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Industrial application of Six Sigma to increase the OEE of a production line

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1. INTRODUCTION

Six Sigma is a flexible method for improved process output performance and enhanced business leadership. Six Sigma's vision is to create a closed-loop feedback system of information that enables relevant business steering. To do so, Six Sigma sets up a measurement system for processes' outputs that is customer-oriented, data-based, and context-tailored. The customer plays an important role as the performance assessment of the company's processes depends on the customer's definition of quality, its needs, and requirements. The setup of data-based measurement systems of processes enables to assess their performance and to spot arising problems from a fact perspective instead of the perception of individuals. Six Sigma provides a framework to solve problems with unknown causes, and to sustain results. Problems are tackled through projects that have a precise structure named DMAIC cycle. It consists in *define*, *measure*, *analyze*, *improve*, and *control* phases. For each phase Six Sigma provides tools to support team working, clear communication, identification of the root causes of the problem, brainstorming of solutions, and control tools for sustainability; such are SIPOC diagram, customer orientation tools, data collection charts, fishbone diagram, cross-functional diagrams, value stream maps, solutions' brainstorming and prioritization tables and charts, and control charts. Six Sigma requires to tailor the provided tools to the company's context to maximize their effectiveness.

This thesis presents an industrial application of the DMAIC cycle to enhance the efficiency of a production line at the company Henkel. The case study origins from the need to reach the target efficiency of this production line which was underperforming. The root causes of such low performance were unknown to employees and Six Sigma offered suitable tools to tackle the problem and solve it. As the project started the team and I started analyzing available data of the manufacturing process' outputs, and variables chosen to be tracked have been line's run time, downtime, and scrap production. The analysis of root causes for high run time, high downtime and increasing scrap production through brainstorming sessions and 5Ws tool, showed that the root causes of the problem had two natures: cultural, organizational, and of maintenance. Lack of leadership of shift leaders, of knowhow about main line's machine, and of preventive maintenance were at the base of poor performance. After actions undertaken such as training, creation of shared and written procedure, creation of maintenance plan, the efficiency of the line reached the desired target and control tools have been developed to ensure sustainability of results over time.

The thesis includes four interviews to managers who dealt and deal with Six Sigma in other companies. The aim of these interviews is to enrich the knowledge of Six Sigma by understanding how Six Sigma is perceived and utilized on the market. The main learning from the interviews is Six Sigma created a standard for quality assessment throughout the market that all companies recognize. The push toward adopting the Six Sigma approach primarily comes from the market through procurement contracts. Starting from the CEO, the organization must identify the correct KPIs and create a relevant processes measurement system. The commitment passes from management to the project manager and eventually becomes the daily culture of all employees and workers.

2. SIX SIGMA'S THEMES

Six Sigma is a flexible method for improved *process output performance* and enhanced *business leadership* [1]. Literature reports different definitions that all together complete the Six Sigma frame. From a problem-solving point of view, Six Sigma can be defined as a set of statistical tools adopted within quality management to construct a framework for process improvement [5]. Similarly, Six Sigma is described by others to be a well-structured continuous improvement methodology to reduce process variability and remove waste within business processes [12]. From a cultural point of view, it is an approach to change the culture of an organization: a broad and comprehensive system for building and sustaining performance, success, and leadership [1]. Thus, despite what the name 'Six Sigma' suggests, its implementation does not rely on statistical tools and techniques only, but also on the commitment of top management to guarantee the involvement of the employees throughout the whole organization [11].

Six Sigma's performance within an organization is expressed with reference to quality. Quality is assessed in terms of customer satisfaction and internal process efficiency. Six Sigma provides tools and best practices to achieve a level of quality of near perfection. These tools cover both process optimization and process control activities and enhance teamwork and people involvement.

Themes of Six Sigma are:

- focus on the customer,
- focus on process,
- data- and fact-driven management,
- proactive management,
- boundaryless collaboration, and
- project based approach.

1.1. Focus on the customer

The customer is the starting point of any Six Sigma effort. To Six Sigma, success is reached when the customer is satisfied. Customers will buy goods and services only if they match their needs and are high quality. Meeting customers' needs requires an understanding of these needs. Thus, knowing what the customer wants is the first step of making business. Despite this, many companies neglect real customer needs or think they truly know them when they don't. They believe they know what is good for the customer as they master their technology [1]. Though, technology should not be the starting point. The customer is the starting point, and the technology is later chosen in such way to best fulfill his needs. The second step will be to deliver high quality products. It entails defining what quality means to the customer. Six Sigma considers high quality products items which are within customer specifications and no complain exists from his side. Product quality is defined by the customer and the company's efforts must work toward achieving that level of quality. Lower quality translates in not meeting customers' requirements. Higher quality translates in an excessive effort and costs. To ensure to meet customers' needs and target quality, companies should align their interests to those of the customer [1]. This can be achieved by comparing the company performance to customer requirements. Satisfaction of the customer becomes the baseline for the assessment of company's performance. In other words, a company should question the customer about how he measures products' performance and work on his processes with the aim of maximizing those measures. Search for quality and perfection should become a company value. Six Sigma provides tools to enable an effective and deep understanding of customer requirements.

1.2. Focus on process

Six Sigma positions the process as the key vehicle of success [1]. A process is a sequence of steps undertaken to transform an input into an output. The supplier supplies the inputs. The customer receives the outputs. A process usually requires human resources and infrastructure to achieve its goal. Though, these two latter elements are not considered inputs as they do not undergo a transformation. Often, the outputs of a process are inputs to the following one. Processes may be internal to a company (manufacturing of a product) or cross different entities (delivering the product to the final customer). They may also consist of subprocesses. In any case, the entity who provides the inputs is called supplier and the one who receives the outputs is called customer. So, suppliers and customers depend on the boundaries chosen when considering and analyzing a process.

For Six Sigma, process is where action takes place [1]. Action is what transforms the input material or semi-finished product and delivers value to the customer. Processes enable the creation of value. For this reason, Six Sigma concentrates on processes and through the enhancement of them reaches product desired quality and process desired quality. While product quality is defined by the customer, process quality is expressed in terms of process efficiency: the number of defects the current process yields. An item is considered a defect based on customer requirements. Low product quality is a cost to the customer in case it receives a defective product, and it is a cost to the company that must introduce quality checks and must fix defectives. Low process quality, i.e., efficiency, is again a cost to both customer and company because of a higher product price and a lower margin. Six Sigma does not only put its focus on reducing waste in terms of non-value adding activities. It mainly addresses the active steps of a process with the aim of stabilizing them, starting from the analysis of variability. The more a process is stable and the more its outputs are in control. When processes have a high degree of variability, their outputs are not in control, their quality is not assured, and excessive quality checks are to be introduced to avoid a low-quality product to reach the customer. An ideal process has no variance at all, its outputs are identical to each other, and no quality check is needed.

1.3. Data- and fact-driven management

The number of decisions companies take based on assumptions and opinions is, in fact, much higher than what people think [1]. Consistent decision taking is possible when there is data and facts support. Six Sigma tools are based on data for three reasons. The first reason is that data allows the visualization, representation, and analysis of processes. Discipline in collecting, analyzing, and interpreting data is strictly needed to ensure consistency and relevancy of measurements and eventually of results. The second reason is that it allows identifying and measuring key success factors. Improvement is only possible through comparison of the current process and its distance from the goal. The last reason is data enables effective communication and increases acceptance of results and decisions taken throughout the organization.

People often do not have an overview on the processes they work in. This leads to a low understanding of the need to change and improve, and they will try to obstruct it. Data allows to represent and effectively communicate the way reality is measured by management and customers and how each person’s effort or activity affects the process performance. When people know how their effort is measured, they will act is such way to meet their goals.

Data-driven management should not get the company to embrace overly analytical procedures [1]. At a certain point, actions need to be undertaken. Creativity in problem solving is hereby appreciated if supported by measurable facts.

1.4. Proactive management

Six Sigma sets up a working environment in which everybody is involved and collaborates toward common goals. Six Sigma identifies proactive and improvement-targeted organizational culture as the pivotal factor for success in terms of customer satisfaction, innovation, and profits [25]. Management adopts a proactive behavior and makes habits of what are often neglected best business practices [1]. Starting from setting ambitious goals and renewing them frequently, setting clear priorities, acting on problem prevention and questioning why the companies is doing what it is doing, management incentivizes involvement, communication, training, and reward for excellence down the hierarchy. Management also gives the right visibility to Six Sigma projects as change is only possible if importance is given to it.

People of an organization are involved and work toward process- and self-improvement when management has a tolerant behavior with respect to failure [1]. Empowerment of people passes through putting trust in their actions and decisions but giving them responsibility as well. Rewarding success incentivizes responsibility. The risk of not tolerating failure reduces people's creativity and effort for enhancement. Rather than punishment, management should favor the use of risk management tools [1].

A pillar of Six Sigma methodology is continuous improvement, which means to improve also what is already working well [4]. This may sound as a waste of time and effort, but it is in fact the idea behind sustainability: things must continuously be questioned, management challenged about decisions, processes reviewed and enhanced. Effective change is enabled by avoiding reactive behaviors of management and employees: bouncing from crisis to crisis makes employees very busy in solving daily unexpected events instead of focusing on structural enhancement [1]. Reactive approach to problems gives the false impression of a management who is on top of things; it has lost control. It has been found out that companies that follow Six Sigma projects sporadically do not gain as much from it as do companies that have a well-coordinated effort [25]. Six Sigma programs and initiatives need to be embedded in the companywide strategy [25].

1.5. Boundaryless collaboration

An important theme is enhancing collaboration both within the organization and with suppliers and customers. Opportunities available through improved collaboration within companies and with their vendors and customers are huge [1]. The idea is to make everyone conscious about how their role fits into the big picture. Six Sigma breaks all barriers and improves teamwork, up, down, and across organizational lines [1].

When people recognize interdependencies between activities they perform, they can act in such way to improve the overall process efficiency. This is true both upstream and downstream the supply chain. Knowing the context the customer receives an item downstream the process, may change the way suppliers work and deliver value. On the other hand, understanding how an input is produced and the technological potentials and limitation of the upstream chain, might change the customer's requests for orders. This is not only true throughout the supply chain, but also for internal processes in which customers and suppliers are simply colleagues or team members that interact at the interface of process' steps. When this collaboration happens, the working experience of both suppliers and customers is enhanced. The process manager has the role of overcoming frictions at process steps' interfaces and search the efficiency of the whole overall process. This role has the task of ensuring a smooth flow of material and information throughout all steps of a process and make sure all people working in that process are satisfied with their inputs received and outputs produced.

Boundaryless collaboration in Six Sigma does not mean self-sacrifice [1]. It requires the understanding of the flow of work through a process [1]. A complete overview of processes is only possible at a higher level. Therefrom, the role of a process manager. A complete understanding of flows and interactions is though only possible at a lower level, by interviewing and observing employees work daily. To make an organization Six Sigma-shaped, everyone needs to be involved, informed, and trained about procedures. Many of the tools provided by Six Sigma are based on workshops. Six Sigma calls for regular meetings in which people think and take decisions together. This way the whole team is aligned on facts, decisions, and objectives, and may work toward the same direction.

