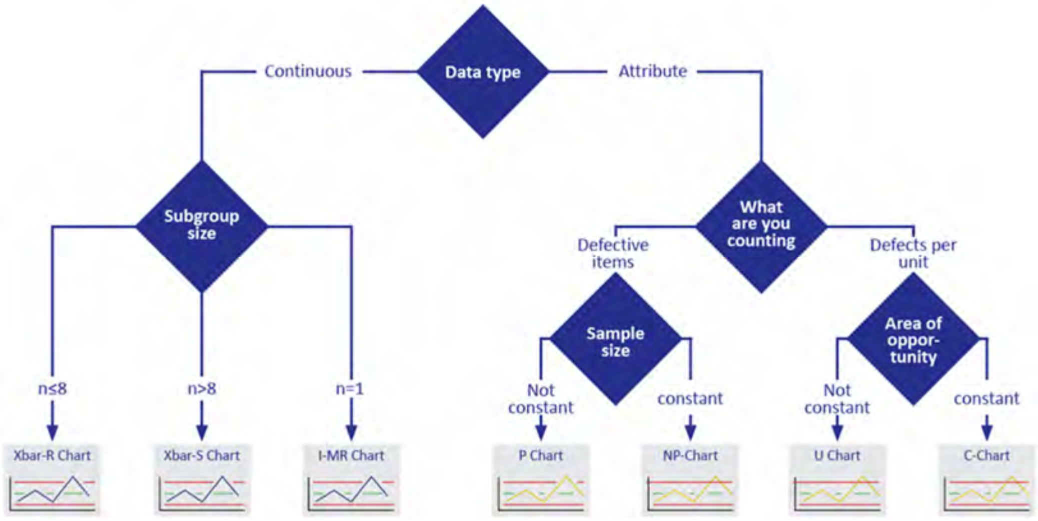


Figure 275 – Choosing the proper SPC chart

Xbar-R chart
(Minitab: Stat > Control Charts > Variables Charts for Subgroups > Xbar-R)

The Xbar-R chart is a Control chart for subgroup averages. This type of chart is used for monitoring process variation and for detecting the presence of special causes, by collecting subgroups from the process at regular intervals. The Xbar-R chart is used when at each of these intervals the subgroup size is small. The upper part of the chart represents the process Mean, while the lower part represents the process variation approximated by the subgroup Range.

- Xbar or $\bar{X}$ is the Mean of the measurements x_1 .. x_i in the subgroup.
- Xbar-bar or $\bar{\bar{X}}$ is the Mean of all 'Xbars' and is drawn as the centerline.
- R is the Range of the measurements x_1 .. x_i in the subgroup.

The Lower and Upper Control limits (LCL and UCL respectively) can be calculated using the following equations. The values for A_2, D_2, D_3, D_4 and d_2 can be found in Appendix D.

- Xbar: $CL_X = \bar{\bar{X}}$ $\quad LCL_X = \bar{\bar{X}} - A_2 \cdot \bar{R}$ and $UCL_X = \bar{\bar{X}} + A_2 \cdot \bar{R}$
- Range: $CL_R = \bar{R}$ $\quad LCL_R = D_3 \cdot \bar{R}$ and $UCL_R = D_4 \cdot \bar{R}$

Example: A Control chart is used to control the weight of a box. The average weight is 9.948, the subgroup sample size is 2, the average range $\bar{R}$ is 0.345.

- $LCL_X = 9.948 - 1.880 \times 0.345 = 9.299$ and $UCL_X = 9.948 + 1.880 \times 0.345 = 10.598$
- $LCL_R = 0 \times 0.345 = 0$ and $UCL_R = 3.267 \times 0.345 = 1.128$

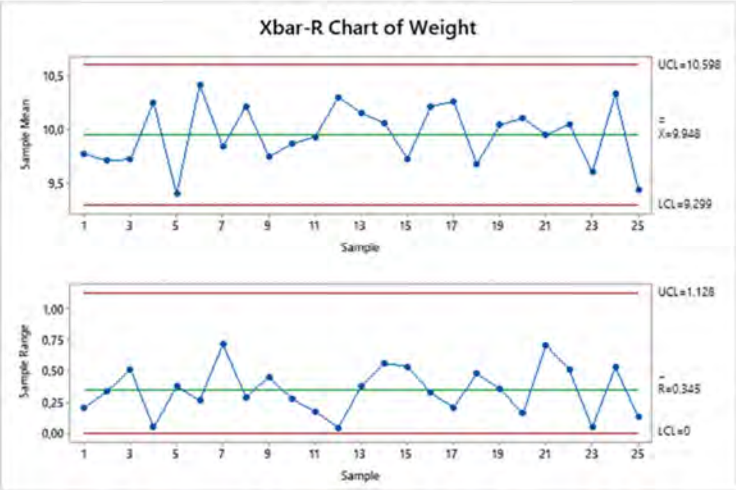


Figure 276 – Xbar-R chart of Weight

When μ and σ are known the following equations can be used:

- Xbar: $CL_\mu = \mu$ $\quad LCL_\mu = \mu - \frac{3\sigma}{\sqrt{n}}$ and $UCL_\mu = \mu + \frac{3\sigma}{\sqrt{n}}$
- Range: $CL_\sigma = d_2 \cdot \sigma$ $\quad LCL_\sigma = D_1 \cdot \sigma$ and $UCL_\sigma = D_2 \cdot \sigma$

Xbar-S chart

(Minitab: Stat > Control Charts > Variables Charts for Subgroups > Xbar-S)

The Xbar-R chart should be used for sample sizes up to *n* = 8. If the sample size is higher, it is better to switch to the Xbar-S chart. The Xbar-S chart plots the standard deviation ‘s’ of a subgroup instead of the range R.

The Control limits can be calculated using the following equations. The values for A_3, B_3, B_4, B_5, B_6 and c_4 can be found in Appendix D. Minitab will define the Control limits automatically, based on the process data.

- Xbar: $CL_X = \bar{\bar{X}}$ $\quad LCL_X = \bar{\bar{X}} - A_3 \cdot \bar{s}\ and\ UCL_X = \bar{\bar{X}} + A_3 \cdot \bar{s}$
- S: $CL_s = \bar{s}$ $\quad LCL_s = B_3 \cdot \bar{s}\ and\ UCL_s = B_4 \cdot \bar{s}$

Example: When we use the same data for Weight as in the example for the Xbar-R chart, while we take a subgroup samples size of 10 (instead of 2), we should use the Xbar-S chart. The average standard deviation $\bar{s}$ is 0.335.

- $LCL_X = 9.948 - 0.975 \times 0.335 = 9.622\ and\ UCL_X = 9.948 + 0.975 \times 0.335 = 10.275$
- $LCL_s = 0.284 \times 0.335 = 0.095\ and\ UCL_s = 1.716 \times 0.335 = 0.574$

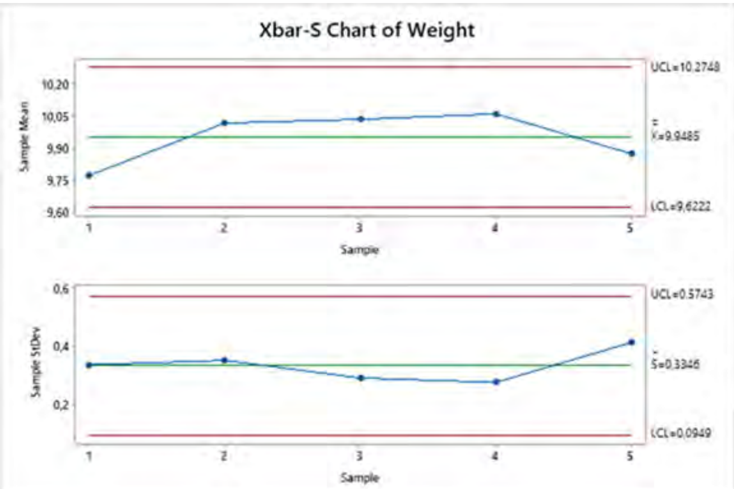


Figure 277 – Xbar-S chart of Weight

When μ and σ are known the following equations can be used:

- Xbar: $CL_\mu = \mu$ $\quad LCL_\mu = \mu - \frac{3\sigma}{\sqrt{n}}\ and\ UCL_\mu = \mu + \frac{3\sigma}{\sqrt{n}}$
- S: $CL_\sigma = c_4 \cdot \sigma$ $\quad LCL_\sigma = B_5 \cdot \sigma\ and\ UCL_\sigma = B_6 \cdot \sigma$

I-MR chart

(Minitab: Stat > Control Charts > Variables Charts for Individuals > I-MR)

The I-MR chart (Individual / Moving-Range chart) is a type of Control chart used to monitor individual measurements from a process. This chart is used if each sample that is taken from the process consists of one unit (one measurement) only. This means the subgroup size = 1. This type of chart is used to monitor the center and spread of a process and to detect special cause variation.

Like the Xbar-R chart, this chart consists of two parts. The upper part of the chart represents the process mean. The lower part represents the process variation, approximated by the sample 'moving range'.

- 'I' is the measurement of an individual sample.
- 'MR' is the Moving Range that is used to monitor the variation, by plotting the Range of the last *n* consecutive observations. Mostly *n* = 2.

We will not review the equations that are used to calculate the Control limits, as most SPC applications and software like Minitab will do this for you.

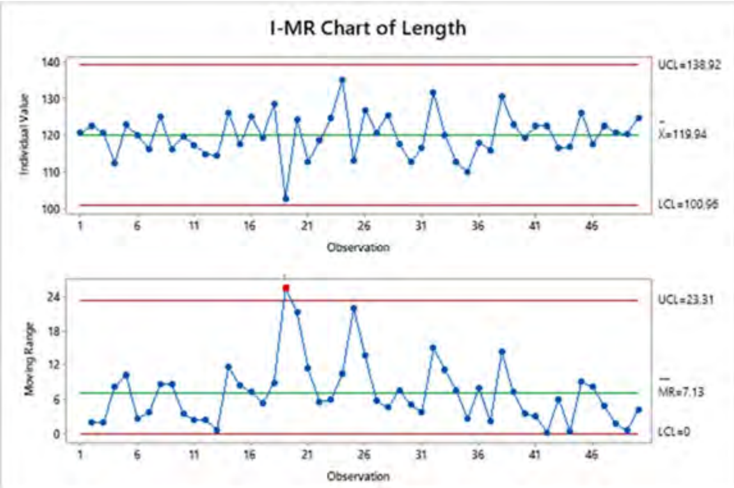


Figure 278 – Example of I-MR chart

P chart & NP chart
(Minitab: Stat > Control Charts > Attributes Charts > P)

P charts and NP charts are applied to track the proportion defectives and detects the presence of special causes. The data to construct the charts are assumed to come from a Binomial distribution with parameters *n* and *p*. The P chart is the most widely used Attributes control chart. While each unit may have many quality characteristics that can be evaluated, the unit itself is always considered as either conforming or nonconforming.

- P chart: Plots proportions of defective products in test samples (subgroups).
  This chart should be used when the samples vary in size and you count defectives.
- NP chart: Plots numbers of defective products in test samples.
  This chart should be used when all samples are the same size and you count defectives.

Example P chart: 28 shipments were delivered each with 1 or 2 crates. Every crate holds 250 peaches. The number of bruised peaches in the shipments has been counted. In total 11,500 peaches were inspected and 685 bruised peaches were found.

The control limits depend on the sample size, which is the number of peaches in a shipment. So, each observation is plotted against its own control limits.

- $CL = \bar{p} = \frac{11,500}{685} = 0.0596$
- $LCL_i = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}} = 0.0596 - 3\sqrt{\frac{0.0596(1-0.0596)}{500}} = 0.0278$
- $LCL_i = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}} = 0.0596 - 3\sqrt{\frac{0.0596(1-0.0596)}{250}} = 0.0147$
- $UCL_i = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}} = 0.0596 + 3\sqrt{\frac{0.0596(1-0.0596)}{500}} = 0.0913$
- $UCL_i = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}} = 0.0596 + 3\sqrt{\frac{0.0596(1-0.0596)}{250}} = 0.1045$

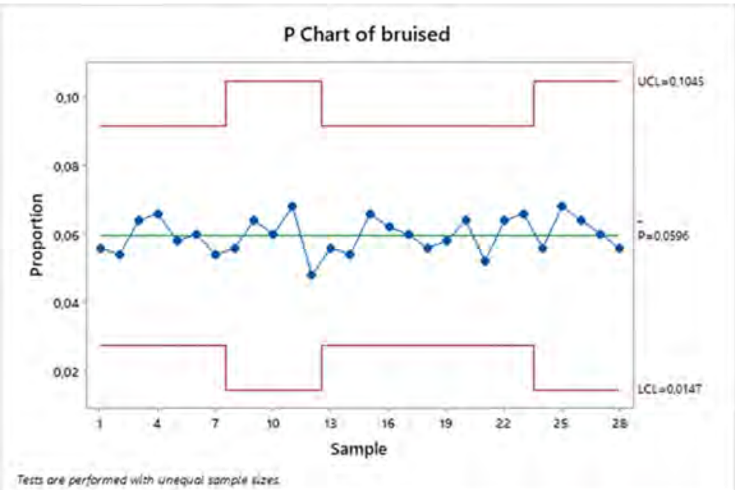


Figure 279 – P chart for bruised peaches

(Minitab: Stat > Control Charts > Attributes Charts > NP)

Example NP chart: During a period of 21 days, a subgroup *n* of 100 applications is checked for completeness. Each application is classified into one of two categories, complete or incomplete. The number of incomplete applications has been recorded. The average failure rate *p* appears to be 3.52%.

The control limits for the NP chart can be calculated using the following equation:

- $CL = n\bar{p} = 100 \times 0.0352 = 3.52$
- $LCL = n\bar{p} - 3\sqrt{n\bar{p}(1-\bar{p})} = 3.52 - 3\sqrt{3.52(1-0.0352)} = -2.01$
- $UCL = n\bar{p} + 3\sqrt{n\bar{p}(1-\bar{p})} = 3.52 + 3\sqrt{3.52(1-0.0352)} = 9.05$

Because a LCL lower than 0 is not possible for this process, we will set the LCL at 0.

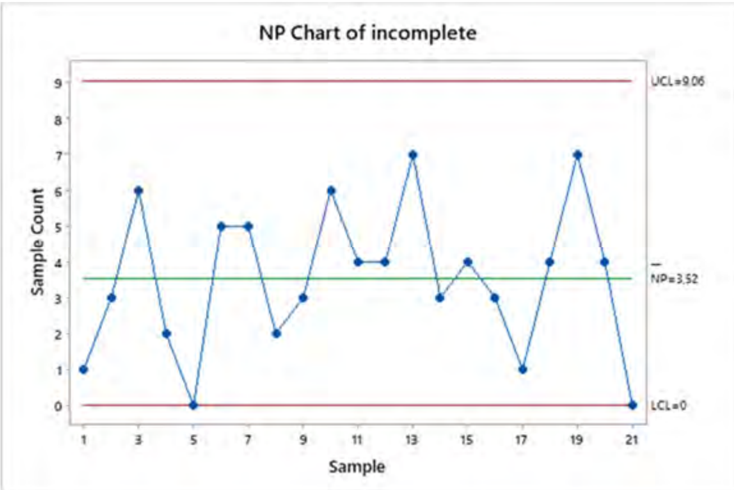


Figure 280 – NP chart for incomplete applications

C chart & U chart
(Minitab: Stat > Control Charts > Attributes Charts > U)

C charts and U charts are applied to track the number of events (e.g. defects) per unit and detects the presence of special causes. A unit can be a time period, an area, a volume, etc. The data to construct the charts are assumed to come from a Poisson distribution with parameter λ, which are both the mean and the variance. The center line of the chart is the average number of events, λ. Minitab also calculates the control limits using λ.

- C chart can be used to plot the number of events within a unit in a graph.
  C chart should be used when all units have the same size and you count events.
- U chart can be used to plot the number of events per unit within a sample in a graph.
  U chart should be used when the samples vary in size and you count events.

Example C chart:
Every day a fixed number of documents are checked and the number of defects is recorded. The sample count is the total number of defect each day.

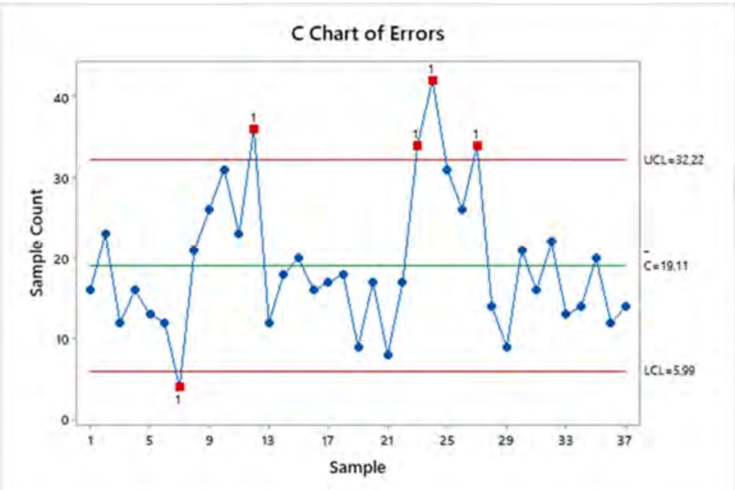


Figure 281 – C chart for number of defects in documents

(Minitab: Stat > Control Charts > Attributes Charts > U)

Example U chart:
The control chart in Figure 281 assumed a constant same sample size of 10 documents for each sample. Suppose it now turns out that the sample size was not 10 documents every day, but that on a particular day sometimes 10 and sometimes 20 documents were checked for spelling errors. Since the sample size is not constant, we cannot assume the same control limits. The control chart in Figure 282 shows the number of spelling errors per day and per document.

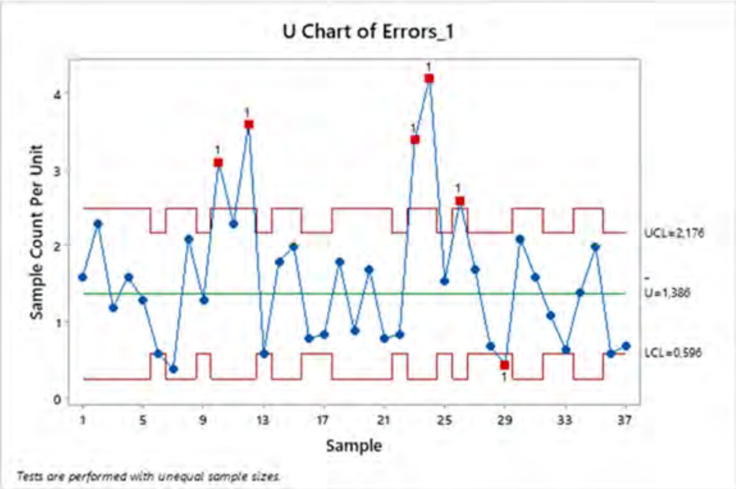


Figure 282 – U chart for number of defects in documents

Individuals Moving Range and R/S chart (I-MR-R/S) chart
(Minitab: Stat > Control Charts > Variables Charts for Subgroups > I-MR-R/S (Between/Within))

When you normally collect data in subgroups, the only source of within-subgroup variation is common-cause variation. However, if you also suspect variability in your sampling technique, you need to consider both between-subgroup and within-subgroup variation. In this case the I-MR-R/S chart is the best chart to use. The I-MR-R/S chart is able to monitor the mean of a process and the variation between and within subgroups. The I-MR-R/S chart consists of a three-way control chart, using both between-subgroup and within-subgroup variations. It consists of the following three elements (Source: Minitab):

- I-chart:
  To monitor the process Mean. The control limits of the I chart are calculated using the between-subgroup variation, but not the within-subgroup variation.
- MR chart:
  To monitor the Moving Range of the subgroup Mean. The MR chart only monitors the between-subgroup component of variation, not the within-subgroup variation.
- R chart or S chart:
  To monitor the R or S chart within-subgroup variation.

Example: Assume a thin coating layer has been applied to rolls of paper. You want to know if the thickness of the layer is correct and if the coating is evenly spread over the length of the rolls. To check this, you have measured 3 samples from each of 15 consecutive rolls. You can select an I-MR-R/S chart to monitor the uniformity of the coating on the rolls and if all rolls have been coated with the correct layer thickness.