1.6. Project-based approach

Operationally, Six Sigma acts through projects. A Six Sigma project must:

- tackle a problem the company is facing, and
- have an unknown solution.

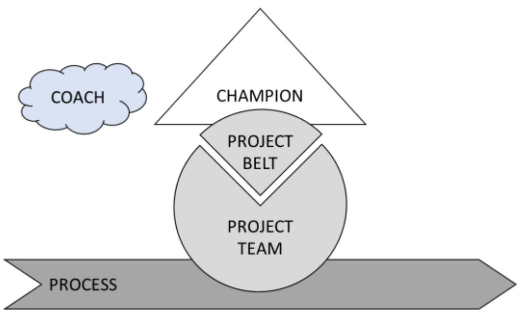
The problem is the starting point of a Six Sigma project. A problem is a situation of dissatisfaction. It hinders from achieving desired results or just makes people's life worse off. In addition, the solution to this problem must be unknown. If the solution were known, no project would be necessary: a direct action could be undertaken.

The approach Six Sigma uses to tackle a problem is called DMAIC: *Define*, *Measure*, *Analyze*, *Improve*, *Control*. It starts from defining the problem and setting an objective; second, it measures the size of the problem; third, it analyzes possible causes in search of the root causes; fourth, it targets causes and designs solutions; finally, it develops procedures to sustain the solution over time.

A Six Sigma project has the following roles:

- *champion*,
- process owner,
- project manager or project *belt*,
- team members, and
- coach.

The champion is the role accountable for the project and assigns a project to a project manager with the aim to solve it. The process owner is responsible for the process and will respond for any failure happening within it. It is also the one who best knows the current process problem. He is a key figure during the execution of the project. The process belt is the one who guides the team through all steps and activities needed to tackle the problem. He his therefore responsible for the project outcomes. Team members are chosen depending on the project needs and skills requested for the project. Depending on the size and scope of the project, the team may be inter-functional as skills and knowledge from different company's functions may be needed. Each time a project phase is concluded, or a major decision needs to be taken, the project manager needs the champion's approval to go. The coach is a supporting role to advice and coach the belt from a theoretical and logical point of view. Picture 1 visualizes these roles.



Picture 1. Six Sigma roles [2].

The attention of management and a consistent economic benefit should also be present to launch a Six Sigma project.

Six Sigma is a journey of increasing skills, comprehension of knowledge, and mindset [21]. The project manager can achieve different levels of Six Sigma skills and knowledge based on his experience. Different levels of experience are indeed defined: yellow belt, green belt, black belt, master black belt. Each level requests from the project manager a certain depth in understanding of Six Sigma themes and tools and their application. Higher belt levels allow the project manager to be assigned project of a wider scope. To be coach, a black or master black belt is usually required. Certification companies that deliver Six Sigma trainings grew on the market to standardize the level of knowledge and expertise a project managers achieve.

1.7. Statistical foundation

The name 'Six Sigma' is a combination of its ambitious goals and its primary objective of reducing process variability. 'Sigma' comes from statistics' standard deviation. 'Six' is about its ambitious goal.

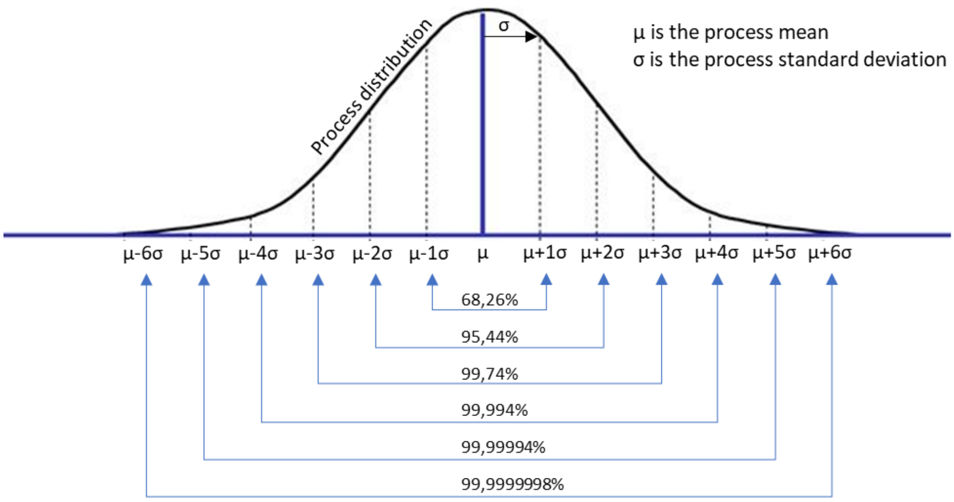
Six Sigma engineers have designed statistical tools to keep track of process variability and eventually to control it. By selecting, collecting, and analyzing numeric variables representative of the process, it is possible to calculate the mean and the variance of the process itself. The mean tells where a process is centered, thus whether the output is, on average, within customer specifications or not. A process' mean that falls outside specifications is a failing process that must be redesigned or changed. Variance tells how much each single piece of output is likely to be within specifications. Variability can be structural or natural. Structural variability is linked to some systematic failure of the process, and it affects all pieces of output with the same degree of impact. Again, the process needs to be fixed, i.e., the cause of failure solved. Natural variability is the statistical description of random fluctuations in process outputs. It is inherent in every process and may therefore be reduced but not eliminated. For this reason, Six Sigma jargon refers to variability as *evil* [1]. Six Sigma concentrates its effort of reducing process' variability in such way to lower the number of defects produced.

The following example will clearly show the impact of cumulative variation over an entire process. Let us assume a process consists of five consecutive steps: raw material incoming, manufacturing step, assembly, product stocking, product delivery. Each step has 1 opportunity per product processed to make a defect. Each step has an efficiency in terms of defects of 98%: it produces 2 defects every 100 opportunities on average. The overall process efficiency will on average be

$$0.98 * 0.98 * 0.98 * 0.98 * 0.98 = 0.90$$

The yield of the process is only 90%: 10 every 100 products come out defective from the line on average.

Six Sigma's ambition is to reach the level of 3.4 defects every million opportunities. An opportunity is defined as any circumstance that can potentially be the cause of a defect. As opposite to the above example, a process step may cause more than a defect on the same product. This goal corresponds to a process efficiency of 99.999998%. In this case, it is said that the *sigma level* is 6. Picture 2 shows the Gauss curve related to the natural variability of any process and the sigma levels.



Picture 2. Gauss curve of natural variance and sigma levels.

Keeping track of process variability is fundamental to have a process in control, which means being able to detect failures.

Having introduced the above concepts and ideas, it is now possible to give a definition of 'Six Sigma organization'. It is an organization that takes up the challenge of improving all processes by applying Six Sigma themes and practices into its daily management activities and creates a closed-looped system for business leadership [1].

3. SIX SIGMA'S VISION FOR BUSINESS LEADERSHIP

Six Sigma's view of business leadership is based on three elements:

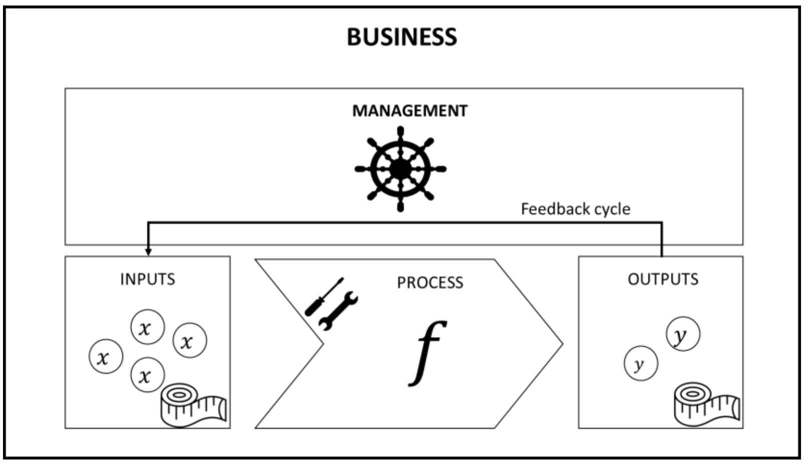
- the creation of a closed-looped system of information to support decision taking,
- process improvement, design, and management, and
- adaptation of tool to the company context.

These three elements are explained below.

3.1. Closed-looped system

The Six Sigma vision is to create a closed-loop system of inputs and outputs. Managers should be able to correct course of action and steer future decisions through a closed-looped system of both internal and external sorts of information [1]. The closed-loop business system should set output measurements sensitive to inputs and allow management to keep the company safely on the path to success by monitoring outputs and controlling inputs. See Picture 3.

Like an equation, it is possible to look at a process as a function f in which input variables are the Xs and output variables are Ys [1] (Table 1). Input variables must have an impact on output variables. It would not make sense to measure, track, and enhance inputs if a change in the Xs would not lead to a change in value of the Ys. To comprehend a process and what elements its outputs change upon, the correct input variables need to be determined and measured.



Picture 3. Feedback cycle of outputs to inputs to monitored and enable business effective steering.

Table 1. Characteristics of X and Y variables [25].

Y	X
Dependent variable	Independent variable
Output of the process	Input to the process
Effect	Cause
Symptom	Problem
It is monitored	It is controlled

Ys can represent:

- a strategic goal,
- a customer requirement,
- profits,
- customer satisfaction,
- overall business efficiency [1].

Xs may represent:

- actions to achieve strategic goals,
- quality of the work delivered by the business,
- key influences on customer satisfaction
- quality of the inputs to the production process (from both customers and suppliers).

Critical to success is then the identification of the correct metrics that can represent inputs and outputs.

Ys are set by the customer. Depending on the scope of the Six Sigma project and whether the analyzed process is internal or cross-companies, customer's needs can be implicit or explicit. An example of implicit customer needs is improving the efficiency of a process, as this will ultimately lower the price of the final product or give the company the opportunity to invest in product quality. Investing money in creating a Six Sigma culture throughout the company will also ultimately benefit the customer. Thus, process efficiency and investment in trainings may be two high level output measures. Explicit customer requirements are, instead, technical requirements the product should have to satisfy the customer today. An example of organizationally low-level output measure is the weight of each item of the final product manufactured.

The identification of Xs comes second. Xs represent input variables to the process. Referring to the previous example, input variables may be the number of trainings per year per operator or employee the company offers, what kind of raw material is fed to the process and its quality, what parameters are set on machines.

The focal point of creating a closed-looped system is to relate Xs and Ys [1]. Understanding what the drivers for quality are, the company will be able to improve his processes and deliver outputs that better fulfil customer requirements.

It is important that the choice of these variables is consistent and dynamic. Consistency allows comparison of collected data thus, of current performance to the desired one. Dynamicity stands on the long run: output measures must be adaptive to changing environment and customer needs [1].

3.2. Process improvement, design, and management

There are three levels of process strategy:

- process improvement,
- process design/redesign, and
- process management.

The first one is based on the idea of continuous and incremental improvement borrowed from Lean Manufacturing Systems [1]. The aim is to spot problems, find root causes to those problems and finally develop targeted solutions. It is, among the three, the lowest level in terms of changes to the process: the aim is to improve the workflow of the process leaving its structure untouched. Workflow refers to “how things are done” i.e., the sum of men and machinery work that allows material and information flow. The process is considered and studied step by step. Every step might need some improvements that will enhance its performance. Yet, solutions will not affect the production line layout and the flow of material and information. At this level, operational and tactical goals are cost reduction and increased customer satisfaction.

The second one addresses the entire process with the goal to replace or redesign it. It is not simply about fixing it [1]. In order to do so, strategic questions like “what are the companies’ skills and knowledge?”, “what are the companies’ customer needs?”, “will the company have to face new competitors on the present of future market?”, “how sustainable in time will the new process be and how much will it be able to adapt to changing environment?”, “does the new process need any related processes or facilities?” need to be answered. Such change will also tie into product and service design.

Design for Six Sigma (DFSS) method is the most common methodology to implement Six Sigma throughout an organization from scratch [5]. While DMAIC is a problem-solving method which aims at process improvement, DFSS is defined as “a process to define, design and deliver innovative products, provide competitively attractive value to customers in a manner that achieves the critical-to-quality characteristics for all the significant functions” [7]. DFSS is thus used in the context of new product development to focus on quality from the very beginning [8].

When classifying a Six Sigma project as process improvement oriented or process design oriented, care must be used. Within a company there are thousands of processes and sub-processes taking place at the same time, often overlapping and interfacing with each other. They usually make use of the same resources as well. High level processes are observable by management and are divided into sub- and sub sub-processes all the way to a single activity performed by a worker. When mentioning process design and re-design we are talking about high-level processes and in particular core processes. Core processes are those who deliver value to the customer and those which directly support them. Manufacturing is a core processes, and it is directly supported by Sales and procurement. Redesigning these processes means to tackle the company’s market strategy. All other side processes, whatever their importance, are not considered core as they do not benefit the customer directly. Low-level processes are subprocesses happening within the frame of a high-level process. They are observable from middle management and workers. At this level we usually talk about process improvement even if some degree of process steps redesign takes place.

Process management is transversal to functions and must be a constant. It is about infrastructure for Six Sigma leadership [1]. Six Sigma effort and approach (starting from DMAIC projects to involving all workers actively) needs some support from an organizational point of view. This step entails the change in focus form direction of functions to the understanding and facilitation of processes. Six Sigma calls for an end-to-end based process management in which responsibility is assigned in such way as to ensure cross-functional collaboration and management of critical processes [1].

3.3. Adaptation of tools to the company’s context

Six Sigma is not a fixed-tool and context-specific approach. Processes and routines differ from company to company depending on the industry, the business, customers, people, and machines employed. A blind application of predesigned tools to any reality will lead to a low degree of success in the best cases and to complete failure in most cases [1]. It is important to keep in mind the necessity of adapting Six Sigma tools to the reality faced in front. Some tools may be useful, some may not comply with a specific need. Even the design of new tools is encouraged by Six Sigma culture, as far as they are data-based and follow the DMAIC approach. What matters is setting high ambitions of quality and performance, and the will for perfection through continuous improvement. All parties involved in a project need to agree on common goals and work as a team to fully reach them.

4. BIRTH, DEVELOPMENT, BENEFITS, AND COSTS OF SIX SIGMA

4.1. Motorola and General Electric experience

Six Sigma was developed by Motorola in the 1980s. All present-day and past successes of Six Sigma are traceable back to Motorola's pioneering work. Motorola developed the essential tools and strategies used to detect and eliminate defects [18]. Although Motorola has always been a high-tech company offering highly reliable products, by 1970, it was struggling facing rising customer expectations in terms of quality and delivery costs [25], increasing product complexity [10] and global competition [22]. Every business in which Motorola was engaged in was targeted by the Japanese who had much higher quality standards. Motorola's customers were unhappy with product defects and customer support and preferred Japanese products. As a result, dealing with severe financial pressure, Motorola had to take action. At the same time, a Japanese company took over control of Motorola's Quasar factory and began implementing unheard of changes. They started restructuring the way the factory operated, addressing processes, and reducing wastes. Soon, Motorola's Quasar factory started producing TV sets with one-twentieth the number of defects than before. The factory maintained the same workforce and machinery. It became clear that Motorola management was the problem [18].

Engineer Bill Smith discovered that the products with fewer non-conformities were the ones that performed well after delivery to the customer. Motorola's top management summoned engineers with the objective to reduce the number of defects on products before they were shipped out of their factories. They collected and combined all quality management practices known and worked toward the creation of a methodology that would be the baseline of the quality improvement program. So, in 1986, Smith set out to devise a way to standardize defect measurement and ultimately drive improvements in manufacturing. Starting from the measuring method. Instead of measuring defects per thousand opportunities, Motorola's engineers decided to switch to million opportunities, to provide more granular data [19]. Thomas Goodwin of Motorola Mobility [21] says, "Over the years, we built on this methodology to include the use of statistical tools, and a step-by-step process to drive improvement, innovation and optimization".

After having presented the ideas to CEO Bob Galvin, Motorola's management started documenting the company's key processes with the aim of later aligning those processes to customer requirements and installing measurement systems to continually monitor and improve them. By maintaining high efficiency and eliminating waste and defects, profits increased [22]. "We implemented large-scale training efforts and applied the methodology beyond manufacturing into transactional, support, service, and engineering functions. Six Sigma became a collaborative effort between our customers, suppliers and stakeholders and an important tool to engage our employees in a culture of continuous improvement. Our employees, suppliers and customers quickly discovered this methodology worked and wanted to use it to improve performance" says Goodwin [21]. As a result, Motorola's performance improved instantly [22].

Yet, Japanese were still way ahead of them. To remain competitive, top management challenged to improve their quality by ten times over a five-year period. Despite this goal seemed initially impossible, by the end of 1985, everyone in Motorola had started working toward it. By the end of the five years period, every business in Motorola had reached their improvement target [22].

A second program of improvements in quality was launched after Motorola's top management flew to Japan and saw Japanese companies were doing 2000 times better than them. This new plan was an even more ambitious one: another tenfold improvement in performance within the span of just two years. Motorola's goal for 1992 was to have 3.4 defects per million opportunities. They have documented more than $16 billion in saving thanks to Six Sigma adoption. Therefore, they decided to make the methodology public for every company [22].

Motorola implementation of Six Sigma has been a milestone in modern quality programs and set the base statistical tools of process monitoring. Following Motorola's learnings, many companies like Texas Instruments and Allied Signal started using Six Sigma methodology to bring organization-wide improvements. In the 1990s General Electric launched Six Sigma in a big way. They implemented Six Sigma in all areas and ensured that the entire organization participated in the initiative. They changed the performance incentives and made them based on individual's ability and enthusiasm to take part in Six Sigma initiatives. Six Sigma had become the culture of the GE's organization and not just a methodology for improvement [25].

General Electric has been a key contributor to the development and diffusion of Six Sigma starting from 1995. The driver for Six Sigma evolution within GE was the realization of a globalized and technologically advanced market in which consumers have access to instant information, meaning there's little room for error [15]. CEO Jack Welch became aware of the company often falling short of its potential. Welch recognized that GE required a complete overhaul of all its fundamental operations and detected a great deal of defects that had previously gone unnoticed. This build-up of waste was slowing down production [19]. Product and process quality was becoming fundamental to survive in the market. So, in the late 1980s, the company began focusing solely on quality control designing tools to measure outputs. This would have been the basis for the successive Six Sigma actual implementation. In 1995, Welch made the goal for GE to become a Six Sigma company within five years by adopting the Six Sigma quality system as a part of the company's culture [15]. In 1996 the company invested $200 million, but only saved $170 million costs. In 1997, Welch made the choice to tie leadership bonuses to Six Sigma results. It proved to work that year, $400 million was invested in Six Sigma, with $700 million savings incurred. At the beginning, GE focused on cost savings. Starting from 1998, the attention was widened including customers and issues impacting them (such as delivery and customer service) [16]. By 2000, Six Sigma was implanted completely and became the company culture, savings accounted were over $2.5 billion [20]. Tying managers bonuses to Six Sigma projects has been the key to a successful implementation companywide and proved results.

GE meant Six Sigma as a methodology to measure the number of defects in the company's processes and to systematically determine how to reduce error and get as close to perfect performance as possible [15]. The primary focus at the time had been improvement on the manufacturing side. Since GE Capital, the financial services side of the company, accounted for nearly 40 percent of the profits of the company, it didn't make sense to just focus on improving the manufacturing aspect. So, GE Capital also adopted Six Sigma. GE's managers created the DMAIC cycle as central tool for Six Sigma projects [16].

Six Sigma has been implemented within GE through three initiatives [16]:

- commercial quality applications: the focus was not put on manufacturing only, but involved inventory management processes and pricing,
- creation of skill belts (green, black, and master black) to identify employees with Six Sigma competences and push learning and skill-development and assessment,
- creation of *design for Six Sigma* (DFSS) with the objective to determine the needs of customers and business at the product or service design level.

The three keys that made the Six Sigma program successful in GE have been training, mentoring and leadership [18, 20]. Strong emphasis was put on training employees. Almost all employees were required to take a two week, 100-hour, Six Sigma Training Program. Even the CEO and President attended training sessions. Following the training the completion of a Six Sigma project implementing acquired methodologies was mandatory to receive the green belt and skills recognition. Mentoring is the activity of supporting green belts. GE put money and effort on the development of mentors: master black belts had the full-time job of coaching and supporting green belts in achieving project's goals. As green belts became black belts, they were asked to carry out different major Six Sigma projects within the company and to coach new green belts generations. Leadership is the commitment from the side of management toward change and processes improvements. Commitment toward Six Sigma goals was required from both executives and workforce. Promotions and bonuses were linked to improvements in quality. A Green Belt certification became a requirement for promotion at GE and almost half of bonuses depended on the successful implementation of a Six Sigma project. Many attribute the immense success of Six Sigma in GE to the focused, hands-on implementation by Welch and upper management. From constant shopfloor visits by management to consistent monthly reviews and reports, the Six Sigma team was always available toward effective implementation [16].

4.2. Strategic benefits of Six Sigma

The application of Six Sigma allows big companywide benefits.

- Enhancement of value to the customer,
- acceleration of the rate of improvement,
- promotion of learning and cross-pollination,
- reduction of costs,
- execution of strategic change, and
- generation of sustained success

are the biggest benefits provided and are explained below.

Enhancement of value to the customer

Customer value is enabled by Six Sigma's end-to-end approach: it considers processes from the supplier to the customer [1]. As direct benefit, the team is forced to question itself who the customer is, thus having a clear and common definition. Then, customer value enhancement is powered by the deep understanding of its needs from which Six Sigma efforts start. It has been demonstrated that the defect rate per unit is reduced after implementation of Six Sigma in manufacturing systems [9].

A broader benefit of end-to-end process analysis is that all steps of a process are considered and measured, making improvements possible at all levels.

Moreover, the selection and prioritization of projects at a strategic level is done according to customer needs as well. This ensures the customer is given most importance in the company's strategy and products are developed in line with changing customer needs [17].

Acceleration of the rate of improvement

Six Sigma approach not only seeks improvement, but it enhances the way improvement takes place. Its tools facilitate the spotting of improvement areas, thus easing their refinement.