Figure 283 demonstrates that 5 points are outside the control limits, while both range charts are in-control (both the between and within variations).

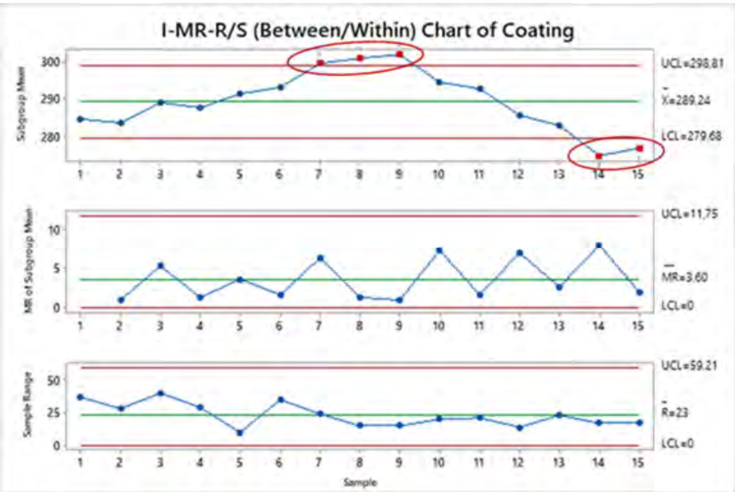


Figure 283 – I-MR-R/S chart for coating thickness

Moving Average chart

(Minitab: Stat > Control Charts > Time Weighted Charts > Moving Average)

The charts discussed so far are all variations of the 'Shewhart' charts. Shewhart charts are sensitive to detect large process shifts, but are not very suitable to detect small shifts of the process mean, as each new point depends only on one subgroup. In the following sections we will discuss a number of control charts that are suitable to detect small shifts because their control limits are closer to the centerline.

'Moving Average charts' are generally used for detecting small shifts in the process Mean. These types of charts are able to detect shifts of 0.5 to 2 sigma much faster than Shewhart charts with the same sample size. Moving Average charts, however, are less sensitive in detecting large shifts of the process Mean. Also, typical run tests cannot be used because of the dependence of data points.

Moving Average charts monitor the process location over time based on the average of the current subgroup and one or more prior subgroups. Many transactional processes and chemical processes are suitable to be controlled by Moving Average charts, as they are a control charts for variables data. These data are both quantitative and continuous in measurement, such as a measured dimension or time.

Example: Figure 284 demonstrates the Moving Average chart of a process with measurements taken every 15 minutes. A large sample is undesirable due to costs; however, we want to detect small shifts. It is therefore decided to use a Moving Average chart with a 'Moving Average' (MA) length of 5.

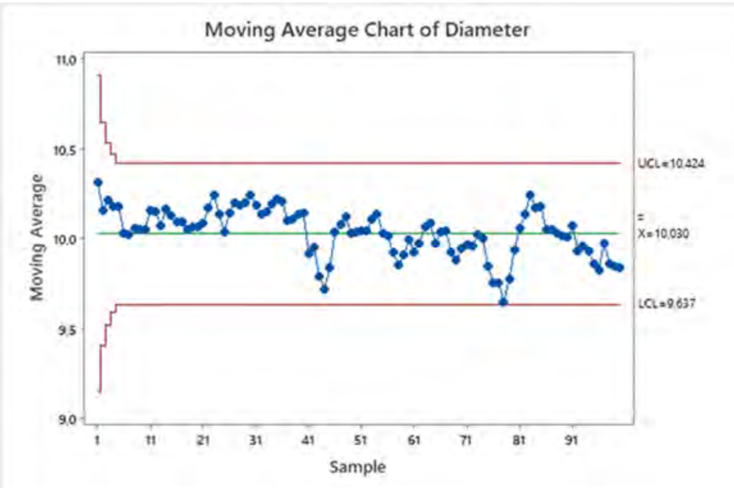


Figure 284 – Moving Average chart

EWMA chart

(Minitab: Stat > Control Charts > Time Weighted Charts > EWMA)

The 'Exponentially Weighted Moving Average' (EWMA) chart is a variant of the Moving Average chart. A weighting factor is chosen to determine how prior data points affect the Mean value compared to more recent ones. All historical values count, but they are weighted. The average is calculated with the last value weighing the most, the previous value weighing the least, etc. The last data point has the most weight and history fades out.

The chart is suitable to smoothen data to emphasize trends. Because the EWMA chart uses information from all samples, it detects much smaller process shifts than a regular Shewhart charts would.

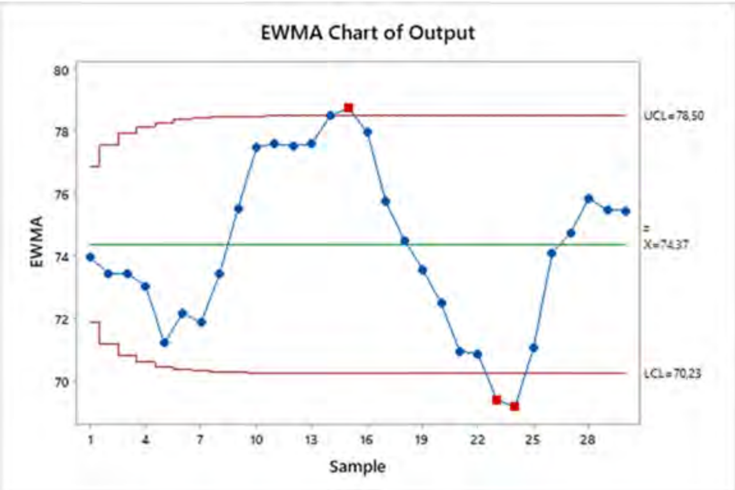


Figure 285 – Example of EWMA chart

CuSum chart

(Minitab: Stat > Control Charts > Time Weighted Charts > CUSUM)

A 'Cumulative Sum chart' (CuSum chart) is a control chart for variables data that plots the cumulative sum of the deviations from a certain target. Similar to the Moving Average and EWMA charts, the CuSum chart uses information from all prior samples and is able to detect small process shifts. CuSum charts are especially effective with a subgroup size of one. The CuSum is relatively slow to respond to large shifts. Also, special patterns are hard to see and analyze.

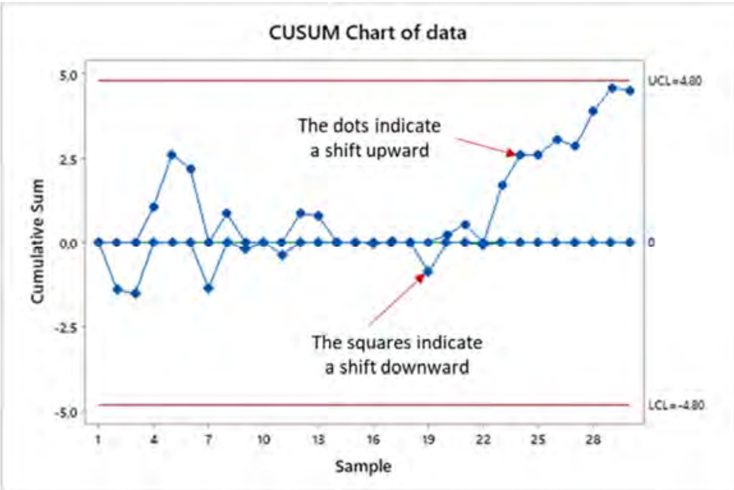


Figure 286 – Example of CuSum chart

Zone chart
(Minitab: Stat > Control Charts > Variables Charts for Subgroups > Zone)

The ‘Zone charts’ are more refined than EWMA and CuSum charts. The charts plot ‘Cumulative scores’ based on ‘Zones’ at 1, 2 and 3 standard deviations from the center line. The scores are cumulated when consecutive measurements are on the same side of the center line. If a measurement crosses the center line, the score is reset to zero.

A point is Out-of-Control if its score is greater than or equal to 8. In general, the ‘Average Run Length’ (ARL) necessary to detect an ‘Out-of-control’ state is smaller for Zone charts than for other types of Control charts.

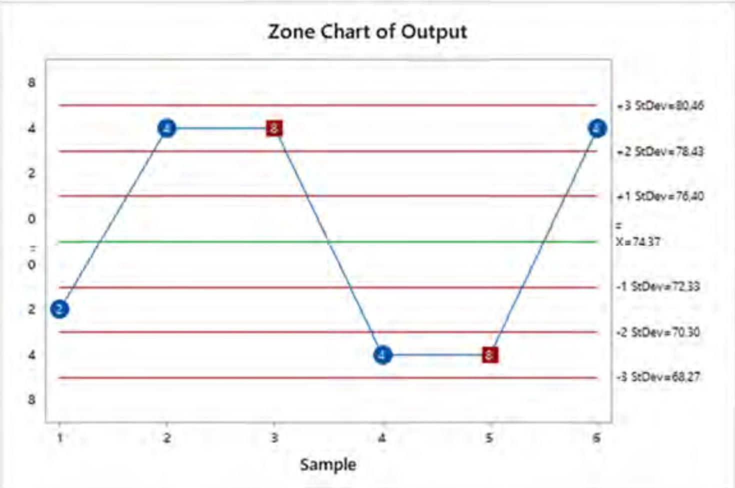


Figure 287 – Example of Zone chart

Short-run SPC chart

(Minitab: Stat > Control Charts > Variables Charts for Individuals > Z-MR)

Short Run SPC analysis combines data from multiple short runs of different products into one single control chart. Short Run is typically used to analyze processes when there is an insufficient amount of data available from a given product or service classification to adequately define the characteristics of each product. In Short-run SPC, common characteristics across different products are used in the same control chart. For instance, a Short run SPC chart can be used to control the time to resolve a customer complaint by the customer service department. The time may be influenced by the type of complaint, such as one week for incorrect item shipment versus five hours for incorrect billing. In both cases we are interested in the same statistical conclusion: “is the process in control to the nominal value?”.

The targets are transformed by subtracting the target from each measurement and when the standard deviation of the characteristic is different across the products, it is also divided by the historical or assumed standard deviation.

In equation: $y = x - \mu_i$ or $z = \frac{x-\mu_i}{\sigma_i}$ wherein μ_i is the target of product i and σ_i is the standard deviation of product i.

Example: A drilling process produces holes within different parts. The machine is reset for each part. The process is fundamentally the same for all part. The diameters of the parts are different though. The difference in the diameter prevents you from charting the different parts on the same chart using a standard I-MR chart. Figure 288 demonstrates how a combined Z-MR chart looks like for parts with different diameters and unequal sample sizes.

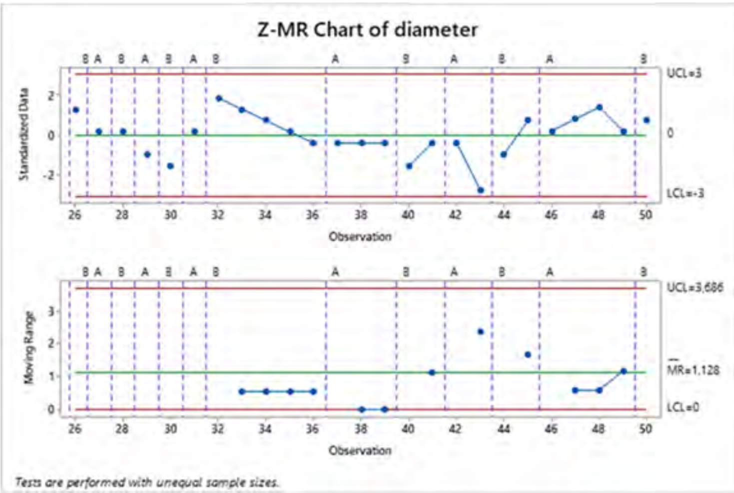


Figure 288 – Short Run Z-MR SPC chart for diameter

7.9.2 Tests for special causes

The purpose of using SPC charts is to identify ‘Out of Control situations’. Standards have been developed to help identify these events. We use the expression ‘Out of Control’ when one of the following eight rules is violated:

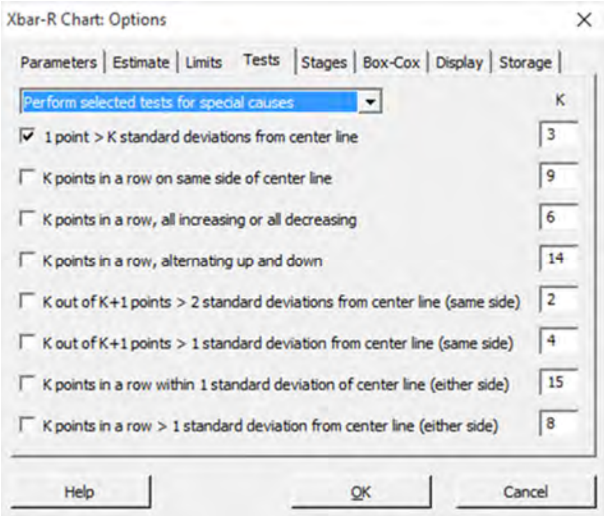


Figure 289 – Out of Control tests

Be aware: When only the first rule is active and the process is stable and centered, the probability of getting a false alarm is 0.27%. Every extra selected rule will increase this probability.

Example: The following Xbar-R chart failed three times on test 1.
(‘One point more than 3σ from center line’).

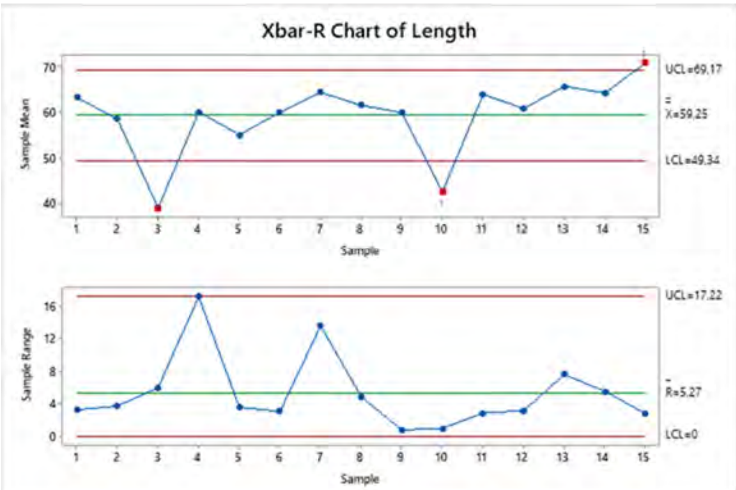
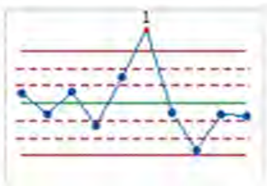
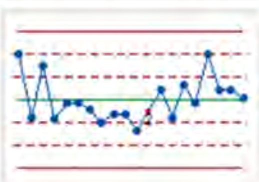
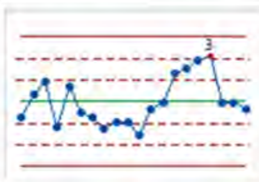
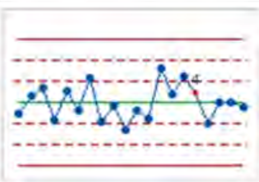


Figure 290 – Out of Control situation on test 1

Overview tests for special causes

This section provides a detailed overview of the eight tests that are included in Minitab. (Source: http://support.minitab.com).

Test 1: One point more than 3σ from center line	
	Test 1 evaluates the pattern of variation for stability. Test 1 provides the strongest evidence of lack of control. If small shifts in the process are of interest, Tests 2, 5, and 6 can be used to supplement Test 1 to create a control chart with greater sensitivity.
Test 2: Nine points in a row on the same side of the center line	
	Test 2 evaluates the pattern of variation for stability. If small shifts in the process are of concern, Test 2 can be used to supplement Test 1 to create a control chart with greater sensitivity.
Test 3: Six points in a row, all increasing or all decreasing	
	Test 3 detects a trend or continuous movement up or down. This test looks for long series of consecutive points without a change in direction.
Test 4: Fourteen points in a row, alternating up and down	
	Test 4 detects the presence of a systematic variable. The pattern of variation should be random, but when a point fails Test 4 it means that the pattern of variation is predictable.

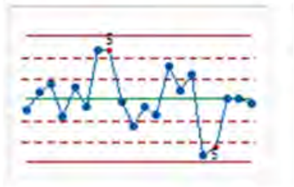
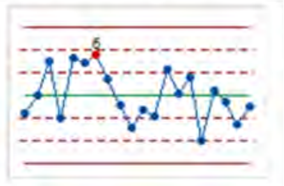
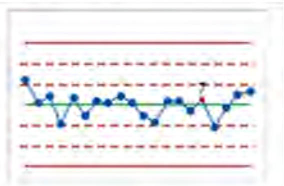
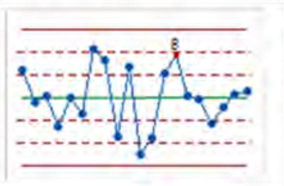
<table>
<tr><td colspan="2">Test 5: Two out of three points more than 2σ from the center line (same side)</td></tr>
<tr><td></td><td>Test 5 evaluates the pattern of variation for small shifts in the process.</td></tr>
<tr><td colspan="2">Test 6: Four out of five points more than 1σ from center line (same side)</td></tr>
<tr><td></td><td>Test 6 evaluates the pattern of variation for small shifts in the process.</td></tr>
<tr><td colspan="2">Test 7: Fifteen points in a row within 1σ of center line (either side)</td></tr>
<tr><td></td><td>Test 7 identifies a pattern of variation that is sometimes mistaken as a display of good control. This type of variation is called stratification and is characterized by points that follow the center line too closely.</td></tr>
<tr><td colspan="2">Test 8: Eight points in a row more than 1σ from center line (either side)</td></tr>
<tr><td></td><td>Test 8 detects a mixture pattern. A mixture pattern occurs when the points tend to avoid the center line and instead fall near the control limits.</td></tr>
</table>

Figure 291 – Overview of tests for special causes

CIMM assessment level IV – Creating capable processes

Level IV focuses on creating capable processes. Are your processes capable enough to deploy the next level? Perform the assessment below by scoring each statement with a rating of 1 to 5. A score of ‘1’ means that the statement does not reflect the situation within your organization; a score of ‘5’ means that the statement fully reflects the situation within your organization.

As there are 15 statements, the maximum score is 75. If you score less than 50 points, we recommend not to start the deployment of the next level, but to continue to deploy the current level first.

Process level IV – Creating capable processes (Capable)
4.1 – Lean Six Sigma organizational structure
There is a Lean Six Sigma organizational structure (Champions, YBs, OBs, GBs, BBs and MBB).
Breakthrough projects are in line with the long-term strategy (Hoshin Kanri).
The DMAIC approach is followed. Project progress is being monitored and Tollgates are scheduled.
Operational activities and continuous improvement activities are balanced.
Champions and (Master) Black Belts have an active role in training and coaching.
4.2 – Variation reduction (Six Sigma)
Key measurable characteristics of a product or process are presented in a CTQ flowdown.
Statistical methods are used to identify and verify the root causes of variation of the CTQ.
The influence of factors and interactions on the CTQ is optimized (e.g. DOE).
Quality is reported in terms of Process Capability (Cpk) and Process Performance (Ppk).
Controls and corresponding actions are in place to reduce and prevent 'Out of control situations'.
4.3 – Advanced analytics (Data Science)
There is active policy on collecting, processing and analyzing (big) data.
Systems are capable of exchanging data easily.
Accuracy, repeatability and reproducibility of measurement systems and data are fine.
The organization uses complex analytical software for data analysis.
There is a clear decision-making process based on data analysis.

Each person in the organization has a certain role and responsibility at creating capable processes. The assessment distinguishes responsibilities and behaviors for top management, middle management and people working at the shop floor. There are again 15 statements with a maximum score of 75.

People level IV – Creating capable processes (Expert)
4.1 – Lean Six Sigma organizational structure
Top management takes the role of Champion in Lean Six Sigma projects across departments.
Management takes the role of Champion in Lean Six Sigma projects within departments.
Management ensures that Belts work on the right projects and are given time and resources for this.
Employees develop themselves in Lean Six Sigma at different Belt levels.
Employees take the lead or participate in Lean Six Sigma projects.
4.2 – Variation reduction (Six Sigma)
Top management stimulates the company to make fact-based decisions.
Management guides the process of translating customer requirements into measurable targets.
Management makes decisions based on variation and trends instead of incidents.
Employees understand process data and are able to interpret deviations to the standard.
Employees understand that variation in the process result, is a consequence of diversity of the input.
4.3 – Advanced analytics (Data Science)
Top management understands the power of (big) data and stimulates the use of it.
Management ensures that data is accessible when needed and is analyzed in a proper way.
Management stimulates the application of advanced analytics.
Employees contribute how to register and monitor process data.
Employees are proactive in collecting, processing and analyzing data.