Acceleration of improvement is supported by:

- improved data integrity,
- elimination of root causes,
- continuous improvement culture and autonomous maintenance,
- setting of performance goals for everyone, and
- training.

Data integrity starts from setting common operational definition of variables and ensuring data is collected in a replicable and reproducible way. These two concepts will be explained in Chapter 3. Having clear data definition and collection secondly grants comparison over time and quantification of improvement.

Elimination of root causes avoids reactive risk management and allows to concentrate effort on strategy and structural change. Continuous improvement culture and autonomous maintenance supported by workers empowerment and the setting of performance goals for everyone permit the gathering of many ideas and continuous refinement of processes.

Training workers about how to carry out jobs effectively and solve problems will make them more aware of the production process. This reflects in high morale and reduced human-related defects [6].

Promotion of learning and cross-fertilization

Communication is at the basis of knowledge sharing among functions and within functions and makes all benefit from individual's achievements. A convenient tool is to ease job rotation within the company. Often, having new people looking at things will facilitate innovative ideas and out-of-the-box thinking. Moreover, by observing how different functions work, workers will also adapt their output is such way to facilitate the overall process efficiency.

Reduction of costs

Research has shown that the cost of poor quality (rework, mistakes) in service-based businesses and processes typically runs as high as 50 percent of the total budget. In manufacturing it is estimated to be around 10 to 20% [1]. Analysis of service processes often reveal that less than 10% of total process cycle time is devoted to real work on tasks that are important to the customer [1].

Reduction of costs is enabled by two main factors:

- spotting of defects at early stages of the process [5], and
- designing the process in such way quality checks are process driven and not people driven [25].

A short projects duration indirectly impacts on costs as well. As the DMAIC project approach is well structured and supported by project management tools, overprocessing of data is avoided and action is undertaken only if necessary. This is mainly possible thanks to a clear problem and goal definition and project scoping [2].

Execution of strategic change

A deep understanding of processes and procedures gives the ability to carry out effective minor adjustments and major shifts [1] to follow strategy. Sometimes, poor performance is due to small deficiencies in the process flow that impact critical items. A correction of them will enable change without the need for big investments or restructurings.
An important stage of Six Sigma is the setting of a clear goal people must achieve. By setting a performance goal for everyone, the company gets people to work toward the same direction [1]. When the final step of the manufacturing process questions the customer about his needs, it will adapt its demand for input materials accordingly. This way the step before the last one will also work toward delivering high quality material and so on. Having a clear final goal will at the end make all processes seek that goal.

Generation of sustained success

Sustainability of results is a major topic of Six Sigma. This concept is incorporated into the *control* phase of the DMAIC cycle [5]. Often, after having addresses root causes, solutions do not become habits as they initially bring workers out of their comfort zone. This leads people to fall back into their previous way to work. Six Sigma establishes guidelines and provides tools to ensure results are maintained over time.

Also, the ISO9000 certification is integrated into Six Sigma [1]. Companies do not need to undertake the same effort twice: the is no risk of implementing a quality program that will then be insufficient from an international standard certification point of view.

4.3. Enablers for Six Sigma

Critical success factors for Six Sigma are all based on the idea of leadership and involvement of people. The following Table 2. presents success factors divided into four groups: strategic factors, operational factors, external factors, and human factors. Picture 4 shows the feedback cycle of the enablers on output quality and customer satisfaction.

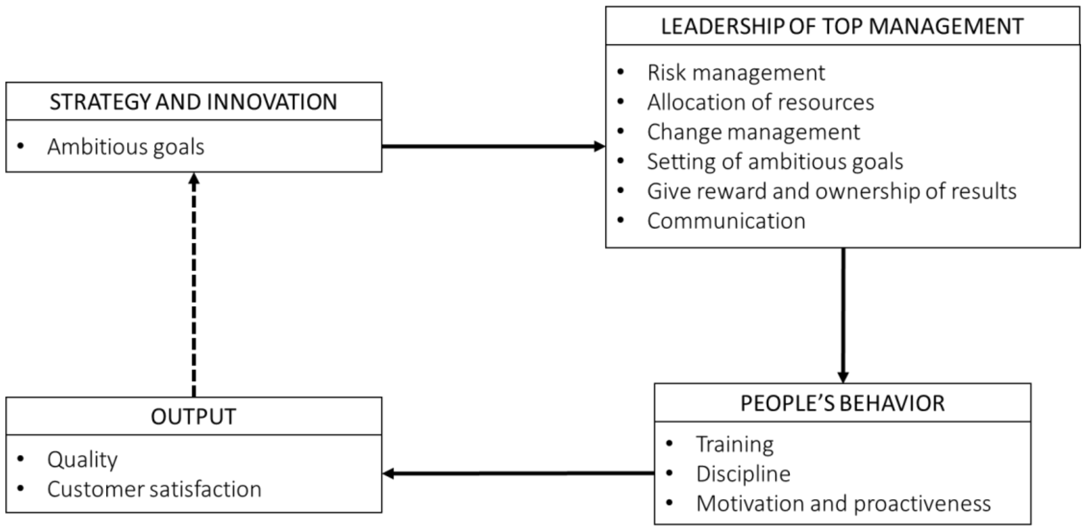
Table 2. Critical strategic factors for a successful implementation of Six Sigma.

Strategic factors	Commitment from top management: leadership	The investigation of the enablers of Six Sigma found management commitment to be the most critical enabler [13]. Six Sigma must start from top management's leadership behavior toward transformation [14] and change [14]. Risk taking and management needs to be part of the strategy [1] and managers need to accept mistakes and must create an atmosphere where they are not feared [17]. Also, management must be enthusiastic, motivate [14] and reward [1] employees about results achieved giving ownership for them as well. Allocation of resources is also fundamental to act and achieve results [14] and make effort for improvement worth it. Ambitious goals may only be set if there is a positive response toward change and investment from higher levels of the hierarchy. Visibility within the organization is the last leadership element that management must grant to Six Sigma projects. This is achieved by communicating the importance of changes in processes throughout the organization. Incentives are, as taught by the GE experience, a fundamental factor in bringing resistant people toward experimentation of Six Sigma tools.
	Empowered middle	Middle management is deeper in contact with how processes really work out. They should be given a greater role in

	management: proactiveness	performance improvement and strategy formulation [23]. Without involving middle management Six Sigma will never be able to reach the shopfloor culture (in case of manufacturing) and broadly all workers involved in processes which is where defects can be eliminated, and failures fixed. If Six Sigma remains too high level, benefits will eventually reach a point of diminishing returns [17].
	Strategic alignment	Projects need to be selected and prioritized in such way they line up to the company's strategy [1] and maximize performance [14].
Operational factors	Ambitious goals in daily work	In daily work scheduling, people should seek ambitious goals of quality. The sum of high-quality process steps will result in high quality output. An example is choosing high quality raw materials [14] and applying best practices.
	Systematic tool for management	Six Sigma should become a systematic approach to problem solving and management [5]. Each time there is a problem with an unknown solution, people need to get back to theory and apply the DMAIC cycle. Sustaining results is the most important step of the DMAIC cycle as its duration is virtually infinite. Improved processes must be kept in control systematically.
	Permeate into all levels of business	From top management to workers, Six Sigma culture management needs to be cascaded down the hierarchy to employees and workers. Operationally, the organization needs to be divided into small teams each with a clear objective and incentive. The teams will find and understand their customer. They will find what variables to monitor. Finally, they will review their way to work and adapt it to the customer requirements. At this point they own the process, they understand it, and can ask management for necessary changes to reach that goal. Cost savings and new ideas will come up very fast [18].
	Communication	When people comprehend how decisions are taken the level of acceptance and proactiveness increases. Effective communication is supported by well-disclosed data related to decisions taken.
External factors	Supplier involvement	Excellence is impacted by raw materials quality and supplier's performance as well. It is important to make sure the supplier understood the company's needs and can deliver the supplies

		as agreed. Delays and bad quality will reflect on the final product and impact the customer. Sharing of objectives is also a strategy to link supplier's performance to company's goals.
	Customer involvement	Knowing customer needs entails involving him actively [2]. Often, the customer is not able to precisely define its requirements. Six Sigma tools help translating his voice into technical requirements that can be measured and therefore monitored. Also, showing to the customer how the company works may help agreeing better on the product requirements. Knowing the potential and the limitations of the company's processes might make the customer change his will and needs.
Human factors	Learning capabilities	Six Sigma initiatives reach their full potential only when learning capabilities are part of the change strategy [3]. Training and skill development are the base for sustainability and proactiveness from the side of employees and workers. Yet, things should be made easy and not complex. A middle manager said during an interview: "I think the main thing is for management to focus more on the simplicity of Six Sigma rather than the complexity" [17]. It is not just teaching tools; it is about providing the context in which to use tools [1]. Trainings are a serious investment for the company in terms of time and cost as they have a duration of two to three weeks, not just a quick roundup of notions. A clear system of certifications of acquired skills based on belts (Green, Black and Master Black) contributes to motivate employees toward personal growth and gives ownership for effort put in knowledge acquisition.
	Discipline	Six Sigma asks for discipline in applying the DMAIC cycle. Skipping measure and analyze phases and jump to improve and problem solving is often rooted in people's minds. Success of a Six Sigma projects comes from meticulously following the DMAIC approach. Discipline must come from top management to be effective down the hierarchy: a middle manager during an interview reported: "top management don't typically spend enough time piloting; they just rush into the implementation" [17].
	Societal factors	Societal-level factors outside the organization have an impact on the organizational culture. Leadership has been recognized

		as a mechanism for embedding cultural values and norms into an organization [24].



Picture 4. Feedback cycle of Six Sigma enabling factors.

4.4. Financials of Six Sigma

Six Sigma's cost of implementation may be high, as high are financial benefits. GE Capital Services launched Six Sigma in 1996 spending about 53 million dollars the first year and reporting a gain of the same amount. These expensed were driven by speed and scale more than by controlling costs concern. The second year, costs rose to 88 million dollars and returns made a 173 million dollars profit possible. In 1998, costs reported were of 98 million dollars and payoff 310 million dollars.

Cost saving benefit

Cost benefits mainly come from savings due to the improvement to poor quality of output and related processes. Estimating the monetary benefit is hard at the beginning of a Six sigma projects and will become clearer when some solutions ideas will come up and their implementation verified. There are three main categories of cost [25]:

- appraisal costs,
- internal deficiency costs, and

- external deficiency costs.

Appraisal costs are due to excessive quality check activities. When the number of defects is high, increasing the number of tests and quality checks will immediately stop delivering defectives to the customer. These testing activities are extra to the routine ones and have both a direct and an indirect voice of cost. Direct cost is due to personnel and tools employed. The activity of extra testing the output will give an apparent impression of perfect quality delivered to customer and will lead to a low degree of discipline by workers in doing things right the first time. Examples are outgoing goods checking and testing, purchased supplies inspecting and bills auditing, all of them sent back to the line to be fixed.

Internal deficiency costs are costs linked to repair, discard, and replace defective products. Repairing defective output products is overprocessing and can be avoided by doing things right the first time [1]. This category of cost is the simplest to estimate as an average cost per defect kind of calculation can be performed or a counting of rework can be performed. Indirectly, defectives also have an impact on lead time [1], thus on inventory costs and customer satisfaction as well. The customer does not perceive these costs, but he pays for them without being willing to do so.

External deficiency costs are failures that happen after delivery to the final customer. These costs are the most 'expensive' ones when it gets down to regain customer confidence and public opinion about the company ability to deliver quality products. Accountable costs under this head are warranty costs (collect defective products, repair, replace, deliver back) and consequent bills correcting. This voice of cost is the most difficult to estimate even after implementation of improvements.

Cost of implementation

The cost of implementing Six Sigma is not negligible. Voices of costs can be categorized as follows:

- direct payroll,
- indirect payroll,
- training, consulting, and teamwork spaces, and
- implementation costs of improvements.

When implementing Six Sigma companywide, the first thing to do is to identify key people with the highest management expertise to lead the biggest and most critical projects and coach other employees through their Six Sigma belts certification process. These roles are full time, and their cost is easy to be measured.

All other employees who deal with Six Sigma projects also will devote a share of their time (usually 25%) to project management. They may be executives who organize and manage Six Sigma activities in general, green belts (projects managers), team members borrowed from functions, processes owners who will at first serve as team member and later as process controller, all other workers who perform measurements. Every Six Sigma project activity must be carried out with discipline, and this can take longer than forecasted.

A relevant voice of cost refers to training and consulting. To teach knowledge and skills the company might be supported by external consultants. Green belt trainings last two full weeks and black belts ones at least three additional weeks. Over the cost of paying external consultants, trainees dedicate their full time and do not work their regular job. Additionally, the company must consider and add the cost of organizing in presence-trainings than aside a pure organizational effort also requires lodging, traveling, and meeting rooms. The cost of meeting rooms is also present during projects execution as team members need to perform workshops.

Implementing the proposed improvements refers to the expenses to install new solutions in fact. These costs are the only ones that may be evaluated up front as a net present value calculation is possible since benefits may be forecasted with a great level of confidence.

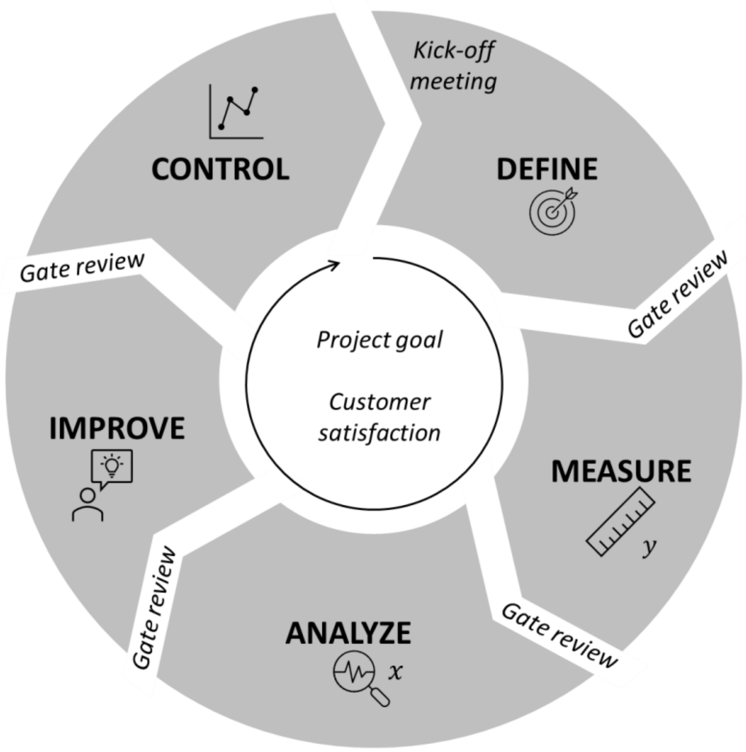
Estimating the timing and size of Six Sigma investment is hard to be done upfront. It highly depends on the implementation speed, the scale of effort that will be devoted and the general company's risk profile. For this reason, a cost-benefit based decision does not fit the evaluation of Six Sigma initiative.

5. DMAIC CYCLE FOR PROCESS IMPROVEMENT

5.1. Overview

DMAIC cycle (*Define*, *Measure*, *Analyze*, *Improve*, *Control*) is a tool to tackle problems which solutions are unknown. If the solution is known but its impact on the problem's cause is to be verified, DMAIC tools may be used but no full DMAIC project is needed. Otherwise, if the solution is known to be successful, that solution may be implemented with no need of further cause analysis. The primary objective of DMAIC is to solve a problem and to ensure the sustainability of the enhanced process. This cycle is the driver of the continuous improvement effort by Six Sigma. This does not mean that improving a process has no end; it means that after a problem is solved, the enhanced process must be controlled and sustained over time. And as a problem is solved, a new one is likely to be detected. Sustaining a process may entail the need for new DMAIC projects.

There are two ideas at the basis of DMAIC cycle and are inherited from Six Sigma's themes and vision. The first one is that improvement is not possible without first measuring the performance of the process. The reason of that is the team would have no figure to compare results against to. The second one is design of solutions follows root cause analysis. And root causes are identifiable only if a clear problem is stated. The correct order of project phases will therefore need to be followed with discipline to ensure a logical approach. The cycle starts by first setting a clear objective and measuring the current process' performance, second, it analyzes causes of that problem and implements solutions, and, at the end, it controls the new process. Picture 5 shows the DMAIC cycle.



Picture 5. DMAIC cycle.

It is important to underline the difference between the words *problem* and *cause*. The problem is detected at business level and refers to process outputs. Causes are the reasons the problem is present and refer to process inputs. The correct DMAIC cycle's semantics is *unknown causes lead to known problems. When a problem is detected by management, an operational team will be in charge of tackling its causes through controlling outputs and the studying inputs and of designing solutions*.

Operationally, the work is mainly carried out in the shape of workshops. Every phase has a meeting point in which the whole team gets together and faces the main objectives of that phase. This practice ensures the alignment of all members on topics, directions and decisions taken. Usually, workshops are expected to have a duration of 3 to 4 hours. The project leader often has the lowest technical skills and know how about the process itself, thus he takes the role of facilitator of workshops. His task is to ensure all members participate, the flow of work is logical, well documented, data-supported and, ultimately, that decisions taken are well understood and shared by all team members. At the end of the workshop individual tasks may be assigned to each member depending on their area of competence. Each phase ends with a *gate review* meeting in which the project leader updates the Champion about results achieved and hands him out the phases' deliverables. After champion's approval, the next phase starts.

The drivers for every decision are project goal and customer satisfaction. Each time a change in direction is needed, and a certain solution is to be give priority, project goal is to be reminded and put upfront again. Deviating from it leads to outcomes that cannot solve the problem at its root cause.

The following Table 3 summarizes objectives and deliverables of each phase of DMAIC project.

Table 3. DMAIC cycle phases' objectives and deliverables.

	Main objectives	Deliverable documentation
Define	1. Problem identification. 2. Goal identification. 3. Customer orientation. 4. Project scoping.	1. Project Charter.
Measure	1. Define output measures (Ys). 2. Measure the current performance and variance of the process.	1. Output variables chosen. 2. Process' performance assessment.
Analyze	1. Find the root causes of the problem. 2. Collect data to support hypothesis. 3. Assess impact of each cause on the output.	1. Root causes and their impact.
Improve	1. Brainstorm solutions to causes. 2. Prioritize solutions and their impact on output. 3. Plan solution execution. 4. Execute change.	1. Newly redesigned process after improvements.
Control	1. Ensure sustainability of the process over time.	1. Project documentation. 2. Risks response plan.

Although phases' order must be followed, DMAIC cycle is not a purely linear activity [1]. Some degree of overlapping or fast fact checking is allowed and encouraged if it is useful to orient the analysis. As the analysis of the process continues and its understanding gets deeper and strengthen, the team might go back and update assumptions, revise the goal and scope, or do more cause analysis.

This chapter will face each phase one by one, detailing the objective and deliverables of each phase and providing some most common tools. Often, tools are about facilitating brainstorming, collecting, structuring, and analyzing ideas, and visualizing results. It is not mandatory to operate these tools in every Six Sigma project. Six Sigma provides a context within which employees are empowered of tackling situations using the tools they think are effective and understand the most. Processes are for the most part made of people who are often well off with their habits and comfort zone. Six Sigma tackles processes with the intent to change them and optimize them. This fact may not be welcomed by those who are part of the process. Especially, if there is the risk of getting rid of their position. Clear communication and ability to not get lost into formalities, i.e., adapting tools and procedures to the context faced, is the starting point to successfully implement Six Sigma culture and succeed in Six Sigma projects [1]. Moreover, the easiest the tools, the higher their understanding and acceptance is created among people who will use those tools and will be affected by the change brought. In general, when employing a tool four guidelines must be followed [1]:

- have a clear objective and communicate it,
- consider options and select the technique that is most likely to meet needs,
- keep the tool simple: match detail and complexity of the tool with the actual situation to face,
- avoid over processing: when the tool is not making the achievement of the objective easier, it is better to stop it instead of forcing it to the result.

The main tools that cross all phases are Tool 1, Tool 2, and Tool 3. They follow the Six Sigma's DMAIC red line of starting from customer needs, creating a measurement system of outputs and inputs and to end design solutions.

5.2. Define phase

Objective

Define phase is the most critical phase as the goal and direction of the project are stated, and a common understanding of the topics is created. The main goal of Define phase is indeed having the whole team aligned on what is about to be tackled. Tasks of this phase are below listed and explained:

- problem definition,
- initial situation statement,
- goal definition,
- team members,
- project scope,
- customer orientation and business needs,
- assumptions and constraints description, and

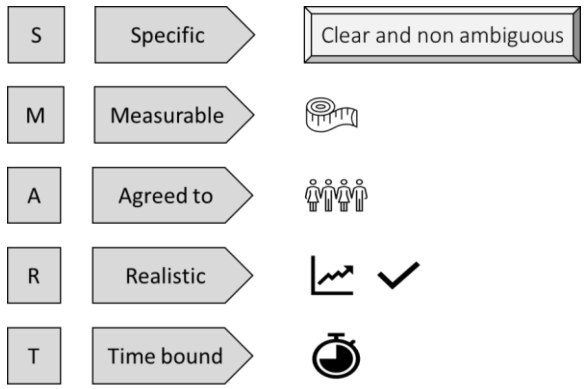
- other project management best practice-activities for success.

These activities are first performed by champion and project manager at a very general level to evaluate the necessity for a Six Sigma project to address the considered pain. If there is potential to start a Six Sigma project, the project manager will give a title to this project and organize a *kick-off meeting* (see Picture 5) in which the team gathers and carries out all the above listed activities through workshops. Tasks do not have a specific sequence, they are faced, changed, and reviewed as the understanding of the problem and the customer gets clearer. This meeting may last as much is needed to fulfill the objective.

Problem definition is a sentence that defines what the pain is. The problem is stated as the outcome of the process from the point of view of management. An effective problem definition must be specific, measurable, and agreed to. A specific problem definition nails the point, it exactly states what the problem is without leaving space to debate. At this stage, the problem is intended as outcome that does not meet expectations, not as cause. A measurable problem allows its assessment and the measurement of improvements. Also, it must be agreed to. People only collaborate on solving problems they see. If there is no common understanding of the problem, people might later work in different directions. Therefore, all team members must see and feel the problem.