"If you keep your eye on the profit,
you're going to skimp on the product.
But if you focus on making really great products,
then the profits will follow."

— Steve Jobs —

8 CIMM level V – Creating future-proof processes (Sustained)

At the fifth level we will change from a reactive approach, where the focus was on improving the current situation, to a proactive approach, where we will focus on developing products and services that will meet customer expectations and will have no problems in production and delivery. This level is a combination of 'Product Lifecycle Management' (PLM) and 'Design for Six Sigma' (DfSS). Both PLM as DfSS describe a number of development aspects from managing descriptions and properties through risk management, development and reliability. Design for Six Sigma is regularly applied by people like Black Belts, reliability engineers and in some cases by Green Belts. It requires knowledge about all tools and techniques that are explained in the previous Chapters (CIMM Level-I to IV). On top of that, Level-V involves the following areas:

1. Product Lifecycle Management (PLM).
2. Design for Six Sigma (DfSS).
3. Risk Management (Design FMEA).
4. Reliability Engineering (RE).
5. Industry 4.0.

As each of the above-mentioned areas is very comprehensive, a detailed review of these areas will be outside the scope of this book. It will suffice for now to give a brief explanation of Product Lifecycle Management, Design for Six Sigma and Industry 4.0.

8.1 Product Lifecycle Management (PLM)

8.1.1 Product Lifecycle

The Product Lifecycle is the essential notion underlying the Product Lifecycle Management. The 'life' of a car for instance begins long before it first takes to the road, and continues beyond its disposal. From an engineering point of view, the lifecycle of a product or system comprises all stages that the product or system goes through from the initial idea to its end-of-life. The principal phases that a product or system typically runs through in its lifecycle are research, development (i.e., engineering design), manufacturing, distribution, usage, end-of-life, and revival by recycling, remanufacturing or reuse. When it comes to sustainable engineering, we always have to take into account the closed lifecycle, and therefore we have to go beyond the often-cited notion of 'Cradle to Grave' to 'Cradle to Cradle'. Recycling, remanufacturing and reuse are the most typical ways of closing the lifecycle, and they lead to what is often called the 'Circular economy'.

Over the recent years, increasingly stringent environmental legislation forces industry to make sustainability over the complete lifecycle, regardless if we are talking about a plastic bottle or a car. Sustainability has become one of the key criteria for any engineering decision. Lifecycle sustainability engineering is an integrated approach to ecological, social and economic impact issues:

- Ecologic factors:
  Permit and license compliance, bio-diversity management, emissions to air, water-chemical usage and discharges, etc.
- Economic factors:
  Consistent, profitable growth, risk management, total shareholder return, etc.
- Social factors:
  Respect for the individual, equal opportunity, diversity, human rights, etc.
- Socio-ecological factors:
  Health and safety, legislation and regulation, climate change, crisis management, etc.
- Eco-economy factors:
  Resource efficiency, energy efficiency, global energy issues, etc.
- Socio-economic factors:
  Employment, training and development, local economies and enterprise, social and community, sponsorships, etc.

The design process is essential for both PLM and the lifecycle of a product. Technological choices made at this time heavily define the cost of the product. About 80% of the manufacturing costs and 95% of the total cost of the product is actually determined in the early product design and development phases. The costs of these phases itself however, are relatively low (typically up to 20%). These costs start to rise strongly as soon as the product is actually manufactured. The second strong cost realization is during use and end-of-life. Likewise, in terms of environmental impact, the biggest contributor to the total lifecycle environmental impact of a vehicle is while it is out on the road and recycled. For a mid-sized vehicle, these phases account for almost three quarters of the total lifecycle CO_2 emissions.

'Life Cycle Assessment' or 'Life Cycle Analysis' (LCA) is a structured method which is applied in a lot of industrial sectors in order to assess the environmental impact of each single phase of a product's, system's or service's lifecycle depending on different design decisions. For example, one of the key criteria nowadays considered in automotive LCAs is recycling. The ultimate objective of OEMs (Original Equipment Manufacturers) is to achieve a 100% recyclability of their cars, and they are getting very close to this number.

Product Lifecycle Management

'Product Lifecycle Management' (PLM) is the process of managing the entire lifecycle of products. The product lifecycle is the collective stages that a product or service goes through from its conception and design through to its ultimate disposal. PLM objectives are to reduce 'Time To Market' (TTM), improve product quality, reduce development costs, identify potential sales opportunities and reduce environmental impacts at 'End-of-Life' (EOL). The process of PLM was initiated by American Motors Corporation (AMC) in 1985. The carmaker was looking for a way to improve its competitiveness by speeding up innovation and shorten the required time to market. The PLM structure can be used for manufacturing, software development and service provision.

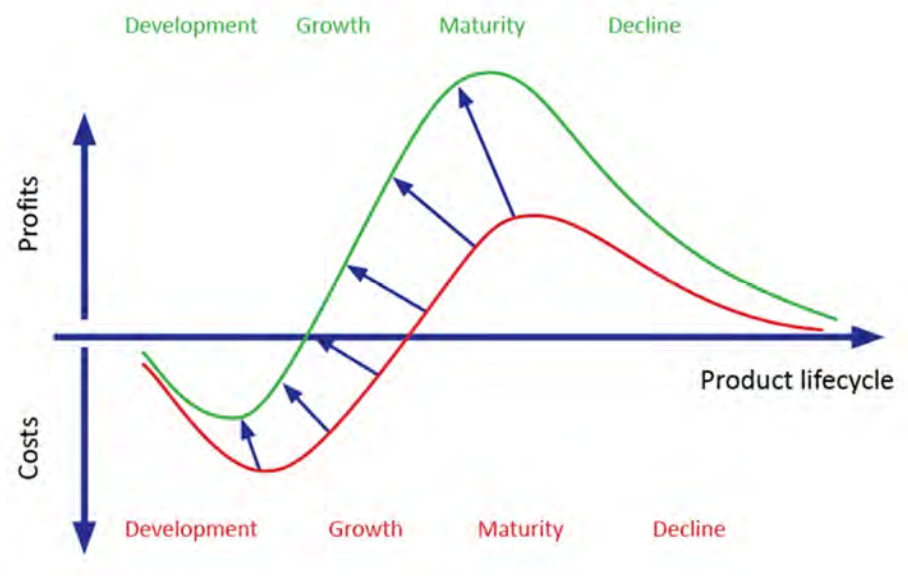


Figure 292 – Product Lifecycle stages

An early launch of new products and services will increase competitiveness and profitability. To accomplish PLM objectives, organizations must understand their customers, markets and competitors. PLM systems help organizations in coping with the increasing complexity and engineering challenges of developing new products. PLM systems incorporate all available information and data about the business, processes, development of new products and services and resources. PLM systems allow the management of this information throughout the entire lifecycle of a product, efficiently and cost-effectively, from ideation, design and manufacture, through to service and disposal. As such it provides an information backbone for companies and can be used to reduce the development process time and associated costs. As the objective is also to reduce the risks of failures during product launch, PLM works in close cooperation with Design for Six Sigma.

8.1.2 Innovation management

Innovation management is the management of processes associated to 'Innovation'. Innovation can be defined as something original and more effective and, as a consequence, new, that 'breaks into' the market or society (Frankelius, P., 2009). Innovation can be viewed as the application of better solutions that meet new requirements, unarticulated needs, or existing market needs (Maranville, S., 1992).

Innovation refers both to product and organizational innovation. In business and economics, innovation is the catalyst to growth. In the organizational context, innovation may be linked to positive changes in efficiency, productivity, quality, competitiveness and market share. However, recent research findings highlight the complementary role of organizational culture in enabling organizations to translate innovative activity into tangible performance improvements (Salge, T.O. & Vera, A., 2012). This is accomplished through more effective products, processes, services, technologies, or ideas that are readily available to markets, governments and society.

Invention is the embodiment of something better and, as a consequence, new. While both invention and innovation have "uniqueness" implications, innovation is related to acceptance in society, profitability and market performance expectation. An improvement on an existing form or embodiment, composition or processes might be an invention, an innovation, both or neither if it is not substantial enough. According to certain business literature, an idea, a change or an improvement is only an innovation when it is put to use, is accepted by users and effectively causes a social or commercial reorganization [16.].

In business, innovation can be easily distinguished from invention. Invention is the conversion of business into ideas. Innovation is the conversion of ideas into business. Therefore, any innovative activity has to take into consideration the underlying interdependencies as well as the company´s competitive strategy [1.1.1]. At any stage of development innovative decisions have to be consistent with business strategy. Central factor of competitive strategy is the choice of the market position and it´s realization.

Innovation Management is the capability to continuously manage inventions/ideas for new products or services, processes, production methods, organizational forms or elementary improvements of a business (model) system and their successful realization (Engel K. et al, 2011). The important part of this definition is the term: up to its successful realization. "Successful" is defined in the business environment by the business success resulting in sustainable income and profit growth. All the dimensions of Innovation Management have to be directed to the overall goal of sustainable business impact and growth.

Innovation, whether related to products, process, organizational methods, or marketing, is a complex, multidisciplinary activity that involves several areas of a single firm (such as Marketing, R&D, Manufacturing, Finances, etc.), their clients, and suppliers. In order for this system to function effectively, an active coordination and management of the different activities it entails is required. Organization forms are sought that facilitate and leverage the innovation life cycle management (Riel, A., 2011).

Product and Process development

As a response to global competition, industrial companies are increasing the introduction of technologically sophisticated products as well as the adoption of advanced technologies and changes in organizational structure and processes. A company's competitive position is determined by the ability and agility to innovate its product and service portfolio in the cycle time demanded by the markets that they address. However, they also have to assure their ability to ramp up to full scale production volume at the required speed and with the demanded quality. Therefore, for industrial companies, product and services innovations have to go hand in hand with innovations of the related processes (Riel, A., 2011).

For industrial companies, innovations of the product system as well as innovations of the manufacturing processes are essential competitive factors. Due to technological facts there is a tight relationship between technical products and the processes implemented to realize these products, much less tight than in the software industry. Innovation management has to take into account the dynamics of the underlying product-process interactions and the resulting constraints (Stumpfe, J., 2010). This close coupling of products and the associated manufacturing processes has to be taken into account from the very early design phases of the product, leading to the need of integrated product-process design and innovation (Tichkiewitch, S., 2000).

Particular challenges to innovation are posed by 'New Product Development' (NPD), which is typically done in the context of creating radical innovations. Contrary to incremental innovations, which add value to existing products, radical innovations imply significant new challenges to the organization, mainly in terms of competencies and skills, and market knowledge and experience. The key issue is that if a 'new product' is really 'new', then it automatically means that the designer or design team must go beyond a simple extrapolation of previous designs or products. Otherwise, this is merely product development but not new product development. By stepping into the domain of the new, the NPD process is necessarily creative and not simply mechanistic. This means that the process at the initial time has different possible outcomes, and these will be explored to a greater or lesser extent by the NPD process. This process must therefore be one in which a new 'bundle' of components is discovered that give rise to a new set of performance attributes that satisfy the customer. This is why it is important that the customer and the design team interact sufficiently for the designers to show some of the possibilities, and for the customers to reflect on which new bundle of performance attributes is most attractive to them.

When it comes to product and process innovation, the most successful companies are those whose organizational structures foster the development of knowledge through formal research and development processes and the development of knowledge based on experience, practice, and interaction between employees, clients, and suppliers (Jensen, M.B et al., 2007).

In the following section we will review several frameworks for the development of products and processes. We will also review the use of Design for Six Sigma tools within the development process, with the objective to mitigate risks and to reduce failures during launch.

Waterfall approach

Because Agile can be seen as the counterpart of the so-called Waterfall approach (V-model), we will first review this approach. The earliest use of the term 'Waterfall' originates from the 70's. Later, in 1985, the United States Department of Defense stated that software development contractors shall implement a development cycle that includes certain phases in sequential order, namely: Preliminary Design, Detailed Design, Coding and Unit Testing, Integration and Testing. In Systems engineering and Automotive, the V-Model has become the established process model for the development of complex mechatronic systems, which is build up from mechanic components, electronic components and software. A characteristic of the V-Model is that for every specification step, a suitable testing strategy is defined, which forms the basis for the component and system validation branch on the right-hand side.

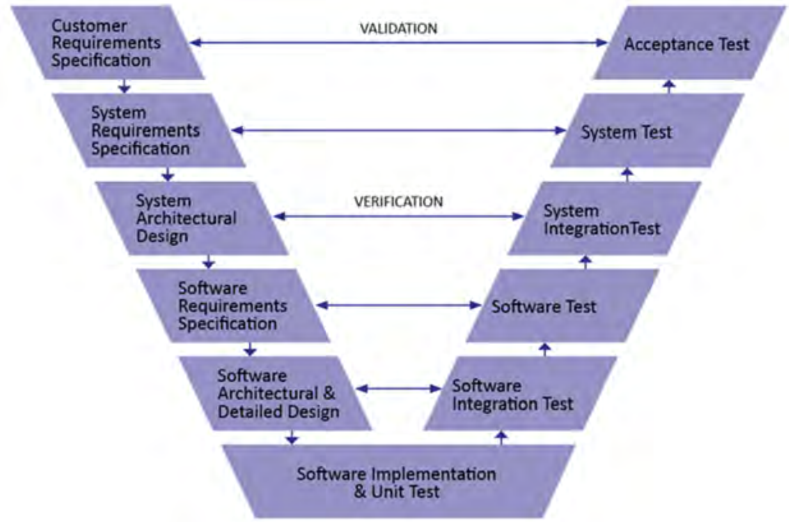


Figure 293 – Waterfall approach and the V-Model

The Waterfall approach is a linear sequential approach for product development. The associated V-Model starts on the left branch with the customer specification. The development team must demonstrate that all requirements will be implemented and validated. The development activities are assigned to certain phases that follow each other downstream (like a Waterfall). Basically, everything is defined at the beginning of the development project. The method is structured and predictable, but at the same time not very flexible.

The 21st-Century business environment is characterized by rapid change that requires great flexibility. Today more and more organizations evolve from using the traditional Waterfall approach to a more Agile approach. Because Agile has a greater degree of flexibility than the Waterfall approach, it is possible to respond more quickly to changes during the development process. This is explained by the Ralph Stacey's Complexity Matrix, in which four different sets of tasks can be distinguished.

‘Simple’ tasks are well defined and easy to solve. We do these activities every day without a lot of thinking. You know exactly what to do and how to do it. ‘Complicated’ tasks are not completely clear in terms of what to do and how to do it. The approach is to sit down and think what to do, before you really do it. Let´s skip one category for a moment and let´s look at the other end of the scale ‘Anarchy’. Here we cannot predict anything at all and we also have no clue how we can tackle things. Examples are a machine breakdown, supplier bankruptcy or a fire. It requires firefighting and management involvement to manage these tasks.

Now let´s look at the big category in the middle of the Stacey complexity model, ‘Complex’ tasks. They have quite a high level of uncertainty in terms of what you have to do and how you want to do it. Product development is an example of complex tasks. In some cases, requirements are not clear from the start and they might change during the development process. It requires multiple skills and a team effort to solve these tasks. You can make a plan, but certainty and predictability are low. You can make a plan, but it is necessary to regularly review results, changed requirements and adapt the plan. So, in order to become predictable, the team works in iterations; adapting the plan after each iteration, considering new and changed requirements, and then continuing execution. This is the basis of Agile working.

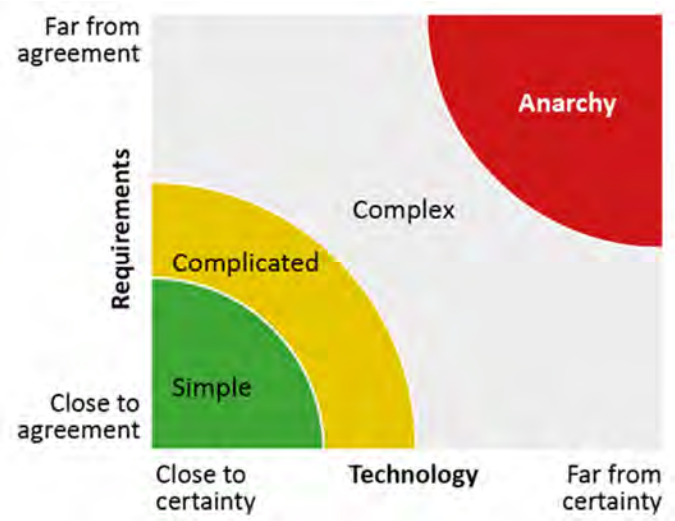


Figure 294 – Complexity Matrix (Ralph Stacey)

Advanced Product Quality Planning

The Automotive industry and some high-tech industries apply the 'Advanced Product Quality Planning' (APQP) approach for New Product Development. It was developed in the late 1980s by the 'Big Three' US automobile manufacturers: Ford, GM and Chrysler. APQP specifies Development, Industrialization and Product Launch. The process involves 23 topics such as: design robustness, design testing and specification compliance, production process design, quality inspection standards, process capability, production capacity, product packaging, product testing and operator training plan.

The APQP project management approach consists of five phases:

- Phase 1: Planning (Preparation, concepts and functional requirements).
- Phase 2: Product Design & Development.
- Phase 3: Process Design & Development.
- Phase 4: Product & Process Validation.
- Phase 5: Production (Launch, assessment and corrective actions).

A visual representation of the APQP process is presented in Figure 295. An extensive explanation of the APQP process can be found in the APQP manual published by the Automotive Industry Action Group (AIAG) [1.].

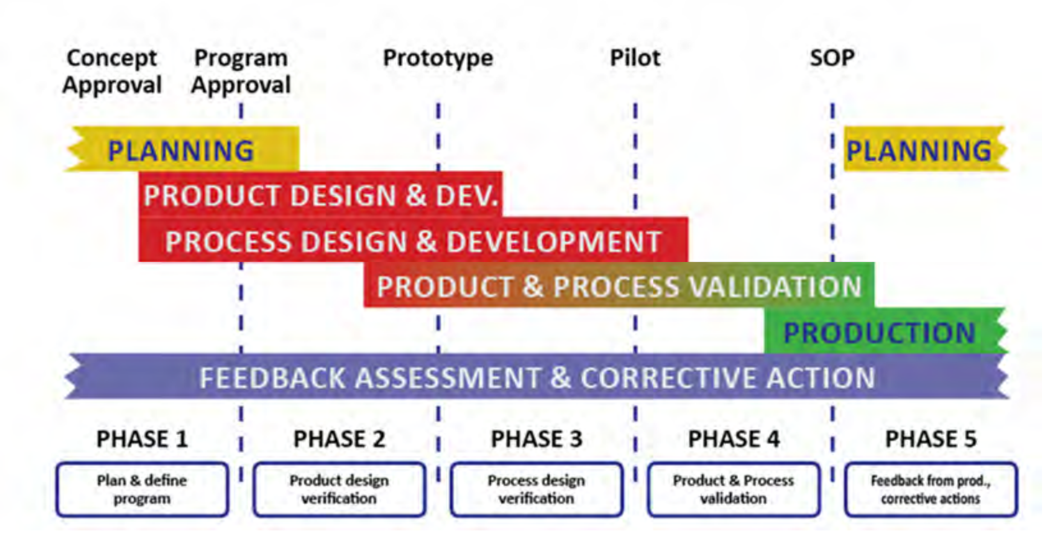


Figure 295 – Advanced Product Quality Planning (APQP)

Different Design for Six Sigma projects can be initiated within the APQP process. These projects follow the DMADV roadmap as described in section 3.2.5. In principle, a DfSS project can be started for every risk that follows from a risk assessment.

One of the topics of the APQP process is the 'Production Part Approval Process' (PPAP). The PPAP is a document to confirm that the new product or process meets the customer requirements. The purpose of the document is to request approval from the customer to start series production and deliver the new parts or product. The full PPAP document consists of 18 elements. A detailed explanation of what needs to be delivered within each of these elements can be found in the PPAP manual that has been published by the AIAG [3.].

1. Design Records.
2. Authorized Engineering Change (note) Documents.
3. Customer Engineering Approval, if required.
4. Design Failure Modes and Effects Analysis (DFMEA).
5. Process Flow Diagram.
6. Process Failure Modes and Effects Analysis (PFMEA).
7. Control Plans.
8. Measurement System Analysis (MSA).
9. Dimensional Results.
10. Records of Material / Performance Test Results.
11. Initial Process Studies.
12. Qualified Laboratory Documentation.
13. Appearance Approval Report (AAR).
14. Sample Production Parts.
15. Master Sample.
16. Checking Aids.
17. Customer-Specific Requirements.
18. Part Submission Warrant (PSW).

The following PPAP elements can be answered by using Lean Six Sigma tools as reviewed in this book:

- Design FMEA:
  A risk analysis that is performed on the functional characteristics in the design phase of the NPD process.
- Process Flow Diagram:
  To indicate all steps and sequence in the fabrication and assembly process.
- Process FMEA:
  A risk analysis of what can go wrong during fabrication and assembly.
- Control Plan:
  To describe how the process and product are controlled/inspected and what will happen in an Out-of-control situation.
- Measurement System Analysis (MSA):
  To demonstrate that the critical characteristics can be measured accurately.
- Performance Tests:
  To demonstrate that the new product will perform over time. In some cases, reliability testing is required.
- Initial Process Studies:
  Capability Analysis or Statistical Process Control charts to demonstrate that the critical characteristics of the process are stable and capable over time.

8.2 Design for Six Sigma

'Design for Six Sigma' (DfSS) is a systematic and rigorous method to support the development of new products and processes that perform at a Six Sigma quality level right from the start. New products and services have a high risk of demonstrating problems during introduction. It is not uncommon to experience growing pains in early stages of delivery and it often takes some time before the process is in control. DfSS brings the process into a controlled state much earlier by focusing on customer requirements and risks, even at the beginning of the development process. Critical requirements and risks will be given extra attention during the development process.

"If I ever started a Six Sigma initiative again,
I would focus on the design instead of the production."

Bob Galvin

'Critical Parameter Management' (CPM) is the central theme in any Design for Six Sigma project. CPM is an engineering practice that is specifically aimed at investigating and demonstrating the robustness of the system or product by focusing on the highest risks and most critical customer specifications. The purpose is to create robust systems and products that are insensitive to common variation by optimizing all critical parameter values to achieve robust performance.

This starts with translating the key customer requirements and key system requirements into key design requirements. These design requirements are cascaded down into key process requirements (internal process) and key component requirements (supplier process). Techniques that support the critical parameter management are 'Quality Function Deployment' (QFD) and CTQ Flowdown.

For each key requirement or critical parameter, it will be necessary to prove its capability (C_{pk}; P_{pk}), as discussed in section 7.7. This starts with translating the critical parameter in one or more CTQs and performing a DMADV (or IDOV) project to investigate its risks, capability and reliability. The design department produces a Design FMEA and the manufacturing department produces a Process FMEA to identify the potential risks of the CTQ not meeting the requirements. Risks need to be mitigated by making the proper design choices and by taking measures to reduce the risk occurrence and increase the risk detection. Variation in both the internal process and the supplier process need to be minimized.

8.2.1 Design for X (DFX)

'Design for Excellence' (DfX) is a design practice which not only focuses on design aspects, but on all aspects of the lifecycle. This includes materials, producibility, maintainability, ergonomics, logistics, reliability, environment and disposal.

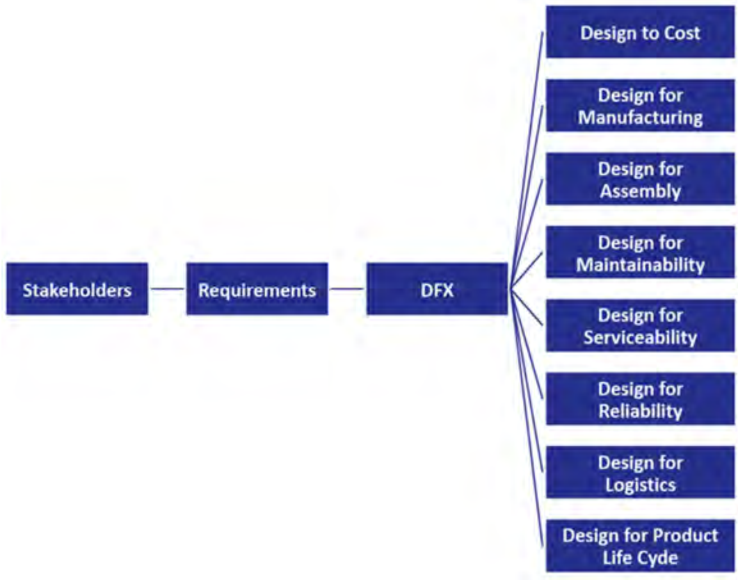


Figure 296 – Design for Excellence

Standardization and simplicity are very important aspects within DfX. This involves the use of proven principles, designs, standard parts and suppliers (partners). DfX also involves strategic alliances with the client and suppliers. In some cases, representatives from the client or suppliers are co-located with the design team.

A number of DfX Guidelines are listed below:

- Standardize processes and procedures.
- Use of common parts and materials.
- Reduce number of parts.
- Reduce number of suppliers.
- Reduce number of features.
- Reduce variation in processes.
- Reduce number of process steps.
- Reduce changes in design team.

"The best design is the simplest one that works."

Einstein

Because it involves so many different aspects, it is essential that people from different departments are involved in an early stage of the development process. Some companies apply the principle of 'Job rotation'. For example, engineers can only design new products after they have been working at the factory floor and have been in service for a certain period of time. This principle will teach them what the consequences are of a bad design for assembly, ergonomics or maintainability.

8.2.2 Quality Function Deployment (QFD)

'Quality Function Deployment' (QFD) is a method whereby customer requirements are transformed into observable variables at every level, from development to delivery. QFD is a means to communicate the requirements of the customer with various departments. It helps to manage and clarify customer requirements and identify the appropriate critical characteristics involved in starting a development project.

QFD was originally developed in Japan (Dr. Yoji Akao and Dr. Shigeru Mizuno, 1964), when they combined their work in quality assurance and quality control points with function deployment used in value engineering. QFD is more than just another DfSS tool. It is a comprehensive methodology on its own. QFD offers a structured approach with various tools. Many of these QFD tools have an overlap with Six Sigma tools. Applying QFD for transforming customer requirements into a prioritized overview of critical characteristics is only one, yet a very helpful part of the QFD methodology.

One of the most powerful and popular tools of QFD is the 'House of Quality' (HOQ), first applied by Mitsubishi Heavy Industries in 1972. The basic structure of the HOQ is a Table with requirements ('Whats') on the left side of the Table and the solutions ('Hows') on the top of the Table. The roof is a diagonal matrix of 'Hows versus Hows' and the body of the house is a matrix of 'Whats versus Hows'. Both are filled with indicators that represent the strength between two specific items. Additional annexes on the right side and bottom hold the 'Whys' and the 'How Muches' that can be used to define priorities for the 'Hows'. Although this explanation is probably confusing, it will become clear after being involved once in the construction of a House of Quality.

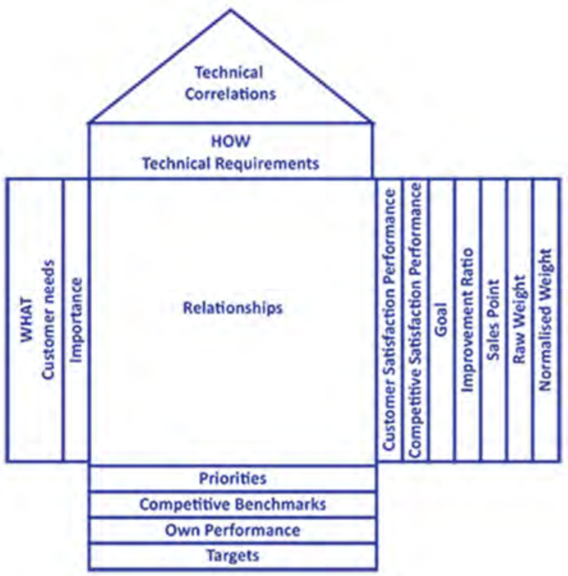


Figure 297 – QFD House of Quality

The House of Quality can also be cascaded along the development trajectory. The 'Hows' from one level becoming the 'Whats' on the next level. For instance, the 'Hows' of the design development become the 'Whats' of the process development. As this progresses, specifications get closer to the operational details.

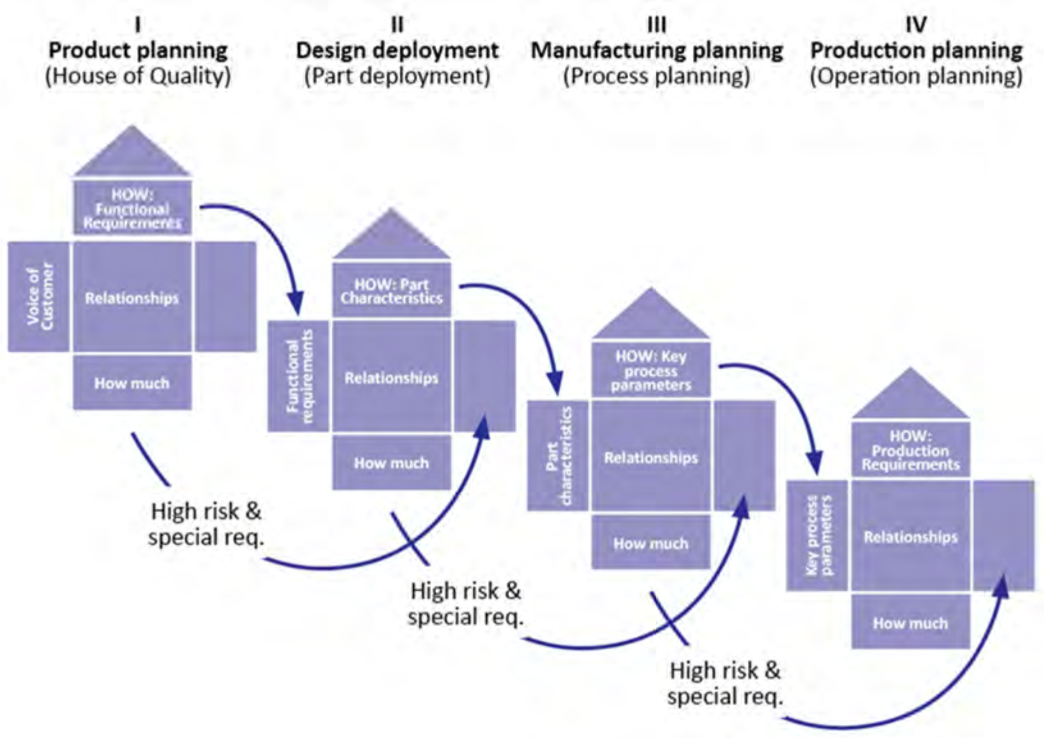


Figure 298 – QFD Cascaded Houses of Quality

During the first phases of the development process Quality Function Deployment and CTQ Flowdown can be applied to really understand the customers critical requirements. During the concept development and design development phases the DMADV roadmap and numerous Six Sigma tools can be applied. One NPD project can incorporate several DMADV projects. One way to select the DMADV projects within the overall NPD project, is to compose a Design FMEA [8.2.3] during the concept development phase, based on the customer critical characteristics. The Design FMEA will expose the biggest risks and design challenges. As most Six Sigma DMAIC projects address one CTQ, the DMADV should address a limited number of risks. The objective of each DMADV project is to investigate the risk and to find (design) solutions to mitigate the risk or to prevent the risk occurring.

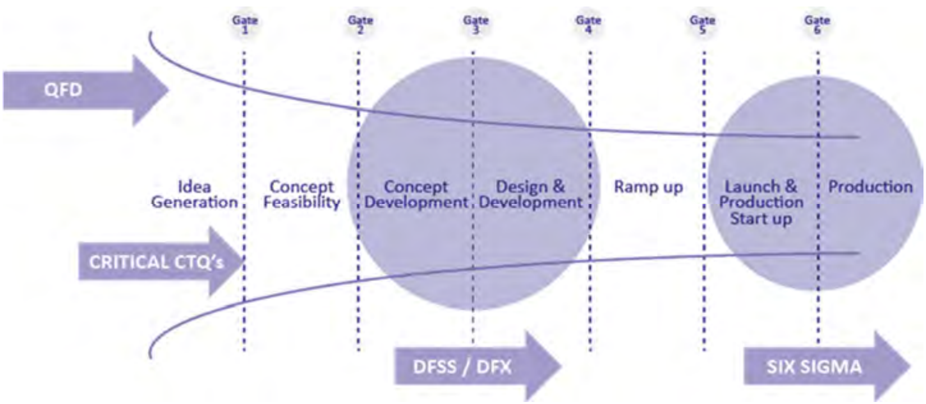


Figure 299 – New Product Development & Design for Six Sigma

8.2.3 Design FMEA (DFMEA)

The Design FMEA analyzes the extent to which the intended design of the product or system will be able to meet the requirements as agreed with the customer. This method is applied in the development phase of a product or system after the concept design has been established. A functional analysis, for example by means of an QFD, forms the basis for the Design FMEA.

The structure of a Design FMEA is built on the structure of the product or system being analyzed and can thus become very extensive and complex. On the Design FMEA form, this must be reduced to 3 levels. This can be done by zooming in on a specific part of the structure and / or by summarizing multiple levels into one. For a simple system the following three levels are chosen:

1. System level:
   Functions and properties that the user (customer) expects from the system.
   Error effects
2. Component Level (Focus Elements):
   Functions and properties of the components or subsystems that enable the system functions.
   Faults
3. Design level:
   Detailing of the design (material properties and geometry).
   Error causes

The Design FMEA analyzes and ranks the potential failure modes, the effects and the causes thereof. The first level of the structure involves analyzing the system or product and the customer's requirements. The second level describes the requirements of the individual components (or subsystems) that must be met to enable the functions at higher levels. The third level describes what the structural design of the individual components or subsystems should be, to enable the functions at the higher levels. For the risk determination, likewise to the Process FMEA, the Severity (how bad is the effect), the Probability (what is the chance that an error cause will occur) and the Detection (the possibility to discover the error or error cause before the design is approved). The probability is lower when there is more certainty about the design choices made, for example through experience with the applied geometry or materials, strength calculations or the application of safety margins. Detection is lower the more relevant the planned tests for product validation are or can be completed at an early stage in the development process.

The relationship between the three levels and their analysis can be built up and displayed in a spreadsheet form, but for more complex products or systems, it is better to use specific FMEA database-software, in which the functional analysis and the Design FMEA form a logical whole.

With the integration of the AIAG standard and the VDA standard in 2019, the FMEA-MSR has also been introduced. This stands for ‘Monitoring and System Response’, and is an extension of the Design-FMEA. FMEA-MSR analyzes the robustness of the diagnostic functions for complex systems. This assesses how certain it is that the driver and/or the system will detect an error in time and whether the response will be fast and effective enough to prevent the failure effect from actually occurring.

8.2.4 Reliability

Reliability may be defined as the probability of an item to perform a required function under stated conditions for a specified period of time. Also, availability and maintainability may be considered part of reliability. Reliability engineering focuses on examining and optimizing the reliability of a product or system so that it is capable of fulfilling its desired functions. Reliability plays a role in cost calculations, warranty, service level agreements and safety. Also, availability plays a part in product line capacity and maintenance. Reliability involves the following techniques and methods:

- Preventive Maintenance management.
- Failure Modes and Effects Analysis (FMEA).
- Fault Tree Analysis (FTA).
- Finite Element method (simulation).
- Functional and performance testing.
- Reliability hazard analysis.
- Accelerated Life Testing (ALT).
- Highly Accelerated Life Testing (HALT).

Failure rate function h(t)
The frequency with which a system or component fails as a function of time, is called the 'Failure rate'. The failure rate can be statistically described by the hazard or failure rate function: *h(t)*. The failure rate may be constant during the lifespan of a system; the system can also have different hazard functions for different timeframes. For example, a new car has a higher probability of demonstrating problems in the first year. Then for a certain amount of time it will hardly demonstrate any problems. After some years however, the car will demonstrate the first signs of wear. The first failure rate is called the 'Infant mortality' phase of the product, which has a decreasing failure rate and is associated with built-in (i.e., not designed-in) defects. The failure rate of the second phase is called 'Normal life'. The failure rate of the third phase is called 'End-of-Life' or 'Wear out'. This behavior with three different failure rates is pretty typical for complex systems and is named 'The Bathtub Curve'.

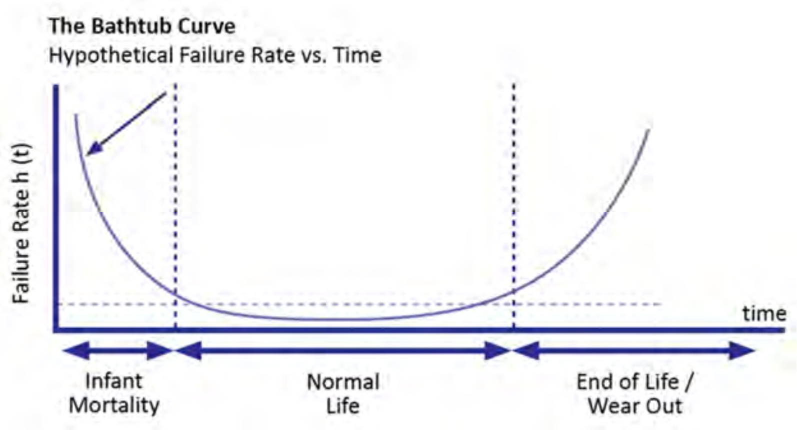


Figure 300 – Bathtub curve

Reliability testing (HALT en ALT)

Both ALT and HALT are two very effective reliability testing methods that are performed during the development process of hardware products and systems. Although their naming is similar, they are two completely different techniques, which might lead to confusion sometimes. We will explain both testing methods briefly. A detailed explanation how the Failure rate functions *h(t)* can be calculated is outside the scope of this book though.

- Highly Accelerated Life Testing (HALT)
  HALT-testing is used for finding predominant failure mechanisms in a product or system, as demonstrated in the first section of the Bathtub curve (Infant mortality). The HALT conditions are such that the product is expected to break. The technique is used to find the weakest part in a design. A stimulus is applied to the component or system to determine weak links or mismatches. During HALT, the stimulus factor is gradually increased until the product fails. For example, this can be voltage for an electrical part, force for a mechanical part or pressure for a pressure sensor.

- Accelerated Life Testing (ALT)
  ALT-testing is a more advanced reliability test method and is used to predict the life expectance of a product under normal conditions. ALT is used to predict or characterize wear as a failure mechanism. This puts the focus on the third part of the bathtub curve. ALT-testing is aimed at accelerating the so-called duty cycle. Common performance variables (responses) include fatigue life, cycle time, wear and corrosion. Common stress factors (factors of influence) include mechanical force, temperature, vibration, pressure, chemicals, humidity and tension. The results of an ALT-test can be extrapolated back to normal living conditions when the 'Acceleration Factor' (AF) and the Failure rate function *h(t)* can be determined. In ALT-testing, the product is exposed in a laboratory environment, in a short time, to conditions such as those occurring in the field over a long period of time. An example is switching a light switch on and off by a mechanism. The switch can be turned on and off 100,000 times within a short time. If the switch survives this test, it can be proven that in real life the switch can last for decades before it breaks.

A benefit of HALT-testing is its speed in finding defects. HALT usually takes a few hours to a few days, while ALT-testing usually takes a few days to a few weeks. When wear-out mechanisms are involved, it is better to apply the ALT-test instead of the HALT-test.

Mean Time Between Failures (MTBF)
A system can demonstrate failures once in a while. A failure is considered as a situation that places the system out of service and sometimes even into a state for repair. Think about a computer that crashes and needs to be rebooted or a car that shows the engine control signal. A parameter showing the average time between two consecutive failures is called 'Mean Time Between Failures' (MTBF). The parameter is used to describe the frequency of failures in a repairable system.