The initial situation statement allows some more explanation of the context around the problem, but only provides information that is strictly necessary to comprehend the process' environment.

Having identified the problem, the next step is to clearly define what the goal of the project is. What is the team working toward? What does it want to reach? The goal is a sentence that states the ending point of the project: as soon as the performance has reached this target, the goal is considered fulfilled. Therefore, the goal is a measurable variable, and the team can clearly tell when it is met or how far away from it the process is. Like problem definition, the whole team needs to have a clear and equal understanding of the goal. Also, the goal must be relevant to the business, and time bound. Relevant because a project that does not have any impact on the company's performance will receive no attention and visibility by management. Agreeing of the project's timeline will make all people responsible for their tasks and reduce the probability of delays. Picture 6 summarizes the characteristics the project goal must have and suggests a way to keep them in mind.



Picture 6. S.M.A.R.T. definition of project goal.

The challenge of defining a goal is to not mention any possible cause or solution as they will be addressed by other steps of DMAIC. It might sound trivial, but a bad definition of the goal at this stage of the project risks to cascade a bias throughout the execution of the entire project. Spending time on a well-stated and unambiguous goal will later benefit the job. Moreover, the Six Sigma culture requests the goal to be ambitious but achievable. If the goal is not ambitious, less effort will be put into it by the team with the consequence of reaching lower results and the project loses visibility by the management. Still, a non-achievable goal risks to demotivate the team and do not reach desired results.

Knowing what the goal is, it is possible to assemble a team with the necessary expected skills to tackle it. It is necessary to have people's names written down next to roles. There are two reasons for that. First, as the success of the project highly depends on teamwork, knowing who is on the team is fundamental to have everyone work positively. Second, because when it comes to improve phase and solutions need to be implemented, there must be a clear understanding of who is in charge and responsible for the execution and the outcome of tasks.

Customer orientation is the activity of creating a deep understanding of customer needs. According to Six Sigma's theme of creating customer-driven processes, the starting point of measuring quality is knowing how quality is perceived by the customer. Thus, defining what the process should deliver. This is done by questioning the customer about what characteristics he expects the product to have, and how he measures quality in fact. It is a mistake to assume customer needs as they may change or be interpreted wrongly (either too strictly or too loosely); attitudes like "the customer has always wanted the product this way", or "we know what is good for the customer" bring the team out of path [1]. The outcome of customer orientation activity is a set of clear requirements that will enable

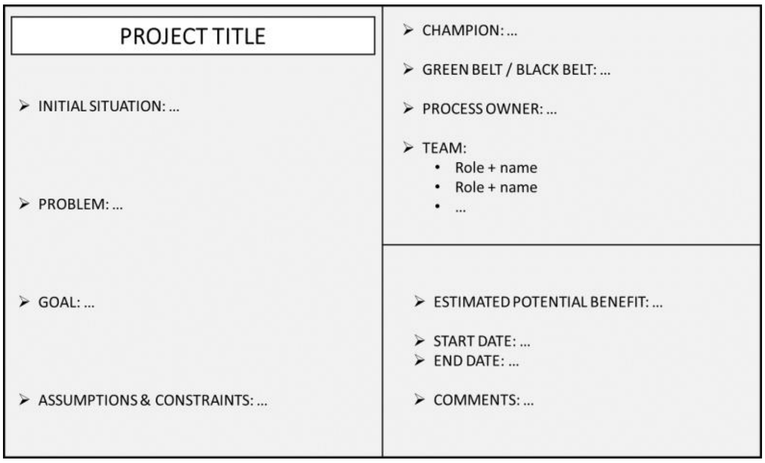
the identification of a variable capable of controlling quality as the customer measures it; this further step will be object of measure phase. Depending on whether the customer is a business or the public, customer orientation activity varies in complexity. Businesses usually state their needs clearly and leave little space to interpretation. Their needs may already be called requirements. People, instead, uses a completely different semantics when expressing their needs. In the latter, more effort is to be put in interpreting needs and wishes. The so-called *voice of the customer* must be translated into technical requirements the company is able to measure.
Business' needs are those requirements the business has and cannot renounce to in delivering value to the customer. The project must also take business' needs into consideration.

Project scoping sets the boundaries within which the team is allowed to work and solve the problem. This activity is critical as all elements that are put out of scope cannot be addresses or explored to find root causes. Agreeing on the boundaries of the project from the very beginning will allow to exclude all non-addressable ideas and complaints that might arise later during cause analysis and solution designing. From this moment on, the team exactly knows where it may go explore causes and where it is not allowed to 'look at'. The project scope may be changed in case it is found out that the root cause or the constraining bottleneck of the process is somewhere else, but it must always be clear and effectively communicated to all team members and stakeholders.

Assumptions and constraint support the description and understanding of the context the project was born. All assumptions made and constraints encountered during project's problem and definition and scoping should be taken note of. This activity will especially help during project reporting when decisions taken must be explained.

As any project, some project management best practice activities may be performed to facilitate success. Examples are stakeholder analysis, risk analysis, resource planning, budget planning, timeframe planning. They are not in the scope of the thesis and related tools will not be discussed. The only aspect to be underlined as it is a Six sigma enabler, is how a well-done risk analysis and mitigation plan makes the team confident to take risks and find innovative solutions.

At the end of the kick-off meeting the project leader arranges all the work done by the team and delivers the *project charter* to the champion. This one-page document summarizes the main points and decision taken during the kickoff meeting to facilitate communication and project reporting. See Picture 7. A section of the project charter is devoted to making explicit assumptions made and constraints identified. Here, relevant factors that might affect positively or negatively the team's efforts can be reported. A common example is time availability of resources [1].



Picture 7. Project Charter.

The project charter may be revised and updated as the project rolls out.

Tools

Tools presented are oriented toward customer definition and project scoping. There is no formal shape these tools have as they must be adapted to the context in which they are utilized. Some companies though create their own templates to facilitate their sharing and understanding among the organization.

Tool 1 is a customer orientation tool. It helps translating the voice of the customer into technical characteristics the product should have to deliver quality. The tool has the shape of a table: the first column identifies voice-of-customer elements, the second one *key issues*, and the last one the technical characteristics the product must fulfill.

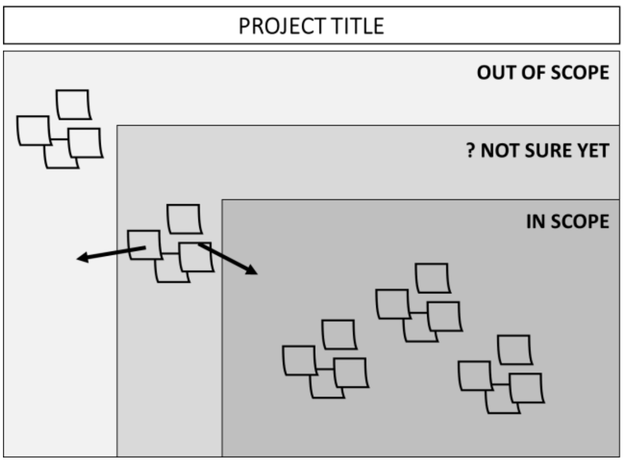
The voice of customer is the exact sentence customers say out loud when questioned about their needs. It usually is an attribute which perception may change from person to person or even depending on the context. These attributes are collected, arranged, and prioritized. For each category a *key issue* or *key variable* must be identified. This identifies a physical and measurable variable linked to each attribute. Last, a range of numeric parameters for each variable is defined. These ranges are the technical characteristics the product must fulfill to be considered of good quality. Technical characteristics are also called *Critical To Customer* (CTC). See Picture 8.

Voice of customer	Key issue	Critical To Customer
«The coffee must be hot».	Serving temperature.	The temperature when delivered must be higher than 30 ºC and lower than 50 ºC.
«The coffee must be long».	Volume.	The volume of the coffee must be 200±10 ml.
...		

Picture 8. Tool 1.

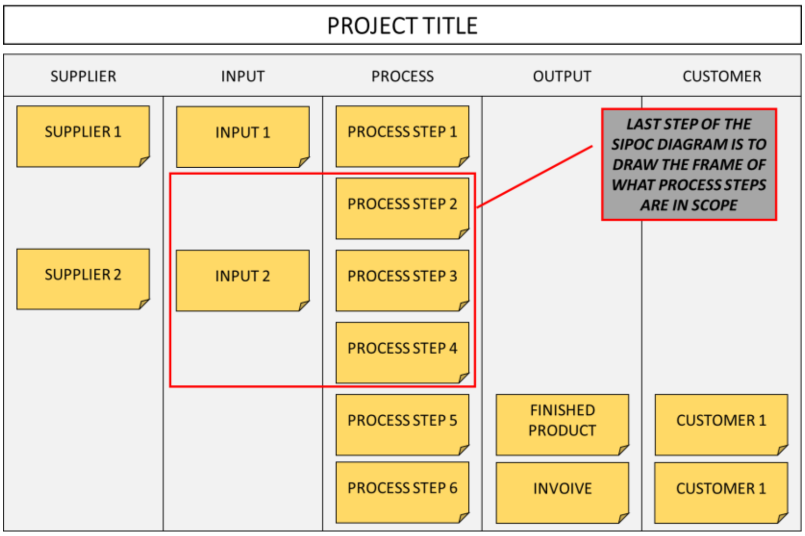
Regarding project scoping, the two most common tools are the in-and-out frame and the SIPOC diagram.

The in-out-frame (see Picture 9) visualizes what elements are inside project boundaries and which are out by drawing two frames. A third area is allowed to serve as a bucket of elements the team is not yet sure where to put. This tool works well when using flip charts and sticky notes. Ideas are written down on sticky notes and handed out to the workshop facilitator. Each element is worth a debate and if people’s mind changes the sticky note is fast to be detached and put in another frame. At the end of the project scoping activity, all members will easily visualize what has been put in scope and what has been left out of scope. In other terms, they know what may later be addresses and what is instead not addressable.



Picture 9. In-out-frame tool for project scoping.

SIPOC stands for *supplier*, *input*, *process*, *output*, *customer*. This tool helps visualizing the high-level process involved and draw a line around what process’ steps are in the scope and which ones are left out of it. Each element is identified by a column. Starting from the supplier and the material supplied on the left, the main steps of the internal process are written down into the central column. Then, the outputs of the process and the customers who receive those outputs are put in the last two columns on the right. Again, sticky notes are used to facilitate the changing of their position on the flip chart during the team's workshop. The following Picture 10 presents a sample SIPOC diagram. This tool is used to scope the project, not to analyze a process. Thus, elements are general, and details are not allowed.