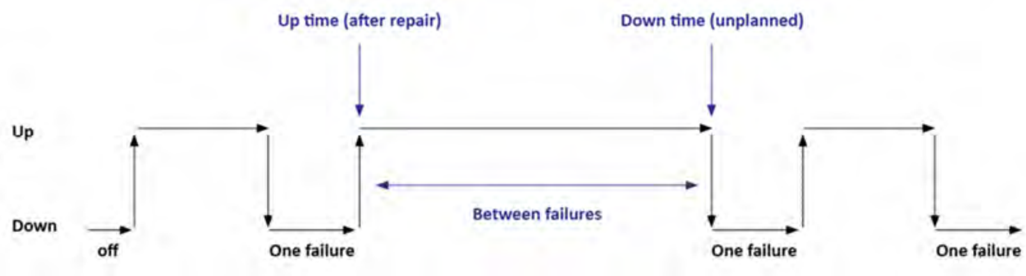


Figure 301 – Mean Time Between Failure

MTBF can be calculated with the equations below:

$$Time\ between\ failure = start\ of\ down\ time - start\ of\ up\ time$$

$$MTBF = \frac{\sum(start\ of\ downtime - start\ of\ uptime)}{number\ of\ failures}$$

Mean Time To Failure (MTTF)
While MTBF describes the expected time between two failures for a repairable system, the parameter 'Mean Time To Failure' (MTTF) designates the expected time to failure for a non-repairable system. For example, MTTF for a light bulb would be the average number of hours that bulbs burn for before going out.

Assume you tested three light bulbs starting from time 0 until all of them failed. The first light bulb failed at 2,050 hours, the second failed at 2,125 hours and the third failed at 2,215 hours. The MTTF is the average of the three failure times, which is 2,130 hours.

$$MTTF = \frac{2{,}050 + 2{,}125 + 2{,}215}{3} = \frac{6{,}390}{3} = 2{,}130\ hour$$

As described in paragraph 7.2.1, the Weibull distribution is one of the most widely used lifetime distributions in reliability engineering due to its versatility. It is very likely that the failure rate function of MTTF also follows a Weibull distribution.

8.2.5 Tolerance analysis

Tolerance analysis, also known as variation analysis, is the study of 'Accumulated variation'. As discussed in various parts of this book, variation is everywhere. Tolerance analysis answers the question "Will the parts fit together in the proper way?"

Tolerance stack-up calculations represent the cumulative effect of part tolerance with respect to assembly requirements. Tolerance analysis is mainly applied by engineers in the development process to specify dimensions and tolerances on engineering drawings. Tolerance stack-ups are vital to address mechanical fit and mechanical performance requirements for parts and assemblies. It also supports a well-founded discussion with suppliers on tolerance specifications.

Tolerance analysis methods are also applied within other fields that are subject to accumulated variation, such as electronics, economics, environmental and demography. Risk tolerance analysis for instance is applied to model the influence of social aspects within a crisis situation on the effect of stock exchange.

Black Belts are expected to understand the basic principles of Tolerance analysis like Worst case, RSS, Monte Carlo and Empirical methods. In this paragraph we will discuss these methods briefly.

Empirical research:
Empirical research is a way of gaining knowledge by means of direct and indirect observation or experimentation. Empirical research is particularly used in social sciences and education where it is difficult to perform experiments in a controlled environment like a laboratory.

Worst case:
Within 'Worst-case' modeling individual variables are placed at their tolerance limits in order to make the measurement as large or as small as possible. The worst-case model does not consider the distribution of the individual variables, but rather that those variables do not exceed their respective specified limits. In production this should then be guaranteed by rejecting parts above this limit. Worst-case modeling is a very traditional approach of a tolerance stack-up calculation. It is used a lot when a limited number of parts are available or for safety critical systems.

'Root Sum Square' (RSS):
The Root Sum of Squares method assumes that extreme values of parameters are rarely simultaneous. Considering that a dimension is normally distributed, the nominal value will be more common than values farther away from the nominal. Therefore, a statistical approach of counting up the individual variances (using RSS) gives a more realistic picture of the tolerance stack-up than considering worst-case scenarios.

Monte Carlo:
Monte Carlo simulation is a method for exploring the sensitivity of a complex system using computational algorithms. Simulations can include financial, physical and mathematical models. Examples are behavior of fluids, reliability, financial markets, demography and cellular structures. Monte Carlo methods are used in simulating systems with many factors of influence or many degrees of freedom. Simulation is done in a loop by repeated random sampling to obtain numerical results. Examples of software that supports Monte Carlo simulation are Minitab Workspace, Crystal Ball, SolidWorks and Mathlab.

8.3 The fourth industrial revolution

You are undoubtedly familiar with the saying 'He who does not advance goes backwards'. If there is something that does not stand still, it is the technological development and the related industrial development. Currently, we are at the beginning of the fourth industrial revolution, also known as ‘Industry 4.0’ or ‘SMART Industry’. The classic competitive strategies Product Leadership, Operational Excellence and Customer Intimacy are merging into one common value strategy. Product Life Cycles are getting shorter and products are becoming more customer-specific.

8.3.1 Industry 4.0

In the Netherlands a consortium of organizations and educational institutes initiated the Smart Industry Network. The consortium developed a framework to visualize and describe all Industry 4.0 elements. This framework provides direction for companies who want to develop a strategy and execution plan for Industry 4.0.

Figure 302 – Industry 4.0 framework (SMART Industry Network, 2017)

We will briefly explain the seven elements of the framework:

1. Co-Creation / SMART Product Development:
   In the development of new products, the design process and production process are performed in parallel and no longer sequentially. The digital design of a new product will develop simultaneously with the production of the physical product. Co-creation, through partnerships, will also become increasingly important.

2. Prosumer / Mass Customization:
   Consumers change to 'Prosumers'. Through the connection of Internet and production in i4.0-factories, the Prosumer will have a direct influence on the production process. Each customer order is unique while production is running at high volume.

3. Internet of Things / Digital Factory:
   Machines, goods and components communicate with each other about planning, processing, maintenance and raw materials needed. The exponential development of 'Big Data' generates such a large amount of operational information that is impossible to be interpret by human. Attention is therefore shifting to data analytics, including algorithms that allow machines to make autonomous decisions.

4. Cyber Physical Systems / Factory Flexibility:
   The factory of the future consists of intelligent self-learning robots. These so-called 'Cyber Physical Systems' are Lego-bricks that all fit into each other and communicate with each other. Machines will become 'clients' themselves and call for raw materials and maintenance when necessary. The factory of the future offers maximum flexibility. Each product has been uniquely identified, communicating which specific machining or assembly operations it needs to undergo. Different types of products are running on the same production line and can undergo different operations.

5. Operational Excellence / Variation reduction:
   Organizations will have to perform at the highest level of Operational Excellence and need to continuously working on improving its processes. Applying Lean, data analytics, and Six Sigma helps reducing variability and increasing process capability. At the same time maintenance will become more predictable which will reduce unscheduled downtime.

6. Enterprise Agility / Competent Workforce:
   To be successful in the future, the speed at which the organization can adapt is playing a crucial role. Organizations must become more Agile. Adaptability depends not only on technological innovation, but also on adaptability of employees and of the organization itself. To keep up with the pace of change, employees have to develop themselves continuously.

7. Sustainability / Circular Economy:
   In the circular economy sustainability is improved by radical innovations and enhancing the eco-effectivity of the product. This means that products do not harm the environment in the production process, the use and in the waste phase. In both design and production, elements such as CO2 neutral and 100% reusability must be taken into account.

CIMM assessment level V – Creating future-proof processes

Level V focuses on creating future proof processes. Is your foundation operating at the level of World Class? Perform the assessment below by scoring each statement with a rating of 1 to 5. A score of '1' means that the statement does not reflect the situation within your organization; a score of '5' means that the statement fully reflects the situation within your organization. As there are 15 statements, the maximum score is 75.

Process level V – Creating Future-proof processes (Sustained)
5.1 – Product Lifecycle Management (PLM)
Product Lifecycle Management (PLM) is applied during the entire lifecycle.
All resources, processes, business systems and available data are integrated in PLM.
The organization is innovative and trendsetter in its market area.
Unique products or services are offered to the market (Customer Intimacy).
Superior products or services are offered to the market (Product Leadership)
5.2 – Design for Excellence (DfX)
There is a standardized project management approach in place for New Product Development.
Customer's critical characteristics are truly understood (e.g. by using QFD and CTQ flowdown).
Design FMEA is applied to identify potential risks in the development phase.
Development is based on Co-creation. All disciplines and essential suppliers are involved early.
Design for Six Sigma is used in the development of new products.
5.3 – Industry 4.0
Mass Customization and Modularization are applied. Each product is uniquely identified.
Cyber Physical Systems, Cobots and/or Robotic Process Automation (RPA) are used.
Internet of Things / Digital Factory: Machines and Business Intelligence systems are connected.
Active policy on Cyber Security and Privacy Certification is present.
Active policy on development and transformation of employees to Industry 4.0 is present.

Each person in the organization has a certain role and responsibility at creating future-proof processes. The assessment distinguishes responsibilities and behaviors for top management, middle management and people working at the shop floor. There are again 15 statements with a maximum score of 75.

People level V – Creating Future-proof processes (Master)
5.1 – Product Lifecycle Management (PLM)
Top management has a clear vision on future product-market combinations and innovation.
Management leads the process of innovation and stimulates creativity.
Management knows the life cycle phase of its products and initiates innovation in a timely manner.
Employees see change as an opportunity and understand that every product is subject to change.
Employees are familiar with the four different product life cycles.
5.2 – Design for Excellence (DfX)
Top management encourages the use of techniques in the design process to prevent problems.
Management organizes the exchange of knowledge, making new products increasingly reliable.
Management ensures that customer experiences are included in the innovation process.
Employees initiate proposals that can be included in the design of new products and services.
Employees make an important contribution to the design of new processes.
5.3 – Industry 4.0
Top management encourages the organization to use new technologies (i.e. RPA, AI, IoT).
Management makes suggestions for process modernization and autonomation.
Management ensures that employees are permanently employable in a complex work environment.
Employees are open to new developments and technologies.
Employees understand they have to develop themselves to be prepared for future roles.

Appendix A – Theoretical assessment

Within the domain of Lean and Six Sigma individuals can be trained and certified at different levels. The levels are listed in the Table below.

Belt level	Level
Lean Yellow Belt	Awareness
Lean Six Sigma Yellow Belt	Awareness
Lean Six Sigma Orange Belt	Foundation
Lean Green Belt	Practitioner
Lean Six Sigma Green Belt	Practitioner
Lean Black Belt	Expert
Lean Six Sigma Black Belt	Expert
Master Black Belt	Master

Table 50 – Overview of Lean Six Sigma Belt levels

The LSSA – Lean Six Sigma Academy® was established in September 2009 with the objective to develop an international recognized certification scheme for all Lean and Six Sigma Belt levels. For each level the LSSA Exam Board has developed Skill sets with clear criteria for skills and competences. These Skill sets specify which of the overall Lean and Six Sigma techniques are expected to be included within certain Belt level competencies.

The structure of this book is based on the LSSA skill sets for Lean and Six Sigma Black Belt [19.]. The LSSA skill sets describe the assessment criteria for the theoretical and practical exam. Candidates are required to pass both elements to be recognized as a certified Lean Six Sigma Black Belt. Passing the theoretical exam is a pre-requisite to subscribe for the practical exam. The Black Belt certification can be achieved independently. It is no pre-requisites to take the Green Belt exam first. After completion of the Lean Six Sigma Black Belt you can subscribe for the Master Black Belt scheme.

Lean Six Sigma training is provided by a global network of 'Accredited Training Organizations' (ATOs). These ATOs provide training programs that are aligned to the LSSA Skill sets. Examination is provided through the LSSA directly or through APM Group Limited. The exams are open to all. Individuals can apply directly or sign up via one of the ATOs. It is recommended that candidates receive training through an ATO to prepare for certification. Check the LSSA website for an overview of ATOs and the actual exam requirements. On the website you will also find information about how you can claim your Digital badge. Then share your Digital badge on LinkedIn and show that you are active as a Black Belt.

Figure 303 – Digital badge theoretical exam

Appendix B – Practical assessment

This appendix describes the assessment criteria for the practical part of Black Belt certification. Black Belts have to submit two practical projects that meet the following criteria:

- For Lean Black Belt: two successful projects at CIMM level-III (or higher).
- For Lean Six Sigma Black Belt: two successful projects at CIMM level-III and IV or higher.
- The project should have a significant impact to the organization. This means that it has a financial impact of € 50,000 on an annual basis or another relevant CTQ (like Lead Time) has substantially been improved.
- The project must follow the PDCA, DMAIC or DMADV roadmap.
- The templates for submitting the projects can be downloaded from the LSSA website (max. of 25 pages).
- The projects should be signed off by the Champion to declare that the projects have been carried out professionally and that objectives have been achieved and sustainable.
- A single Black Belt can submit the projects for certification in its role of project manager.
- The project must be submitted no later than three years after passing the theoretical examination.

The projects will be assessed by a Master Black Belt, assigned by the LSSA. The criterion listed in Table 51 to Table 53 will be applied. It is advisable to use these criteria during your project. It is additionally strongly advised that the submission is also checked by an internal (Master) Black Belt or coach.

- A ‘Pass’ result will be awarded when all criteria are addressed within the submission and are deemed to be ‘Correct’ or ‘Not Applicable’.
- The submission must contain a justification of any criteria that is claimed to be ‘Not Applicable’.

The result of the practical assessment will be either Pass or Fail. No score will be given. In the event of a ‘Fail’ result, brief guidance will be given on those criteria that are deemed ‘Missing’ or ‘Incorrect’. Subsequently, a single retake resubmission is allowable.

The assessment criteria on the LSSA website are superseding the criteria listed in this book. Check the LSSA website for the latest version.

Figure 304 – Digital badge practical exam

Kaizen & Lean project criteria PDCA

Phase	Nr	Criteria
Plan	1	The project addresses a customer complaint, problem or business case.
	2	There is a clear problem definition.
	3	Objectives are clearly defined and are measurable.
	4	VOC and VOB are defined and specifications are clear.
	5	The scope of the project is clearly defined.
	6	The most important stakeholders have been identified.
	7	Relevant CTQ (s) have been selected and a CTQ flowdown has been made.
	8	A high level process description has been made (e.g. SIPOC).
	9	The reliability of the data has been investigated.
	10	Process performance has been constructed and assessed against specifications.
	11	A detailed process description has been made (e.g. VSM Current State).
	12	Potential causes have been identified.
	13	Analyzes have been used to identify factors of influence (e.g. Fishbone or FMEA).
	14	The main root causes have been identified and explained.
	15	Conclusions are clear and supported.
Do	1	Risks have been defined and addressed (e.g. pFMEA).
	2	The improved process meets the specifications of the VOC and VOB.
	3	There is a clear communication and action plan towards the stakeholders.
	4	The client has approved the improvement proposals.
Check	1	There is a proven improvement of the CTQ compared to the baseline measurement.
	2	Standards have been adjusted and documentation has been updated.
	3	Roles and responsibilities have been described.
	4	Employees are instructed and/or trained.
	5	It has been shown that the improvements are sustainable.
Act	1	It has been indicated how performance will be monitored in the future.
	2	Final report is ready and lessons learned have been communicated.
	3	Champion has indicated that objectives and/or savings have been achieved.

Table 51 – Project Practical Assessment PDCA

Lean en Six Sigma project criteria DMAIC

Phase	Nr	Criteria
Define	1	Project addresses a clear problem description or business opportunity.
	2	Problem description has been clearly defined.
	3	Goals have been clearly defined and are measurable.
	4	VOC and VOB have been clearly defined and requirements are understood.
	5	Scope of the project has been clearly delineated.
	6	Key stakeholders have been identified.
	7	Relevant CTQ(s) have been selected and a CTQ-flowdown has been constructed.
	8	High level process description has been made (e.g. SIPOC).
Measure	1	The collected data has been proven to be representative for the project.
	2	Validity of the data has been verified in an appropriate way.
	3	Historical data has been used to visualize process performance over time.
	4	Performance against requirements has been checked.
	5	Variation in the process has been considered (common cause or special cause).
	6	Short term versus long term performance has been considered.
Analyze	1	Process has been mapped in detail (e.g. VSM Current State).
	2	Potential factors of influence have been determined.
	3	Analyses have been used to identify factors with highest influence.
	4	Hypothesis for root cause has been defined properly.
	5	Input data has been collected and analyzed correctly.
	6	Graphical and statistical techniques have been applied to investigate root causes.
	7	Major root causes have been identified.
	8	Conclusions are clear and have demonstrated strong evidence/are statistically valid.
Improve	1	Risks have been identified and addressed (e.g. pFMEA).
	2	Improved process meets the requirements of the VOC and VOB.
	3	There is a clear communication and action plan towards the stakeholders.
	4	The client (Champion) has approved the improvement proposal.
	5	An improvement of the CTQ compared to the baseline is demonstrated.
Control	1	Standards are adjusted and documentation has been updated (pFMEA, CP).
	2	Rolls and responsibilities have been described.
	3	Employees are instructed and/or trained.
	4	Evidence of 'In-Control situation' is available and sufficient.
	5	Improvements have proven to be sustainable.
	6	Measures have been put in place to monitor process performance.
	7	Project report has been completed. Lessons learned have been communicated.
	8	Champion states that project targets and/or savings have been achieved.
	9	Champion or controller has signed off the project.

Table 52 – Project Practical Assessment DMAIC

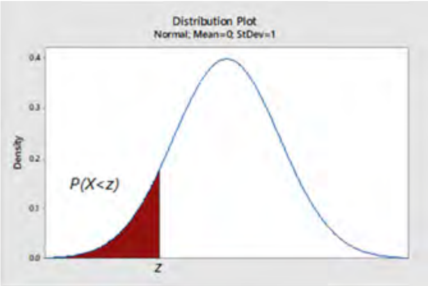
Design for Six Sigma project criteria DMADV

Phase	Nr	Criteria
Define	1	Project addresses a clear problem description or business opportunity.
	2	Project charter includes the risks to investigate.
	3	Goals have been clearly defined and are measurable.
	4	VOC and VOB have been clearly defined and requirements are understood.
	5	Scope of the project has been clearly delineated.
	6	Key stakeholders have been identified.
	7	Functional requirements have been defined.
	8	High level process description has been made (e.g. SIPOC).
Measure	1	Risks or customer requirements have been made tangible and specific.
	2	Historical data and issues have been taken into account.
	3	Customer requirements have been translated into technical requirements.
	4	Relevant CTQ(s) have been selected and a CTQ-flowdown has been constructed.
	5	It has been defined how the CTQs are measured.
	6	The measurement procedure has been validated (Gage R&R)
Analyze	1	All risks have been identified and a mitigation plan is available (e.g. dFMEA)
	2	Design concepts have been develop.
	3	Potential factors of influence have been identified.
	4	Data have been collected and analyzed.
	5	Transfer functions $Yi = f(X_1, X_2,\dots,X_n)$ have been developed.
	6	Graphical and statistical techniques have been applied to investigate risks.
	7	Transfer function shows (theoretical) that capability meets customers specifications.
	8	There is a clear difference between confirmed and non-confirmed information.
Design	1	Validation plan is designed.
	2	Samples, prototypes or concepts are available for validation.
	3	Risk mitigation measures have been identified (e.g. Poka Yoke, Control Plan).
	4	Product Lifecycle management and reliability have been addressed (if applicable).
	5	Optimum settings for all significant factors of influence have been defined.
Verify	1	Pilot run results have been evaluated.
	2	Factors of influence will be controlled in a way that the risk will not appear.
	3	Documentation has been updated (pFMEA, CP, SOPs).
	4	Training has been performed for the new product/process.
	5	Project report has been completed. Lessons learned have been communicated.
	6	Full scale ramp-up plan has been developed.
	7	Project has been completed within time and budget.
	8	Champion signed that project targets and/or savings have been achieved.