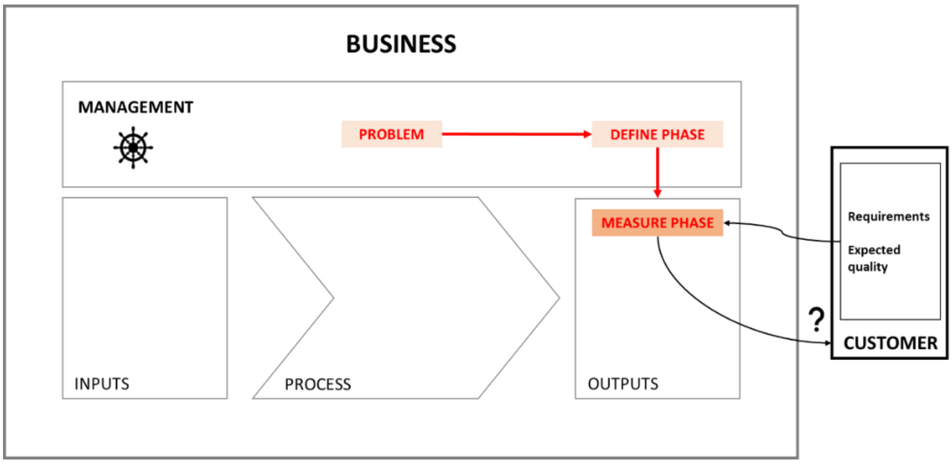


Picture 10. SIPOC diagram for project scoping.

5.3. Measure phase

Objective

Define phase identifies the problem and the customer requirements. Yet, it does not provide any tool to assess whether those requirements are met. Measure phase has the aim of creating a measurement system to assess the problem's entity, i.e., answering the questions "how do we measure the process' performance" and "how big is the problem?". Picture 11 shows measure phase is about the Ys i.e., the outputs of the process.



Picture 11. Measure phase.

The measurement system is based on the identification of variables able to represent the process output and its variance. As Six Sigma pivots around customer satisfaction, effective performance metrics are linked to customer requirements. To do so each CTC and CTB must be represented by one output variable at least. By measuring those variables, it is possible to assess the process performance, i.e., the degree customer requirements are fulfilled. On the one side, it is possible to appraise the process current performance. On the other side, it is possible to compute the desired performance. Current performance is assessed by simply measuring the current output. The desired performance is computed by linking output variables to the project's goal and find what values they should reach to satisfy the project's goal. The difference of these two values represents the entity of the problem and is the starting point of problem's causes analysis.

$$entity\ of\ the\ problem = desired\ process\ performance - current\ process\ performance$$

Having these two figures clear benefits communication as well and establishes a level of acceptance among people [1]. Displaying the performance helps understanding the need for change, visualizing improvements and gives an end to the effort people will put into the implementation of solutions.

The first challenge is to choose relevant variables. The importance of this choice is that it affects the whole project's success throughout next phases. A variable capable of representing an output will lead to an effective performance assessment and cause exploration. It will also enable a correct evaluation of solutions' impacts on performance further in the project. A variable that does not represent requirements might still lead to some secondary problem solving but will not tackle the project's stated problem. The same concept applies from a process' variability perspective. As Six

Sigma puts his focus on process variability, output variables should be able to assess process' stability. A stable process is easy to control, maintain and, finally, improve. Controlling a process is the act of checking if outputs are stably within customer specifications. An unstable process leads to reactive process management. Six Sigma's goal is to prevent problems to happen by reducing and controlling process' variability. To do so, the number of defects is count. As a process might fulfill the target in average, it might still have a high percentage of items that do not comply with requirements. Taking defects as measure of quality will drastically lower the process performance when it is unstable. This kind of measurement for quality assessment is called *Sigma measure* as introduced in Chapter XX.

The second challenge is to set up an effective data collection plan. This plan creates a common understanding of the definition of variables among the team and the data collectors. Often, indeed, the actual collection of data is performed by line operators who are not part of the team. Instructing them properly ensures data consistency. This enables meaningful data processing, comparison, and analysis. Instructions are made of an operational definition and a collection plan for each variable. The operational definition is an exact and unambiguous definition of how a certain variable is defined together with its unit of measurement. A collection plan defines how, where and when a variable should be measured. It specifies the data type, the sampling strategy, who is responsible for collection, and the measuring instrument. It also defines where in the process the measurement should take place and when. A consistent measurement system delivers the same result when inputs are constant. The risk of having differences in interpreting the quality of the same piece of output is especially true when collection is performed manually, and the test is visual. A well communicated operational definition of variables and data collection plan will ensure reproducibility and repeatability of collection procedure. Respectively, the same collector and different collectors provide the same results when analyzing the same item. Thus, first the team must clarify definitions, second collectors need to be trained. Skipping this activity leads to time loss as soon as it is found out the poor quality of data. This might also lead to frustration and reduce the level of proactiveness of workers. Evaluating data sensitivity also helps appraising data quality. In case the precision of measurement is requested to be very high, as for strict tolerances, it is necessary to assess the impact of error on results. This evaluation can lead to a change of the measurement instruments or the sampling strategy.

What must be clear and fixed at the end of the Measure phase is what variables will be controlled during next phases to assess the process' performance. Moreover, the champion must be updated on the current process performance.

Tools

Measure phase's tools support the identification of output variables and of data collection plans.

Tool 2 takes as input Tool 1's outputs, i.e., CTCs and CTBs, and output measures, Ys. CTCs and CTB may together called *critical to quality* (CTQ). So, the first step is to identify Ys that refer to CTQs. The design of the tool is a two-entrance matrix. Rows refer to CTQs while columns refer to output measures. The aim of the tool is to prioritize Ys based on their impact on CTQs. This is done by assigning a weight to each couple CTQ-Y based on their degree of relationship. A common weight system that helps visualizing relationships' strength is showed in Table 4.

Table 4. Tool 2 legend.

Symbol	Meaning
╲	No relationship
△	Weak degree of relationship
○	Medium degree of relationship
●	Strong degree of relationship

Picture 12 presents a template of Tool 2.

	Y1	Y2	Y3
CTQ1	●	╲	○
CTQ2	╲	△	●
...			

Picture 12. Tool 2 template.

Looking at relationships strengths it is possible to select the variables that best represent the CTQs. At least one Y with strong relationship to each CTQ must be present. If not, it must be identified.

Data collection is critical to represent the process meaningfully. The first step is to clarify the operational definition and collection procedure (instrument and method) of each Y. Further information to be created covers the variable's data type, responsible for collection, sampling strategy and criteria for decision (Picture 13).

	Y1	Y2	Y3
Operational definition	*A detailed description of the object to be measured and of the measurement.*	…	
Unit of measurement	*Specify unit of measurement.*		
Measurement instrument	*A description of the measurement instrument (visual inspection, device).*		
Measurement method	*A detailed description of the measurement procedure: where, when and under what conditions the measurement must take place.*		
Data type	*(Continuous, Discrete).*		
Responsible for collection	*Person responsible for data collection (manual collection, device control).*		
Sampling strategy	*Sampling strategy and sample size (if needed).*		
Criteria for decision	*In case of discrete data, this is the criteria to classify units into categories (tolerances).*		

Picture 13. Variable's operational definition and data collection plan [2].

Once clarified the above concepts, a data collection form must be distributed among collectors to allow data collection, or the measurement device set up. In case of manual discrete data collection, especially if it is a visual check, the Gauge R&R tool might help in ensuring reproducibility and replicability of data by collectors [2]. A sample items is taken, and an expert is asked to classify items into possible categories. Then, each collector is asked to perform the same task twice on the same sample items, reshuffling items each time. At this point it is possible to check if collectors are consistent and stick to the expert's classification. If not, some training is due.

After collection, data is to be processed and variation must be explained. The process is represented through centering and variation variables as mean, median, variance or range depending on the process and project needs. Pie charts, bar charts, Pareto Charts, Dot plots, histograms, box plots, run charts, scatter plots, and probability plots are examples of data visualization tools. This is done from a process efficiency point of view, i.e., the process capability of yielding high-quality products. Common Six Sigma measures for output quality are *defects per million opportunities* (DPMO), *parts per million* (PPM), *yield*, and *overall equipment efficiency* (OEE). Below Table 5 describes these measures.

Table 5. Variable's operational definition and data collection plan [2].

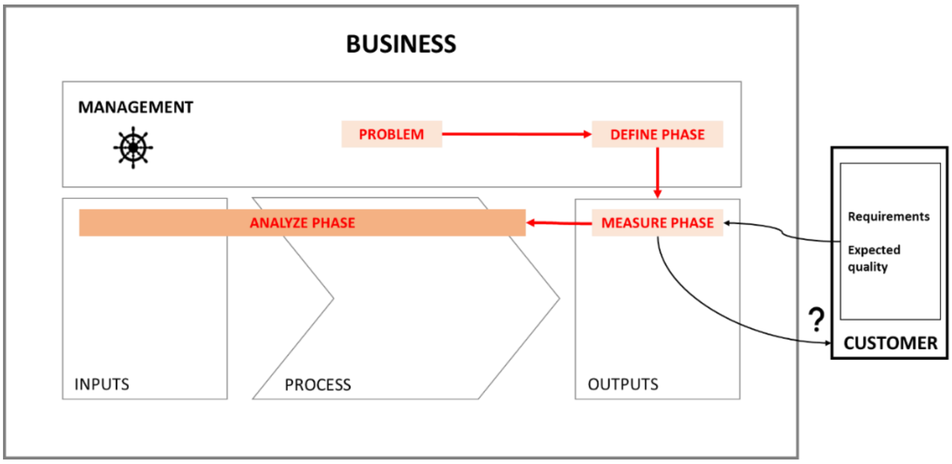
Measure	Description
DPMO	It is the count of how many defects the process generates every million opportunities. It is the customer perspective.
PPM	It is the count of accepted products every million items produced. 1M-PPM yields the number of defectives. It is the customer perspective
Yield	It is the proportion of non-defective parts from production.
OEE	It is the total effectiveness of the plant or a single line of it.

Six Sigma vision of near perfection is about making processes such stable the number of defects is incredibly low. Defects are defined by customer requirements. The challenge is to understand what opportunities to make a defect are present within the product production and delivering process and adapt this vision to the considered process.

5.4. Analyze phase

Objective

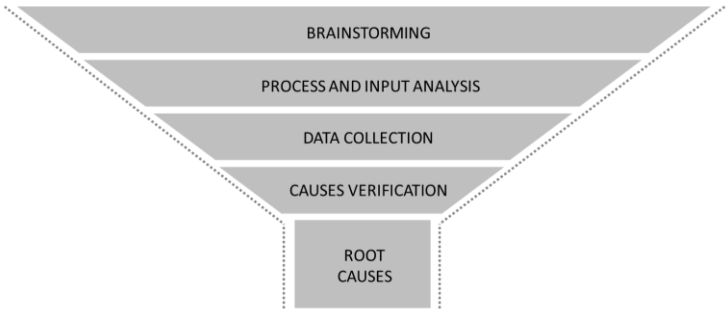
Analyze phase concentrates on the process inputs: Xs. The aim is to find the root causes of the problem. The team must answer the question "why are current outputs not at the desired level of performance?". This phase is where Six Sigma's closed-looped system vision takes place. Understanding how inputs impact outputs allows solutions prioritization and process optimization. Picture 14 shows this concept. The search of perfection by Six Sigma approach is hereby interpreted by the search of the causes at the roots of the problem. Patches are not sufficient to solve a problem, they will only temporarily hide it and are not sustainable.



Picture 14. Analyze phase.