Table 53 – Project Practical Assessment DMADV

Appendix C – Statistical tables

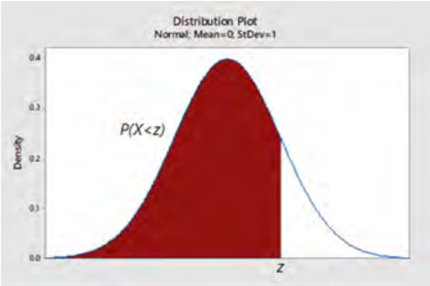
Standardized normal distribution



$$P(X \leq z) = \int_{-\infty}^{z} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dz$$

Table C.1. *Standardized normal distribution*

Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
-3.4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002
-3.3	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003
-3.2	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005
-3.1	0.0010	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007
-3.0	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0011	0.0010	0.0010
-2.9	0.0019	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014
-2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
-2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
-2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
-2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
-2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
-2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
-2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
-2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
-2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
-1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
-1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
-1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
-1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
-1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
-1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
-1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
-1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
-1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
-1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
-0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
-0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
-0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
-0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
-0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
-0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
-0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
-0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
-0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641



Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.1	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

Student’s t-distribution

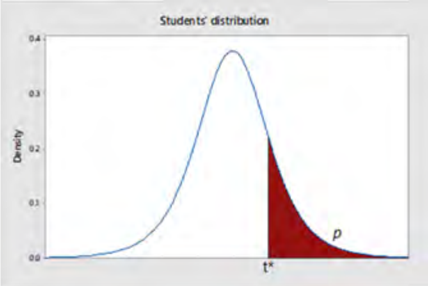


Table C.2. *Student's t-distribution*

	p									
df	0.40	0.30	0.20	0.10	0.05	0.025	0.010	0.005	0.001	0.0005
1	0.325	0.727	1.376	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.289	0.617	1.061	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.277	0.584	0.978	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.271	0.569	0.941	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.267	0.559	0.920	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.265	0.553	0.906	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.263	0.549	0.896	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.262	0.546	0.889	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.261	0.543	0.883	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.260	0.542	0.879	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.260	0.540	0.876	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.259	0.539	0.873	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.259	0.538	0.870	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.258	0.537	0.868	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.258	0.536	0.866	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.258	0.535	0.865	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.257	0.534	0.863	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.257	0.534	0.862	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.257	0.533	0.861	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.257	0.533	0.860	1.325	1.725	2.086	2.528	2.845	3.552	3.850
25	0.256	0.531	0.856	1.316	1.708	2.060	2.485	2.787	3.450	3.725
30	0.256	0.530	0.854	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.255	0.529	0.851	1.303	1.684	2.021	2.423	2.704	3.307	3.551
50	0.255	0.528	0.849	1.299	1.676	2.009	2.403	2.678	3.261	3.496
60	0.254	0.527	0.848	1.296	1.671	2.000	2.390	2.660	3.232	3.460
70	0.254	0.527	0.847	1.294	1.667	1.994	2.381	2.648	3.211	3.435
80	0.254	0.526	0.846	1.292	1.664	1.990	2.374	2.639	3.195	3.416
90	0.254	0.526	0.846	1.291	1.662	1.987	2.368	2.632	3.183	3.402
100	0.254	0.526	0.845	1.290	1.660	1.984	2.364	2.626	3.174	3.390
200	0.254	0.525	0.843	1.286	1.653	1.972	2.345	2.601	3.131	3.340
500	0.253	0.525	0.842	1.283	1.648	1.965	2.334	2.586	3.107	3.310
1000	0.253	0.525	0.842	1.282	1.646	1.962	2.330	2.581	3.098	3.300
10000	0.253	0.524	0.842	1.282	1.645	1.960	2.327	2.576	3.091	3.291

Chi-square distribution

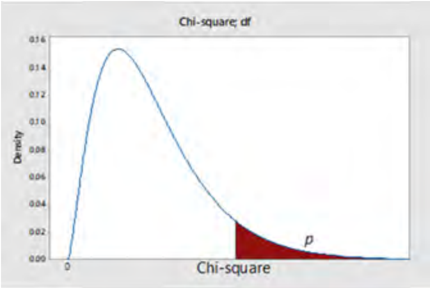


Table C.3. *Chi-square distribution*

	p											
df	0.995	0.990	0.975	0.950	0.900	0.750	0.500	0.100	0.050	0.025	0.010	0.005
1	0.00	0.00	0.00	0.00	0.02	0.10	0.45	2.71	3.84	5.02	6.63	7.88
2	0.01	0.02	0.05	0.10	0.21	0.58	1.39	4.61	5.99	7.38	9.21	10.60
3	0.07	0.11	0.22	0.35	0.58	1.21	2.37	6.25	7.81	9.35	11.34	12.84
4	0.21	0.30	0.48	0.71	1.06	1.92	3.36	7.78	9.49	11.14	13.28	14.86
5	0.41	0.55	0.83	1.15	1.61	2.67	4.35	9.24	11.07	12.83	15.09	16.75
6	0.68	0.87	1.24	1.64	2.20	3.45	5.35	10.64	12.59	14.45	16.81	18.55
7	0.99	1.24	1.69	2.17	2.83	4.25	6.35	12.02	14.07	16.01	18.48	20.28
8	1.34	1.65	2.18	2.73	3.49	5.07	7.34	13.36	15.51	17.53	20.09	21.95
9	1.73	2.09	2.70	3.33	4.17	5.90	8.34	14.68	16.92	19.02	21.67	23.59
10	2.16	2.56	3.25	3.94	4.87	6.74	9.34	15.99	18.31	20.48	23.21	25.19
11	2.60	3.05	3.82	4.57	5.58	7.58	10.34	17.28	19.68	21.92	24.72	26.76
12	3.07	3.57	4.40	5.23	6.30	8.44	11.34	18.55	21.03	23.34	26.22	28.30
13	3.57	4.11	5.01	5.89	7.04	9.30	12.34	19.81	22.36	24.74	27.69	29.82
14	4.07	4.66	5.63	6.57	7.79	10.17	13.34	21.06	23.68	26.12	29.14	31.32
15	4.60	5.23	6.26	7.26	8.55	11.04	14.34	22.31	25.00	27.49	30.58	32.80
16	5.14	5.81	6.91	7.96	9.31	11.91	15.34	23.54	26.30	28.85	32.00	34.27
17	5.70	6.41	7.56	8.67	10.09	12.79	16.34	24.77	27.59	30.19	33.41	35.72
18	6.26	7.01	8.23	9.39	10.86	13.68	17.34	25.99	28.87	31.53	34.81	37.16
19	6.84	7.63	8.91	10.12	11.65	14.56	18.34	27.20	30.14	32.85	36.19	38.58
20	7.43	8.26	9.59	10.85	12.44	15.45	19.34	28.41	31.41	34.17	37.57	40.00
21	8.03	8.90	10.28	11.59	13.24	16.34	20.34	29.62	32.67	35.48	38.93	41.40
22	8.64	9.54	10.98	12.34	14.04	17.24	21.34	30.81	33.92	36.78	40.29	42.80
23	9.26	10.20	11.69	13.09	14.85	18.14	22.34	32.01	35.17	38.08	41.64	44.18
24	9.89	10.86	12.40	13.85	15.66	19.04	23.34	33.20	36.42	39.36	42.98	45.56
25	10.52	11.52	13.12	14.61	16.47	19.94	24.34	34.38	37.65	40.65	44.31	46.93
26	11.16	12.20	13.84	15.38	17.29	20.84	25.34	35.56	38.89	41.92	45.64	48.29
27	11.81	12.88	14.57	16.15	18.11	21.75	26.34	36.74	40.11	43.19	46.96	49.64
28	12.46	13.56	15.31	16.93	18.94	22.66	27.34	37.92	41.34	44.46	48.28	50.99
29	13.12	14.26	16.05	17.71	19.77	23.57	28.34	39.09	42.56	45.72	49.59	52.34
30	13.79	14.95	16.79	18.49	20.60	24.48	29.34	40.26	43.77	46.98	50.89	53.67
40	20.71	22.16	24.43	26.51	29.05	33.66	39.34	51.81	55.76	59.34	63.69	66.77
50	27.99	29.71	32.36	34.76	37.69	42.94	49.33	63.17	67.50	71.42	76.15	79.49
60	35.53	37.48	40.48	43.19	46.46	52.29	59.33	74.40	79.08	83.30	88.38	91.95
70	43.28	45.44	48.76	51.74	55.33	61.70	69.33	85.53	90.53	95.02	100.43	104.21
80	51.17	53.54	57.15	60.39	64.28	71.14	79.33	96.58	101.88	106.63	112.33	116.32
90	59.20	61.75	65.65	69.13	73.29	80.62	89.33	107.57	113.15	118.14	124.12	128.30
100	67.33	70.06	74.22	77.93	82.36	90.13	99.33	118.50	124.34	129.56	135.81	140.17

F-distribution

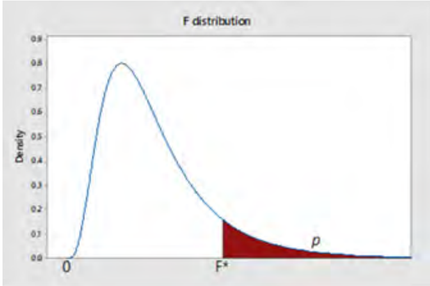


Table C.4. *F-distribution*

degrees of freedom of denominator v_2		degrees of freedom of numerator v_1									
	p	1	2	3	4	5	6	7	8	9	10
1	0.100	39.86	49.50	53.59	55.83	57.24	58.20	58.91	59.44	59.86	60.19
	0.050	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5	241.9
	0.010	4052	5000	5403	5625	5764	5859	5928	5981	6022	6056
2	0.100	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39
	0.050	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40
	0.010	98.50	99.00	99.17	99.25	99.30	99.33	99.36	99.37	99.39	99.40
3	0.100	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24	5.23
	0.050	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79
	0.010	34.12	30.82	29.46	28.71	28.24	27.91	27.67	27.49	27.35	27.23
4	0.100	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92
	0.050	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96
	0.010	21.20	18.00	16.69	15.98	15.52	15.21	14.98	14.80	14.66	14.55
5	0.100	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32	3.30
	0.050	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74
	0.010	16.26	13.27	12.06	11.39	10.97	10.67	10.46	10.29	10.16	10.05
6	0.100	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94
	0.050	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06
	0.010	13.75	10.92	9.78	9.15	8.75	8.47	8.26	8.10	7.98	7.87
7	0.100	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70
	0.050	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64
	0.010	12.25	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72	6.62
8	0.100	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54
	0.050	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35
	0.010	11.26	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91	5.81
9	0.100	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44	2.42
	0.050	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14
	0.010	10.56	8.02	6.99	6.42	6.06	5.80	5.61	5.47	5.35	5.26
10	0.100	3.29	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35	2.32
	0.050	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98
	0.010	10.04	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.94	4.85
11	0.100	3.23	2.86	2.66	2.54	2.45	2.39	2.34	2.30	2.27	2.25
	0.050	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85
	0.010	9.65	7.21	6.22	5.67	5.32	5.07	4.89	4.74	4.63	4.54
12	0.100	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19
	0.050	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75
	0.010	9.33	6.93	5.95	5.41	5.06	4.82	4.64	4.50	4.39	4.30
13	0.100	3.14	2.76	2.56	2.43	2.35	2.28	2.23	2.20	2.16	2.14
	0.050	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67
	0.010	9.07	6.70	5.74	5.21	4.86	4.62	4.44	4.30	4.19	4.10
14	0.100	3.10	2.73	2.52	2.39	2.31	2.24	2.19	2.15	2.12	2.10
	0.050	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60
	0.010	8.86	6.51	5.56	5.04	4.69	4.46	4.28	4.14	4.03	3.94
15	0.100	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.06
	0.050	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54
	0.010	8.68	6.36	5.42	4.89	4.56	4.32	4.14	4.00	3.89	3.80

		degrees of freedom of numerator v_1									
degrees of freedom of denominator v_2	*p*	12	15	20	25	30	40	50	60	120	1000
1	0.100	60.71	61.22	61.74	62.05	62.26	62.53	62.69	62.79	63.06	63.30
	0.050	243.9	245.9	248.0	249.3	250.1	251.1	251.8	252.2	253.3	254.2
	0.010	6106	6157	6209	6240	6261	6287	6303	6313	6339	6363
2	0.100	9.41	9.42	9.44	9.45	9.46	9.47	9.47	9.47	9.48	9.49
	0.050	19.41	19.43	19.45	19.46	19.46	19.47	19.48	19.48	19.49	19.49
	0.010	99.42	99.43	99.45	99.46	99.47	99.47	99.48	99.48	99.49	99.50
3	0.100	5.22	5.20	5.18	5.17	5.17	5.16	5.15	5.15	5.14	5.13
	0.050	8.74	8.70	8.66	8.63	8.62	8.59	8.58	8.57	8.55	8.53
	0.010	27.05	26.87	26.69	26.58	26.50	26.41	26.35	26.32	26.22	26.14
4	0.100	3.90	3.87	3.84	3.83	3.82	3.80	3.80	3.79	3.78	3.76
	0.050	5.91	5.86	5.80	5.77	5.75	5.72	5.70	5.69	5.66	5.63
	0.010	14.37	14.20	14.02	13.91	13.84	13.75	13.69	13.65	13.56	13.47
5	0.100	3.27	3.24	3.21	3.19	3.17	3.16	3.15	3.14	3.12	3.11
	0.050	4.68	4.62	4.56	4.52	4.50	4.46	4.44	4.43	4.40	4.37
	0.010	9.89	9.72	9.55	9.45	9.38	9.29	9.24	9.20	9.11	9.03
6	0.100	2.90	2.87	2.84	2.81	2.80	2.78	2.77	2.76	2.74	2.72
	0.050	4.00	3.94	3.87	3.83	3.81	3.77	3.75	3.74	3.70	3.67
	0.010	7.72	7.56	7.40	7.30	7.23	7.14	7.09	7.06	6.97	6.89
7	0.100	2.67	2.63	2.59	2.57	2.56	2.54	2.52	2.51	2.49	2.47
	0.050	3.57	3.51	3.44	3.40	3.38	3.34	3.32	3.30	3.27	3.23
	0.010	6.47	6.31	6.16	6.06	5.99	5.91	5.86	5.82	5.74	5.66
8	0.100	2.50	2.46	2.42	2.40	2.38	2.36	2.35	2.34	2.32	2.30
	0.050	3.28	3.22	3.15	3.11	3.08	3.04	3.02	3.01	2.97	2.93
	0.010	5.67	5.52	5.36	5.26	5.20	5.12	5.07	5.03	4.95	4.87
9	0.100	2.38	2.34	2.30	2.27	2.25	2.23	2.22	2.21	2.18	2.16
	0.050	3.07	3.01	2.94	2.89	2.86	2.83	2.80	2.79	2.75	2.71
	0.010	5.11	4.96	4.81	4.71	4.65	4.57	4.52	4.48	4.40	4.32
10	0.100	2.28	2.24	2.20	2.17	2.16	2.13	2.12	2.11	2.08	2.06
	0.050	2.91	2.85	2.77	2.73	2.70	2.66	2.64	2.62	2.58	2.54
	0.010	4.71	4.56	4.41	4.31	4.25	4.17	4.12	4.08	4.00	3.92
11	0.100	2.21	2.17	2.12	2.10	2.08	2.05	2.04	2.03	2.00	1.98
	0.050	2.79	2.72	2.65	2.60	2.57	2.53	2.51	2.49	2.45	2.41
	0.010	4.40	4.25	4.10	4.01	3.94	3.86	3.81	3.78	3.69	3.61
12	0.100	2.15	2.10	2.06	2.03	2.01	1.99	1.97	1.96	1.93	1.91
	0.050	2.69	2.62	2.54	2.50	2.47	2.43	2.40	2.38	2.34	2.30
	0.010	4.16	4.01	3.86	3.76	3.70	3.62	3.57	3.54	3.45	3.37
13	0.100	2.10	2.05	2.01	1.98	1.96	1.93	1.92	1.90	1.88	1.85
	0.050	2.60	2.53	2.46	2.41	2.38	2.34	2.31	2.30	2.25	2.21
	0.010	3.96	3.82	3.66	3.57	3.51	3.43	3.38	3.34	3.25	3.18
14	0.100	2.05	2.01	1.96	1.93	1.91	1.89	1.87	1.86	1.83	1.80
	0.050	2.53	2.46	2.39	2.34	2.31	2.27	2.24	2.22	2.18	2.14
	0.010	3.80	3.66	3.51	3.41	3.35	3.27	3.22	3.18	3.09	3.02
15	0.100	2.02	1.97	1.92	1.89	1.87	1.85	1.83	1.82	1.79	1.76
	0.050	2.48	2.40	2.33	2.28	2.25	2.20	2.18	2.16	2.11	2.07
	0.010	3.67	3.52	3.37	3.28	3.21	3.13	3.08	3.05	2.96	2.88

		degrees of freedom of numerator v_1									
degrees of freedom of denominator v_2	*p*	1	2	3	4	5	6	7	8	9	10
16	0.100	3.05	2.67	2.46	2.33	2.24	2.18	2.13	2.09	2.06	2.03
	0.050	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49
	0.010	8.53	6.23	5.29	4.77	4.44	4.20	4.03	3.89	3.78	3.69
17	0.100	3.03	2.64	2.44	2.31	2.22	2.15	2.10	2.06	2.03	2.00
	0.050	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45
	0.010	8.40	6.11	5.18	4.67	4.34	4.10	3.93	3.79	3.68	3.59
18	0.100	3.01	2.62	2.42	2.29	2.20	2.13	2.08	2.04	2.00	1.98
	0.050	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41
	0.010	8.29	6.01	5.09	4.58	4.25	4.01	3.84	3.71	3.60	3.51
19	0.100	2.99	2.61	2.40	2.27	2.18	2.11	2.06	2.02	1.98	1.96
	0.050	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38
	0.010	8.18	5.93	5.01	4.50	4.17	3.94	3.77	3.63	3.52	3.43
20	0.100	2.97	2.59	2.38	2.25	2.16	2.09	2.04	2.00	1.96	1.94
	0.050	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35
	0.010	8.10	5.85	4.94	4.43	4.10	3.87	3.70	3.56	3.46	3.37
22	0.100	2.95	2.56	2.35	2.22	2.13	2.06	2.01	1.97	1.93	1.90
	0.050	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34	2.30
	0.010	7.95	5.72	4.82	4.31	3.99	3.76	3.59	3.45	3.35	3.26
24	0.100	2.93	2.54	2.33	2.19	2.10	2.04	1.98	1.94	1.91	1.88
	0.050	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25
	0.010	7.82	5.61	4.72	4.22	3.90	3.67	3.50	3.36	3.26	3.17
26	0.100	2.91	2.52	2.31	2.17	2.08	2.01	1.96	1.92	1.88	1.86
	0.050	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22
	0.010	7.72	5.53	4.64	4.14	3.82	3.59	3.42	3.29	3.18	3.09
30	0.100	2.88	2.49	2.28	2.14	2.05	1.98	1.93	1.88	1.85	1.82
	0.050	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16
	0.010	7.56	5.39	4.51	4.02	3.70	3.47	3.30	3.17	3.07	2.98
35	0.100	2.85	2.46	2.25	2.11	2.02	1.95	1.90	1.85	1.82	1.79
	0.050	4.12	3.27	2.87	2.64	2.49	2.37	2.29	2.22	2.16	2.11
	0.010	7.42	5.27	4.40	3.91	3.59	3.37	3.20	3.07	2.96	2.88
40	0.100	2.84	2.44	2.23	2.09	2.00	1.93	1.87	1.83	1.79	1.76
	0.050	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12	2.08
	0.010	7.31	5.18	4.31	3.83	3.51	3.29	3.12	2.99	2.89	2.80
50	0.100	2.81	2.41	2.20	2.06	1.97	1.90	1.84	1.80	1.76	1.73
	0.050	4.03	3.18	2.79	2.56	2.40	2.29	2.20	2.13	2.07	2.03
	0.010	7.17	5.06	4.20	3.72	3.41	3.19	3.02	2.89	2.78	2.70
60	0.100	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74	1.71
	0.050	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99
	0.010	7.08	4.98	4.13	3.65	3.34	3.12	2.95	2.82	2.72	2.63
80	0.100	2.77	2.37	2.15	2.02	1.92	1.85	1.79	1.75	1.71	1.68
	0.050	3.96	3.11	2.72	2.49	2.33	2.21	2.13	2.06	2.00	1.95
	0.010	6.96	4.88	4.04	3.56	3.26	3.04	2.87	2.74	2.64	2.55
100	0.100	2.76	2.36	2.14	2.00	1.91	1.83	1.78	1.73	1.69	1.66
	0.050	3.94	3.09	2.70	2.46	2.31	2.19	2.10	2.03	1.97	1.93
	0.010	6.90	4.82	3.98	3.51	3.21	2.99	2.82	2.69	2.59	2.50
1000	0.100	2.71	2.31	2.09	1.95	1.85	1.78	1.72	1.68	1.64	1.61
	0.050	3.85	3.00	2.61	2.38	2.22	2.11	2.02	1.95	1.89	1.84
	0.010	6.66	4.63	3.80	3.34	3.04	2.82	2.66	2.53	2.43	2.34

degrees of freedom of denominator v_2		degrees of freedom of numerator v_1									
	p	12	15	20	25	30	40	50	60	120	1000
16	0.100	1.99	1.94	1.89	1.86	1.84	1.81	1.79	1.78	1.75	1.72
	0.050	2.42	2.35	2.28	2.23	2.19	2.15	2.12	2.11	2.06	2.02
	0.010	3.55	3.41	3.26	3.16	3.10	3.02	2.97	2.93	2.84	2.76
17	0.100	1.96	1.91	1.86	1.83	1.81	1.78	1.76	1.75	1.72	1.69
	0.050	2.38	2.31	2.23	2.18	2.15	2.10	2.08	2.06	2.01	1.97
	0.010	3.46	3.31	3.16	3.07	3.00	2.92	2.87	2.83	2.75	2.66
18	0.100	1.93	1.89	1.84	1.80	1.78	1.75	1.74	1.72	1.69	1.66
	0.050	2.34	2.27	2.19	2.14	2.11	2.06	2.04	2.02	1.97	1.92
	0.010	3.37	3.23	3.08	2.98	2.92	2.84	2.78	2.75	2.66	2.58
19	0.100	1.91	1.86	1.81	1.78	1.76	1.73	1.71	1.70	1.67	1.64
	0.050	2.31	2.23	2.16	2.11	2.07	2.03	2.00	1.98	1.93	1.88
	0.010	3.30	3.15	3.00	2.91	2.84	2.76	2.71	2.67	2.58	2.50
20	0.100	1.89	1.84	1.79	1.76	1.74	1.71	1.69	1.68	1.64	1.61
	0.050	2.28	2.20	2.12	2.07	2.04	1.99	1.97	1.95	1.90	1.85
	0.010	3.23	3.09	2.94	2.84	2.78	2.69	2.64	2.61	2.52	2.43
22	0.100	1.86	1.81	1.76	1.73	1.70	1.67	1.65	1.64	1.60	1.57
	0.050	2.23	2.15	2.07	2.02	1.98	1.94	1.91	1.89	1.84	1.79
	0.010	3.12	2.98	2.83	2.73	2.67	2.58	2.53	2.50	2.40	2.32
24	0.100	1.83	1.78	1.73	1.70	1.67	1.64	1.62	1.61	1.57	1.54
	0.050	2.18	2.11	2.03	1.97	1.94	1.89	1.86	1.84	1.79	1.74
	0.010	3.03	2.89	2.74	2.64	2.58	2.49	2.44	2.40	2.31	2.22
26	0.100	1.81	1.76	1.71	1.67	1.65	1.61	1.59	1.58	1.54	1.51
	0.050	2.15	2.07	1.99	1.94	1.90	1.85	1.82	1.80	1.75	1.70
	0.010	2.96	2.81	2.66	2.57	2.50	2.42	2.36	2.33	2.23	2.14
30	0.100	1.77	1.72	1.67	1.63	1.61	1.57	1.55	1.54	1.50	1.46
	0.050	2.09	2.01	1.93	1.88	1.84	1.79	1.76	1.74	1.68	1.63
	0.010	2.84	2.70	2.55	2.45	2.39	2.30	2.25	2.21	2.11	2.02
35	0.100	1.74	1.69	1.63	1.60	1.57	1.53	1.51	1.50	1.46	1.42
	0.050	2.04	1.96	1.88	1.82	1.79	1.74	1.70	1.68	1.62	1.57
	0.010	2.74	2.60	2.44	2.35	2.28	2.19	2.14	2.10	2.00	1.90
40	0.100	1.71	1.66	1.61	1.57	1.54	1.51	1.48	1.47	1.42	1.38
	0.050	2.00	1.92	1.84	1.78	1.74	1.69	1.66	1.64	1.58	1.52
	0.010	2.66	2.52	2.37	2.27	2.20	2.11	2.06	2.02	1.92	1.82
50	0.100	1.68	1.63	1.57	1.53	1.50	1.46	1.44	1.42	1.38	1.33
	0.050	1.95	1.87	1.78	1.73	1.69	1.63	1.60	1.58	1.51	1.45
	0.010	2.56	2.42	2.27	2.17	2.10	2.01	1.95	1.91	1.80	1.70
60	0.100	1.66	1.60	1.54	1.50	1.48	1.44	1.41	1.40	1.35	1.30
	0.050	1.92	1.84	1.75	1.69	1.65	1.59	1.56	1.53	1.47	1.40
	0.010	2.50	2.35	2.20	2.10	2.03	1.94	1.88	1.84	1.73	1.62
80	0.100	1.63	1.57	1.51	1.47	1.44	1.40	1.38	1.36	1.31	1.25
	0.050	1.88	1.79	1.70	1.64	1.60	1.54	1.51	1.48	1.41	1.34
	0.010	2.42	2.27	2.12	2.01	1.94	1.85	1.79	1.75	1.63	1.51
100	0.100	1.61	1.56	1.49	1.45	1.42	1.38	1.35	1.34	1.28	1.22
	0.050	1.85	1.77	1.68	1.62	1.57	1.52	1.48	1.45	1.38	1.30
	0.010	2.37	2.22	2.07	1.97	1.89	1.80	1.74	1.69	1.57	1.45
1000	0.100	1.55	1.49	1.43	1.38	1.35	1.30	1.27	1.25	1.18	1.08
	0.050	1.76	1.68	1.58	1.52	1.47	1.41	1.36	1.33	1.24	1.11
	0.010	2.20	2.06	1.90	1.79	1.72	1.61	1.54	1.50	1.35	1.16

Binomial distribution

$$P(X \leq x) = \sum_{k=0}^{k=x} \binom{n}{k} \cdot p^k \cdot (1-p)^{n-k}$$

Table C.5. *Binomial distribution*

		p								
n	*x*	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1	0	0.9900	0.9800	0.9700	0.9600	0.9500	0.9400	0.9300	0.9200	0.9100
	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	0	0.9801	0.9604	0.9409	0.9216	0.9025	0.8836	0.8649	0.8464	0.8281
	1	0.9999	0.9996	0.9991	0.9984	0.9975	0.9964	0.9951	0.9936	0.9919
	2	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0	0.9703	0.9412	0.9127	0.8847	0.8574	0.8306	0.8044	0.7787	0.7536
	1	0.9997	0.9988	0.9974	0.9953	0.9928	0.9896	0.9860	0.9818	0.9772
	2	1.0000	1.0000	1.0000	0.9999	0.9999	0.9998	0.9997	0.9995	0.9993
	3				1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4	0	0.9606	0.9224	0.8853	0.8493	0.8145	0.7807	0.7481	0.7164	0.6857
	1	0.9994	0.9977	0.9948	0.9909	0.9860	0.9801	0.9733	0.9656	0.9570
	2	1.0000	1.0000	0.9999	0.9998	0.9995	0.9992	0.9987	0.9981	0.9973
	3			1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
	4									1.0000
5	0	0.9510	0.9039	0.8587	0.8154	0.7738	0.7339	0.6957	0.6591	0.6240
	1	0.9990	0.9962	0.9915	0.9852	0.9774	0.9681	0.9575	0.9456	0.9326
	2	1.0000	0.9999	0.9997	0.9994	0.9988	0.9980	0.9969	0.9955	0.9937
	3		1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9998	0.9997
	4						1.0000	1.0000	1.0000	1.0000
	5									
6	0	0.9415	0.8858	0.8330	0.7828	0.7351	0.6899	0.6470	0.6064	0.5679
	1	0.9985	0.9943	0.9875	0.9784	0.9672	0.9541	0.9392	0.9227	0.9048
	2	1.0000	0.9998	0.9995	0.9988	0.9978	0.9962	0.9942	0.9915	0.9882
	3		1.0000	1.0000	1.0000	0.9999	0.9998	0.9997	0.9995	0.9992
	4					1.0000	1.0000	1.0000	1.0000	1.0000
	5									
	6									
7	0	0.9321	0.8681	0.8080	0.7514	0.6983	0.6485	0.6017	0.5578	0.5168
	1	0.9980	0.9921	0.9829	0.9706	0.9556	0.9382	0.9187	0.8974	0.8745
	2	1.0000	0.9997	0.9991	0.9980	0.9962	0.9937	0.9903	0.9860	0.9807
	3		1.0000	1.0000	0.9999	0.9998	0.9996	0.9993	0.9988	0.9982
	4				1.0000	1.0000	1.0000	1.0000	0.9999	0.9999
	5								1.0000	1.0000
	6									
8	0	0.9227	0.8508	0.7837	0.7214	0.6634	0.6096	0.5596	0.5132	0.4703
	1	0.9973	0.9897	0.9777	0.9619	0.9428	0.9208	0.8965	0.8702	0.8423
	2	0.9999	0.9996	0.9987	0.9969	0.9942	0.9904	0.9853	0.9789	0.9711
	3	1.0000	1.0000	0.9999	0.9998	0.9996	0.9993	0.9987	0.9978	0.9966
	4			1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997
	5							1.0000	1.0000	1.0000
	6									

		p								
n	*x*	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
1	0	0.9000	0.8500	0.8000	0.7500	0.7000	0.6500	0.6000	0.5500	0.5000
	1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	0	0.8100	0.7225	0.6400	0.5625	0.4900	0.4225	0.3600	0.3025	0.2500
	1	0.9900	0.9775	0.9600	0.9375	0.9100	0.8775	0.8400	0.7975	0.7500
	2	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0	0.7290	0.6141	0.5120	0.4219	0.3430	0.2746	0.2160	0.1664	0.1250
	1	0.9720	0.9393	0.8960	0.8438	0.7840	0.7183	0.6480	0.5748	0.5000
	2	0.9990	0.9966	0.9920	0.9844	0.9730	0.9571	0.9360	0.9089	0.8750
	3	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4	0	0.6561	0.5220	0.4096	0.3164	0.2401	0.1785	0.1296	0.0915	0.0625
	1	0.9477	0.8905	0.8192	0.7383	0.6517	0.5630	0.4752	0.3910	0.3125
	2	0.9963	0.9880	0.9728	0.9492	0.9163	0.8735	0.8208	0.7585	0.6875
	3	0.9999	0.9995	0.9984	0.9961	0.9919	0.9850	0.9744	0.9590	0.9375
	4	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0	0.5905	0.4437	0.3277	0.2373	0.1681	0.1160	0.0778	0.0503	0.0313
	1	0.9185	0.8352	0.7373	0.6328	0.5282	0.4284	0.3370	0.2562	0.1875
	2	0.9914	0.9734	0.9421	0.8965	0.8369	0.7648	0.6826	0.5931	0.5000
	3	0.9995	0.9978	0.9933	0.9844	0.9692	0.9460	0.9130	0.8688	0.8125
	4	1.0000	0.9999	0.9997	0.9990	0.9976	0.9947	0.9898	0.9815	0.9688
	5		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
6	0	0.5314	0.3771	0.2621	0.1780	0.1176	0.0754	0.0467	0.0277	0.0156
	1	0.8857	0.7765	0.6554	0.5339	0.4202	0.3191	0.2333	0.1636	0.1094
	2	0.9842	0.9527	0.9011	0.8306	0.7443	0.6471	0.5443	0.4415	0.3438
	3	0.9987	0.9941	0.9830	0.9624	0.9295	0.8826	0.8208	0.7447	0.6563
	4	0.9999	0.9996	0.9984	0.9954	0.9891	0.9777	0.9590	0.9308	0.8906
	5	1.0000	1.0000	0.9999	0.9998	0.9993	0.9982	0.9959	0.9917	0.9844
	6			1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
7	0	0.4783	0.3206	0.2097	0.1335	0.0824	0.0490	0.0280	0.0152	0.0078
	1	0.8503	0.7166	0.5767	0.4449	0.3294	0.2338	0.1586	0.1024	0.0625
	2	0.9743	0.9262	0.8520	0.7564	0.6471	0.5323	0.4199	0.3164	0.2266
	3	0.9973	0.9879	0.9667	0.9294	0.8740	0.8002	0.7102	0.6083	0.5000
	4	0.9998	0.9988	0.9953	0.9871	0.9712	0.9444	0.9037	0.8471	0.7734
	5	1.0000	0.9999	0.9996	0.9987	0.9962	0.9910	0.9812	0.9643	0.9375
	6		1.0000	1.0000	0.9999	0.9998	0.9994	0.9984	0.9963	0.9922
	7				1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
8	0	0.4305	0.2725	0.1678	0.1001	0.0576	0.0319	0.0168	0.0084	0.0039
	1	0.8131	0.6572	0.5033	0.3671	0.2553	0.1691	0.1064	0.0632	0.0352
	2	0.9619	0.8948	0.7969	0.6785	0.5518	0.4278	0.3154	0.2201	0.1445
	3	0.9950	0.9786	0.9437	0.8862	0.8059	0.7064	0.5941	0.4770	0.3633
	4	0.9996	0.9971	0.9896	0.9727	0.9420	0.8939	0.8263	0.7396	0.6367
	5	1.0000	0.9998	0.9988	0.9958	0.9887	0.9747	0.9502	0.9115	0.8555
	6		1.0000	0.9999	0.9996	0.9987	0.9964	0.9915	0.9819	0.9648
	7			1.0000	1.0000	0.9999	0.9998	0.9993	0.9983	0.9961
	8					1.0000	1.0000	1.0000	1.0000	1.0000

		p								
n	*x*	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
9	0	0.9135	0.8337	0.7602	0.6925	0.6302	0.5730	0.5204	0.4722	0.4279
	1	0.9966	0.9869	0.9718	0.9522	0.9288	0.9022	0.8729	0.8417	0.8088
	2	0.9999	0.9994	0.9980	0.9955	0.9916	0.9862	0.9791	0.9702	0.9595
	3	1.0000	1.0000	0.9999	0.9997	0.9994	0.9987	0.9977	0.9963	0.9943
	4			1.0000	1.0000	1.0000	0.9999	0.9998	0.9997	0.9995
	5						1.0000	1.0000	1.0000	1.0000
	6									
	7									
	8									
	9									
10	0	0.9044	0.8171	0.7374	0.6648	0.5987	0.5386	0.4840	0.4344	0.3894
	1	0.9957	0.9838	0.9655	0.9418	0.9139	0.8824	0.8483	0.8121	0.7746
	2	0.9999	0.9991	0.9972	0.9938	0.9885	0.9812	0.9717	0.9599	0.9460
	3	1.0000	1.0000	0.9999	0.9996	0.9990	0.9980	0.9964	0.9942	0.9912
	4			1.0000	1.0000	0.9999	0.9998	0.9997	0.9994	0.9990
	5					1.0000	1.0000	1.0000	1.0000	0.9999
	6									1.0000
	7									
	8									
	9									
	10									
12	0	0.8864	0.7847	0.6938	0.6127	0.5404	0.4759	0.4186	0.3677	0.3225
	1	0.9938	0.9769	0.9514	0.9191	0.8816	0.8405	0.7967	0.7513	0.7052
	2	0.9998	0.9985	0.9952	0.9893	0.9804	0.9684	0.9532	0.9348	0.9134
	3	1.0000	0.9999	0.9997	0.9990	0.9978	0.9957	0.9925	0.9880	0.9820
	4		1.0000	1.0000	0.9999	0.9998	0.9996	0.9991	0.9984	0.9973
	5				1.0000	1.0000	1.0000	0.9999	0.9998	0.9997
	6							1.0000	1.0000	1.0000
	7									
	8									
	9									
	10									
	11									
	12									
15	0	0.8601	0.7386	0.6333	0.5421	0.4633	0.3953	0.3367	0.2863	0.2430
	1	0.9904	0.9647	0.9270	0.8809	0.8290	0.7738	0.7168	0.6597	0.6035
	2	0.9996	0.9970	0.9906	0.9797	0.9638	0.9429	0.9171	0.8870	0.8531
	3	1.0000	0.9998	0.9992	0.9976	0.9945	0.9896	0.9825	0.9727	0.9601
	4		1.0000	0.9999	0.9998	0.9994	0.9986	0.9972	0.9950	0.9918
	5			1.0000	1.0000	0.9999	0.9999	0.9997	0.9993	0.9987
	6					1.0000	1.0000	1.0000	0.9999	0.9998
	7								1.0000	1.0000
	8									
	9									
	10									
	11									
	12									
	13									
	14									

		p								
n	*x*	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
9	0	0.3874	0.2316	0.1342	0.0751	0.0404	0.0207	0.0101	0.0046	0.0020
	1	0.7748	0.5995	0.4362	0.3003	0.1960	0.1211	0.0705	0.0385	0.0195
	2	0.9470	0.8591	0.7382	0.6007	0.4628	0.3373	0.2318	0.1495	0.0898
	3	0.9917	0.9661	0.9144	0.8343	0.7297	0.6089	0.4826	0.3614	0.2539
	4	0.9991	0.9944	0.9804	0.9511	0.9012	0.8283	0.7334	0.6214	0.5000
	5	0.9999	0.9994	0.9969	0.9900	0.9747	0.9464	0.9006	0.8342	0.7461
	6	1.0000	1.0000	0.9997	0.9987	0.9957	0.9888	0.9750	0.9502	0.9102
	7			1.0000	0.9999	0.9996	0.9986	0.9962	0.9909	0.9805
	8				1.0000	1.0000	0.9999	0.9997	0.9992	0.9980
	9						1.0000	1.0000	1.0000	1.0000
10	0	0.3487	0.1969	0.1074	0.0563	0.0282	0.0135	0.0060	0.0025	0.0010
	1	0.7361	0.5443	0.3758	0.2440	0.1493	0.0860	0.0464	0.0233	0.0107
	2	0.9298	0.8202	0.6778	0.5256	0.3828	0.2616	0.1673	0.0996	0.0547
	3	0.9872	0.9500	0.8791	0.7759	0.6496	0.5138	0.3823	0.2660	0.1719
	4	0.9984	0.9901	0.9672	0.9219	0.8497	0.7515	0.6331	0.5044	0.3770
	5	0.9999	0.9986	0.9936	0.9803	0.9527	0.9051	0.8338	0.7384	0.6230
	6	1.0000	0.9999	0.9991	0.9965	0.9894	0.9740	0.9452	0.8980	0.8281
	7		1.0000	0.9999	0.9996	0.9984	0.9952	0.9877	0.9726	0.9453
	8			1.0000	1.0000	0.9999	0.9995	0.9983	0.9955	0.9893
	9					1.0000	1.0000	0.9999	0.9997	0.9990
	10							1.0000	1.0000	1.0000
12	0	0.2824	0.1422	0.0687	0.0317	0.0138	0.0057	0.0022	0.0008	0.0002
	1	0.6590	0.4435	0.2749	0.1584	0.0850	0.0424	0.0196	0.0083	0.0032
	2	0.8891	0.7358	0.5583	0.3907	0.2528	0.1513	0.0834	0.0421	0.0193
	3	0.9744	0.9078	0.7946	0.6488	0.4925	0.3467	0.2253	0.1345	0.0730
	4	0.9957	0.9761	0.9274	0.8424	0.7237	0.5833	0.4382	0.3044	0.1938
	5	0.9995	0.9954	0.9806	0.9456	0.8822	0.7873	0.6652	0.5269	0.3872
	6	0.9999	0.9993	0.9961	0.9857	0.9614	0.9154	0.8418	0.7393	0.6128
	7	1.0000	0.9999	0.9994	0.9972	0.9905	0.9745	0.9427	0.8883	0.8062
	8		1.0000	0.9999	0.9996	0.9983	0.9944	0.9847	0.9644	0.9270
	9			1.0000	1.0000	0.9998	0.9992	0.9972	0.9921	0.9807
	10					1.0000	0.9999	0.9997	0.9989	0.9968
	11						1.0000	1.0000	0.9999	0.9998
	12								1.0000	1.0000
15	0	0.2059	0.0874	0.0352	0.0134	0.0047	0.0016	0.0005	0.0001	0.0000
	1	0.5490	0.3186	0.1671	0.0802	0.0353	0.0142	0.0052	0.0017	0.0005
	2	0.8159	0.6042	0.3980	0.2361	0.1268	0.0617	0.0271	0.0107	0.0037
	3	0.9444	0.8227	0.6482	0.4613	0.2969	0.1727	0.0905	0.0424	0.0176
	4	0.9873	0.9383	0.8358	0.6865	0.5155	0.3519	0.2173	0.1204	0.0592
	5	0.9978	0.9832	0.9389	0.8516	0.7216	0.5643	0.4032	0.2608	0.1509
	6	0.9997	0.9964	0.9819	0.9434	0.8689	0.7548	0.6098	0.4522	0.3036
	7	1.0000	0.9994	0.9958	0.9827	0.9500	0.8868	0.7869	0.6535	0.5000
	8		0.9999	0.9992	0.9958	0.9848	0.9578	0.9050	0.8182	0.6964
	9		1.0000	0.9999	0.9992	0.9963	0.9876	0.9662	0.9231	0.8491
	10			1.0000	0.9999	0.9993	0.9972	0.9907	0.9745	0.9408
	11				1.0000	0.9999	0.9995	0.9981	0.9937	0.9824
	12					1.0000	0.9999	0.9997	0.9989	0.9963
	13						1.0000	1.0000	0.9999	0.9995
	14								1.0000	1.0000

Poisson distribution

$$P(X \leq x) = \sum_{k=0}^{k=x} \frac{\lambda^k \cdot e^{-\lambda}}{k!}$$

Table C.6. *Poisson distribution*

	λ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$x=$	0	0.9048	0.8187	0.7408	0.6703	0.6065	0.5488	0.4966	0.4493	0.4066	0.3679
	1	0.9953	0.9825	0.9631	0.9384	0.9098	0.8781	0.8442	0.8088	0.7725	0.7358
	2	0.9998	0.9989	0.9964	0.9921	0.9856	0.9769	0.9659	0.9526	0.9371	0.9197
	3	1.0000	0.9999	0.9997	0.9992	0.9982	0.9966	0.9942	0.9909	0.9865	0.9810
	4	1.0000	1.0000	1.0000	0.9999	0.9998	0.9996	0.9992	0.9986	0.9977	0.9963
	5	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9998	0.9997	0.9994
	6	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
	7	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

	λ	1.2	1.4	1.6	1.8	2.2	2.4	2.6	2.8	3.0	3.2
$x=$	0	0.3012	0.2466	0.2019	0.1653	0.1108	0.0907	0.0743	0.0608	0.0498	0.0408
	1	0.6626	0.5918	0.5249	0.4628	0.3546	0.3084	0.2674	0.2311	0.1991	0.1712
	2	0.8795	0.8335	0.7834	0.7306	0.6227	0.5697	0.5184	0.4695	0.4232	0.3799
	3	0.9662	0.9463	0.9212	0.8913	0.8194	0.7787	0.7360	0.6919	0.6472	0.6025
	4	0.9923	0.9857	0.9763	0.9636	0.9275	0.9041	0.8774	0.8477	0.8153	0.7806
	5	0.9985	0.9968	0.9940	0.9896	0.9751	0.9643	0.9510	0.9349	0.9161	0.8946
	6	0.9997	0.9994	0.9987	0.9974	0.9925	0.9884	0.9828	0.9756	0.9665	0.9554
	7	1.0000	0.9999	0.9997	0.9994	0.9980	0.9967	0.9947	0.9919	0.9881	0.9832
	8	1.0000	1.0000	1.0000	0.9999	0.9995	0.9991	0.9985	0.9976	0.9962	0.9943
	9	1.0000	1.0000	1.0000	1.0000	0.9999	0.9998	0.9996	0.9993	0.9989	0.9982
	10	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9998	0.9997	0.9995
	11	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999
	12	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

	λ	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
$x=$	0	0.0302	0.0183	0.0111	0.0067	0.0041	0.0025	0.0015	0.0009	0.0006	0.0003
	1	0.1359	0.0916	0.0611	0.0404	0.0266	0.0174	0.0113	0.0073	0.0047	0.0030
	2	0.3208	0.2381	0.1736	0.1247	0.0884	0.0620	0.0430	0.0296	0.0203	0.0138
	3	0.5366	0.4335	0.3423	0.2650	0.2017	0.1512	0.1118	0.0818	0.0591	0.0424
	4	0.7254	0.6288	0.5321	0.4405	0.3575	0.2851	0.2237	0.1730	0.1321	0.0996
	5	0.8576	0.7851	0.7029	0.6160	0.5289	0.4457	0.3690	0.3007	0.2414	0.1912
	6	0.9347	0.8893	0.8311	0.7622	0.6860	0.6063	0.5265	0.4497	0.3782	0.3134
	7	0.9733	0.9489	0.9134	0.8666	0.8095	0.7440	0.6728	0.5987	0.5246	0.4530
	8	0.9901	0.9786	0.9597	0.9319	0.8944	0.8472	0.7916	0.7291	0.6620	0.5925
	9	0.9967	0.9919	0.9829	0.9682	0.9462	0.9161	0.8774	0.8305	0.7764	0.7166
	10	0.9990	0.9972	0.9933	0.9863	0.9747	0.9574	0.9332	0.9015	0.8622	0.8159
	11	0.9997	0.9991	0.9976	0.9945	0.9890	0.9799	0.9661	0.9467	0.9208	0.8881
	12	0.9999	0.9997	0.9992	0.9980	0.9955	0.9912	0.9840	0.9730	0.9573	0.9362
	13	1.0000	0.9999	0.9997	0.9993	0.9983	0.9964	0.9929	0.9872	0.9784	0.9658
	14	1.0000	1.0000	0.9999	0.9998	0.9994	0.9986	0.9970	0.9943	0.9897	0.9827
	15	1.0000	1.0000	1.0000	0.9999	0.9998	0.9995	0.9988	0.9976	0.9954	0.9918
	16	1.0000	1.0000	1.0000	1.0000	0.9999	0.9998	0.9996	0.9990	0.9980	0.9963
	17	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9998	0.9996	0.9992	0.9984
	18	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9993
	19	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9997
	20	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
	21	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

	λ	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	18.0	20.0
x=	0	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	1	0.0012	0.0005	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	2	0.0062	0.0028	0.0012	0.0005	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000
	3	0.0212	0.0103	0.0049	0.0023	0.0011	0.0005	0.0002	0.0001	0.0000	0.0000
	4	0.0550	0.0293	0.0151	0.0076	0.0037	0.0018	0.0009	0.0004	0.0001	0.0000
	5	0.1157	0.0671	0.0375	0.0203	0.0107	0.0055	0.0028	0.0014	0.0003	0.0001
	6	0.2068	0.1301	0.0786	0.0458	0.0259	0.0142	0.0076	0.0040	0.0010	0.0003
	7	0.3239	0.2202	0.1432	0.0895	0.0540	0.0316	0.0180	0.0100	0.0029	0.0008
	8	0.4557	0.3328	0.2320	0.1550	0.0998	0.0621	0.0374	0.0220	0.0071	0.0021
	9	0.5874	0.4579	0.3405	0.2424	0.1658	0.1094	0.0699	0.0433	0.0154	0.0050
	10	0.7060	0.5830	0.4599	0.3472	0.2517	0.1757	0.1185	0.0774	0.0304	0.0108
	11	0.8030	0.6968	0.5793	0.4616	0.3532	0.2600	0.1848	0.1270	0.0549	0.0214
	12	0.8758	0.7916	0.6887	0.5760	0.4631	0.3585	0.2676	0.1931	0.0917	0.0390
	13	0.9261	0.8645	0.7813	0.6815	0.5730	0.4644	0.3632	0.2745	0.1426	0.0661
	14	0.9585	0.9165	0.8540	0.7720	0.6751	0.5704	0.4657	0.3675	0.2081	0.1049
	15	0.9780	0.9513	0.9074	0.8444	0.7636	0.6694	0.5681	0.4667	0.2867	0.1565
	16	0.9889	0.9730	0.9441	0.8987	0.8355	0.7559	0.6641	0.5660	0.3751	0.2211
	17	0.9947	0.9857	0.9678	0.9370	0.8905	0.8272	0.7489	0.6593	0.4686	0.2970
	18	0.9976	0.9928	0.9823	0.9626	0.9302	0.8826	0.8195	0.7423	0.5622	0.3814
	19	0.9989	0.9965	0.9907	0.9787	0.9573	0.9235	0.8752	0.8122	0.6509	0.4703
	20	0.9996	0.9984	0.9953	0.9884	0.9750	0.9521	0.9170	0.8682	0.7307	0.5591
	21	0.9998	0.9993	0.9977	0.9939	0.9859	0.9712	0.9469	0.9108	0.7991	0.6437
	22	0.9999	0.9997	0.9990	0.9970	0.9924	0.9833	0.9673	0.9418	0.8551	0.7206
	23	1.0000	0.9999	0.9995	0.9985	0.9960	0.9907	0.9805	0.9633	0.8989	0.7875
	24	1.0000	1.0000	0.9998	0.9993	0.9980	0.9950	0.9888	0.9777	0.9317	0.8432
	25	1.0000	1.0000	0.9999	0.9997	0.9990	0.9974	0.9938	0.9869	0.9554	0.8878
	26	1.0000	1.0000	1.0000	0.9999	0.9995	0.9987	0.9967	0.9925	0.9718	0.9221
	27	1.0000	1.0000	1.0000	0.9999	0.9998	0.9994	0.9983	0.9959	0.9827	0.9475
	28	1.0000	1.0000	1.0000	1.0000	0.9999	0.9997	0.9991	0.9978	0.9897	0.9657
	29	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9996	0.9989	0.9941	0.9782
	30	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9998	0.9994	0.9967	0.9865
	31	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9997	0.9982	0.9919
	32	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9990	0.9953
	33	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9995	0.9973
	34	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9998	0.9985
	35	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9992
	36	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9996
	37	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9998
	38	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
	39	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999
	40	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Appendix D – Factors for Control charts

Observations in Sample, n	Chart for Averages			Chart for Standard Deviations					Chart for Ranges					
	Factors for Control Limits			Factors for Center Line	Factors for Control Limits				Factors for Center Line	Factors for Control Limits				
	A	A_2	A_3	c_4	B_3	B_4	B_5	B_6	d_2	D_1	D_2	D_3	D_4
2	2,121	1,880	2,659	0,7979	0	3,267	0	2,606	1,128	0	3,686	0	3,267
3	1,732	1,023	1,954	0,8862	0	2,568	0	2,276	1,693	0	4,358	0	2,574
4	1,500	0,729	1,628	0,9213	0	2,266	0	2,088	2,059	0	4,698	0	2,282
5	1,342	0,577	1,427	0,9400	0	2,089	0	1,964	2,326	0	4,918	0	2,114
6	1,225	0,483	1,287	0,9515	0,030	1,970	0,029	1,874	2,534	0	5,078	0	2,004
7	1,134	0,419	1,182	0,9594	0,118	1,882	0,113	1,806	2,704	0,204	5,204	0,076	1,924
8	1,061	0,373	1,099	0,9650	0,185	1,815	0,179	1,751	2,847	0,388	5,306	0,136	1,864
9	1,000	0,337	1,032	0,9693	0,239	1,761	0,232	1,707	2,970	0,547	5,393	0,184	1,816
10	0,949	0,308	0,975	0,9727	0,284	1,716	0,276	1,669	3,078	0,686	5,469	0,223	1,777
11	0,905	0,285	0,927	0,9754	0,321	1,679	0,313	1,637	3,173	0,811	5,535	0,256	1,744
12	0,866	0,266	0,886	0,9776	0,354	1,646	0,346	1,610	3,258	0,922	5,594	0,283	1,717
13	0,832	0,249	0,850	0,9794	0,382	1,618	0,374	1,585	3,336	1,025	5,647	0,307	1,693
14	0,802	0,235	0,817	0,9810	0,406	1,594	0,399	1,563	3,407	1,118	5,696	0,328	1,672
15	0,775	0,223	0,789	0,9823	0,428	1,572	0,421	1,544	3,472	1,203	5,741	0,347	1,653
16	0,750	0,212	0,763	0,9835	0,448	1,552	0,440	1,526	3,532	1,282	5,782	0,363	1,637
17	0,728	0,203	0,739	0,9845	0,466	1,534	0,458	1,511	3,588	1,356	5,820	0,378	1,622
18	0,707	0,194	0,718	0,9854	0,482	1,518	0,475	1,496	3,640	1,424	5,856	0,391	1,608
19	0,688	0,187	0,698	0,9862	0,497	1,503	0,490	1,483	3,689	1,487	5,891	0,403	1,597
20	0,671	0,180	0,680	0,9869	0,510	1,490	0,504	1,470	3,735	1,549	5,921	0,415	1,585
21	0,655	0,173	0,663	0,9876	0,523	1,477	0,516	1,459	3,778	1,605	5,951	0,425	1,575
22	0,640	0,167	0,647	0,9882	0,534	1,466	0,528	1,448	3,819	1,659	5,979	0,434	1,566
23	0,626	0,162	0,633	0,9887	0,545	1,455	0,539	1,438	3,858	1,710	6,006	0,443	1,557
24	0,612	0,157	0,619	0,9892	0,555	1,445	0,549	1,429	3,895	1,759	6,031	0,451	1,548
25	0,600	0,153	0,606	0,9896	0,565	1,435	0,559	1,420	3,931	1,806	6,056	0,459	1,541

Appendix E – Six Sigma conversion table

Sigma level	Specification width	ppm outside spec	Percent defective	Cp; Cpk
1	2σ	317,311	31.7%	0.33
2	4σ	45,500	4.55%	0.67
3	6σ	2,700	0.27%	1.00
4	8σ	63	0.0063%	1.33
5	10σ	0.57	0.00006%	1.67
6	12σ	0.002	0.0000002%	2.00

Table 54 – Six Sigma metrics (centered process)

Sigma level	Specification width	ppm outside spec	Percent defective	Ppk (long term)
1	2σ	691,462	69%	-0.17
2	4σ	308,538	31%	0.17
3	6σ	66,807	6.7%	0.50
4	8σ	6,210	0.62%	0.83
5	10σ	233	0.023%	1.17
6	12σ	3.4	0.00034%	1.50

Table 55 – Six Sigma metrics, incorporating 1.5σ shift

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Appendix G – Abbreviations

1PF	One-Piece-Flow
3W	What – Who – When
5S	5S-Housekeeping
5W	5-Why
5W2H	Is – Is Not Analysis
6σ	Six Sigma
7QC	7 Quality Control Tools
8D	Eight Disciplines
A3	A3-report
ABC	Activity-Based Costing
AD	Anderson-Darling
AF	Acceleration Factor
AIAG	Automotive Industry Action Group
ALT	Accelerated Life Testing
ANOVA	Analysis of Variance
APQP	Advanced Product Quality Planning
AQL	Acceptable Quality Limit
ATO	Assemble-to-Order
ATO	Accredited Training Organization
BB	Black Belt
BPM	Business Process Management
BPR	Business Process Reengineering
BSC	Balanced Scorecard
BTO	Build-to-Order
C&E diagram	Cause and Effect diagram
C&E matrix	Cause and Effect matrix
C/O	Change-Over Time
C/T	Cycle Time
CCD	Central Composite Design
CDF	Cumulative Distribution Function
CI	Confidence Interval
CI	Continuous Improvement
CIMM	Continuous Improvement Maturity Model
CM	Change Management
CM	Configuration Management
CONWIP	Constant Work In Process.
COPQ	Cost of Poor-Quality
Cp	Capability index
CPA	Critical Path Analysis
Cpk	Capability index
CPM	Critical Path Method
CPM	Critical Parameter Management
CRB	Change Review Board
CSF	Critical Success Factor
CTC	Critical To Cost
CTD	Critical To Delivery
CTP	Critical To Process
CTQ	Critical to Quality
CUSUM	Cumulative Sum
DC	Digital Copy
df	Degrees of Freedom

DFA	Design for Assembly
DFMEA	Design Failure Mode, Effects, and Analysis
DfSS	Design for Six Sigma
DfX	Design for Excellence
DMADV	Define, Measure, Analyze, Design, Verify
DMAIC	Define, Measure, Analyze, Improve, Control
DOE	Design of Experiments
DPM	Defects per Million
DPMO	Defects Per Million Opportunities
DPO	Defects Per Opportunity
DPU	Defects Per Unit
EBIT	Earnings Before Interest and Tax
EPEx	Every Part, Every time x
ERP	Enterprise Resource Planning
ETO	Engineer-to-Order
EVOP	Evolutionary Operation
EWMA	Exponentially Weighted Moving Average
FIFO	First-In-First-Out
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
FTY	First Time Yield
G8D	Global 8D
GB	Green Belt
GLM	General Linear Model
H(t)	Cumulative Hazard Function
h(t)	Hazard Function
H0	Null Hypothesis
HA	Alternative Hypotheses
HALT	Highly Accelerated Life Testing
HOQ	House Of Quality
HPO	High Performance Organization
ICA	Interim Containment Action
IQR	Interquartile Range
ITR	Inventory Turn Ratio
JI	Job Instruction
JIT	Just-In-Time
JM	Job Methods
JR	Job Relation
KPI	Key Performance Indicator
KPIV	Key Process Input Variable
KPOV	Key Process Output Variable
L/T	Lead Time
LSL	Lower Specification Limit
LSS	Lean Six Sigma
LSSA	Lean Six Sigma Academy
MA	Moving Average
MANOVA	Multiple Analysis of Variance
MBB	Master Black Belt
MBTI	Myers Bridge Type Indicator
MRP	Manufacturing Resource Planning
MSA	Measurement System Analysis
MTBF	Mean Time Between Failures
MTO	Make-to-Order
MTS	Make-to-Stock

MTTF	Mean Time To Failure
NCR	Non Conformity Report
NPC	Name Plate Capacity
NPI	New Product Introduction
NPS	Net Promoter Score
NPV	New Product Development
NVA	Non-Value Added Activities
OCAP	Out-of-Control Action Plan
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OFAT	One-Factor-At-a-Time
Opex	Operational Excellence
OPL	One Point Lesson
OR	Odds Ratio
OTD	On-Time Delivery
p	Probability
P/T Ratio	Precision to Tolerance ratio
PBS	Product Breakdown Structure
PCA	Permanent Corrective Actions
PCA	Principal Component Analysis
PCP	Product Creation Process
PDCA	Plan-Do-Check-Act Circle
PDF	Probability Density Function
PERT	Program Evaluation and Review Technique
PFD	Process Flow Diagram
PFM	Process Flow Map
PFMEA	Process Failure Mode, Effects, and Analysis
PID	Project Initiation Document
PLM	Product Lifecycle Management
PM	Preventive Maintenance
PO	Product Owner
Pp	Process Performance Index
PPAP	Production Part Approval Process
Ppk	Process Performance Index
ppm	Parts per Million
PPM	Project Portfolio Management
Q	Quartile
QA	Quality Assurance
QC	Quality Control
QFD	Quality Function Deployment
QHSE	Quality, Health, Safety & Environment
QMS	Quality Management System
R&R% Study	Gage R&R Study
RACI	RACI Roles & Responsibilities
RCA	Root Cause Analysis
RPN	Risk Priority Number
RQL	Rejectable Quality Level
RSM	Response Surface Methods
RSS	Root Sum of Squares Method
RTY	Rolled Throughput Yield
s	Standard deviation of a dataset
s^2	Variance of a dataset
SCM	Supply Chain Management
SIM	Short Interval Management

SIPOC	Suppliers, Inputs, Process, Outputs, Customers
SMART	Specific Measurable Achievable Realistic Timely
SMED	Single Minute Exchange of Die
SOP	Standard Operating Procedure
SPC	Statistical Process Control
TOC	Theory of Constraints
SPL	Single Point Lesson
TPM	Total Productive Maintenance
TPS	Toyota Production System
TTE	Total Team Effectiveness
TQM	Total Quality Management
TTM	Time-To-Market
TWI	Training Within Industry
USL	Upper Specification Limit
VIF	Variance Inflation Factor
VOB	Voice Of Business
VOC	Voice Of Customer
VSM	Value Stream Map
WBS	Work Breakdown Structure
WCM	World Class Manufacturing
WIP	Work in Process
YB	Yellow Belt
Z	Z-Value
P	Correlation
Σ	Sigma of a population
σ^2	Variance in a population

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