Root causes of the problem are unknown and must be explored from a process point of view: inputs and structure [1]. This approach reflects Six Sigma's characteristic of being process-based. Some degree of engineering and technological causes may also be found but they should not be the causes of major impact as the project could no longer be categorized as Six Sigma project. Six Sigma's approach does not start from data analysis right away. It requires thinking first. Supporting causes' impact with data is a further step. If it is found that the cause is indeed impactful, it will not be discarded. Instead of collecting data, the team must go some levels downward in causes exploration and research root causes.

The first step for collection of causes is performing a brainstorming session. The team should invite to this session all stakeholders that are part of the process or impacted by it. The brainstorming session has the aim of collecting all hypotheses whatever their perceived impact, level of importance or relationship to the problem. They may refer to machine, people's behavior, line layout, process structure and effectiveness, and communication activities among stakeholders or process steps. All plausible hypotheses are then classified into categories to enhance readability and effectiveness of cause-effect analysis. By questioning the reason these causes take place, the team reaches potential root causes. Root causes should not be many as it would mean a further investigation of each could be performed and deeper root causes are still to be identified. At this point the team may start collecting data to support the impact of the identified root causes. For each root cause, the team must find its related process inputs and understand what variables describe their quality. First, a standard quality expected for inputs is set. Second, inputs are measured in terms of mean and variance. Last, the degree at which inputs meet the required standard and the impact variance has on process outputs are computed. This can be done for both inputs that are tangible materials and for structure-related elements as time of task execution or process cycle time. Having this information clear, root causes assessment and prioritization is possible. Prioritization of causes has the aim of tackling those that have more impact on process outputs, thus will lead to solutions carrying the most potential for reaching the project goal. See Picture 15.



Picture 15. Causes funnel.

Two mistakes often incurred into during analyze phase are to shortcut DMAIC cycle prematurely and, on the opposite side, to remain stuck into it. The first one happens when the team has not sufficient patience for cause investigation, analysis and data collection and jumps into improve phase. This approach is called *define-improve-define-improve* approach. It makes the team define a problem and go to solutions implementation without thinking and investigating and, when seen that results are not achieved, a new problem is defined. The second mistake happens when the team never gets convinced with the root causes identified. It is important to recognize these two mistakes as they take place and stop the team and bring the project back on the DMAIC path either by reminding the phase's objective or by taking a decision and continue.

When analyzing the problem's causes some "quick-win" solutions can directly be implemented. These are solutions that do not need any investigation and if this is seen to be a small obstacle which elimination can already contribute a little improvement. Although, they do not solve the problem. Moreover, *quick wins* enhance acceptance of people for the change the project is about to establish.

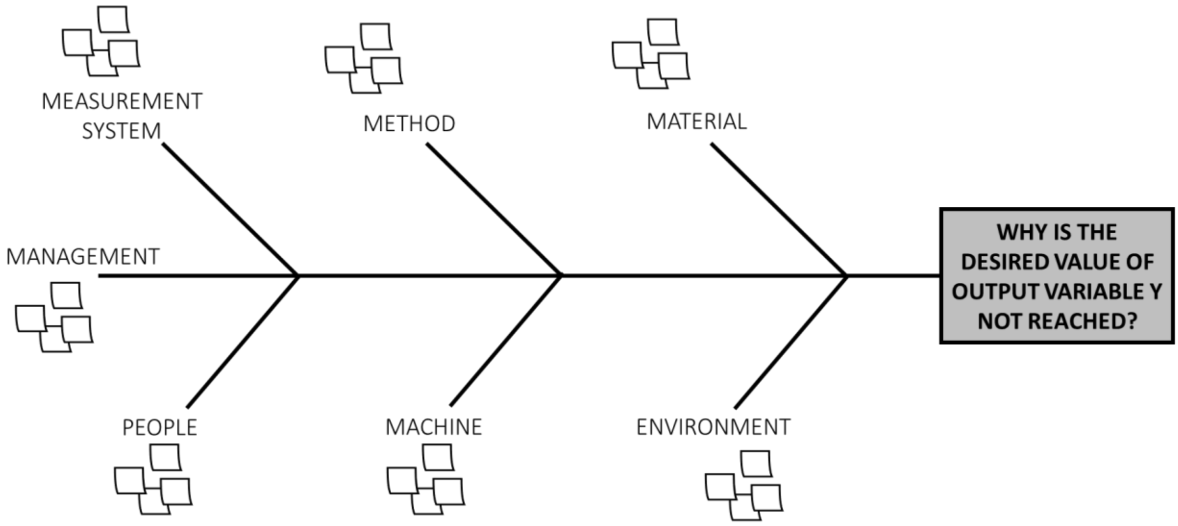
It might be found that the cause is outside the project's scope as the considered portion of the overall process is performing either good or is accountable for minor impact causes. This is the case a change in scope is needed to include the root cause location as well.

Analyze phase ends with updating the Champion of the project's status. Root causes must be validated by the champion and, if necessary, a change in scope is officialized.

Tools

The following tools help visualizing the process, questioning the reason things happen the way they do, and searching the root causes of the problem. There is not a correct order of employment nor all of them must be used. Usually, a causes brainstorming is performed first, and data support comes second. In case no team member has any idea about the problem's causes, process visualization and analysis may be directly performed with the aim of controlling the process and spot the cause.

The first step to perform a cause analysis is to brainstorm potential causes. The aim of a brainstorming session is to collect ideas about the problem's causes from team, workers, and stakeholders. A good practice is to set some ground rules at the beginning of the brainstorming session to make everyone confident about participating. As root causes are not known, any idea should be welcomes by the team as a possible analysis path. The fishbone diagram tool helps brainstorming causes by providing a framework for causes classification and it also creates a basis for further analysis. It has the shape of a fishbone with seven branches and head box. Branches identify classes of causes: management, measurement system, method, people, material, machine, environment. The box contains a question. The success of this tool depends on how this question is formulated. The question must refer to the problem through one output variable. It asks why the current performance value of that variable is not the desired one. People can then try to answer the question addressing all classes of causes. The team should perform a fishbone diagram for each output variable. Picture 16 is a template of fishbone diagram. Once completed, each element must be classified as variable, constant or noise. Variables are those elements that are possible to control. Constants are those elements which control is out of the project's scope. Noises are elements that hinder from getting a clean measurement. Excluding a scope enlargement, variables are the only elements the team may tackle, control and change.



Picture 16. Template of fishbone diagram.

The second step is to go further in depth from each cause using the 5-Why tool. This tool consists in asking five times "why?" for each cause and derive the root cause. If the logic of this analysis is correct, it is possible to start from the identified root cause and get back to the high-level cause by saying five times "therefore".

In case the team is reluctant in suggesting causes, the brain-writing technique may help. It consists in sitting the team around a table and handing out blank sheets of paper. Each member writes down a solution and passes his paper over to the next person. The same exercise is run again by writing a cause's cause. After some rounds, there will be multiple causes and root causes written down on papers.

The last step is to prioritize causes based on their impact on the problem. At this stage tools presented can create the required data support. Tool 3 (see Picture 17) links potential causes to output variables and it creates a data collection plan for causes verification. A relationship matrix is set up by crossing output measurement and potential causes identified through the fishbone. These relationships represent the influence causes have on outputs and can take four different values: 9 for strong relationship, 3 for medium, 1 for small, 0 for no relationship. Prioritization for verification is given by summing up relationship values of each cause and by sorting them in decreasing order. For each cause a data collection plan is established similarly as for output measurements. After data verification and causes validation, root causes are identified.

TOOL 3	X1	X2	X3	…
Y1	9	0	0	
Y2	3	3	9	
Y3	9	3	0	
…				
Priority	Σ=21	Σ=6	Σ=9	
Operational definition				
Unit of measurement				
Measurement instrument				
Measurement method				
Data type				
Responsible for collection				
Sampling strategy				

Picture 17. Tool 3 template.

Another tool that may be implemented is FMEA (failure mode and effect analysis). The presenting of this tool is out of the scope of the thesis.

The below tools focus, instead, on process visualization and value chain analysis.

The *activity diagram* shows all process steps following the sequence they are performed. This model requests any process to start and end with a defined and stated event. Process steps are divided into activities and decisions. Activities are those steps in which material or information is processed. Decision steps, instead, do not process anything, they assess a variable's value (qualitative or quantitative) and split the process path into two or more branches depending on the decision taken. Decisions needs to be clearly stated and admit a finite number of possible solutions. The diagram also represents the mutual relationships between activities and decisions and identify the process flow. When drawing an activity diagram, there must be at least one path connecting the start point to the end point. Moreover, no activity may start by itself. Only events may trigger the process to start or end. The following Table 6 summarizes the activity diagram's symbology according to UML (*Unified Modelling Language*). More elements about information flow (digital or paper-based), inputs and outputs, databases, and delays, are also available in case a complete and formal representation of the process in needed.

Table 6. UML activity diagram symbology.

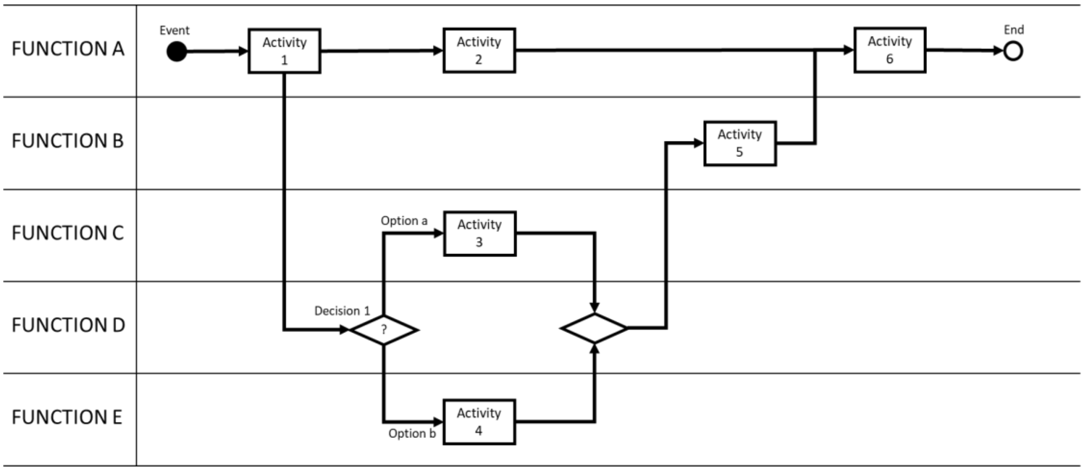
Symbol	Meaning
●	Start
○	End

▭	Activity
→	Connector
◇	Decision

Visualizing all process steps and their mutual relationships is particularly helpful when people either do not know the process at all or do know the activity they perform and those adjacent to it but ignore how the entire process is structured. This kind of diagrams allow to understand the process' path. Process analysis can therefore tackle both process' structure and process' load. The structure is the sequence activities are performed and the events that trigger an activity to start or to end. The structure is inconvenient when, for example, some activities that are performed in sequence could be parallelized. The process load addresses the balance in terms of resources utilization. Process load analysis leads to the finding of bottlenecks and constraints. The difference between bottleneck and constraint is the former one identifies the step with highest utilization, the latter one, instead, identifies an element that hinders from meeting market demand. Thus, a bottleneck may or not be a constraint.

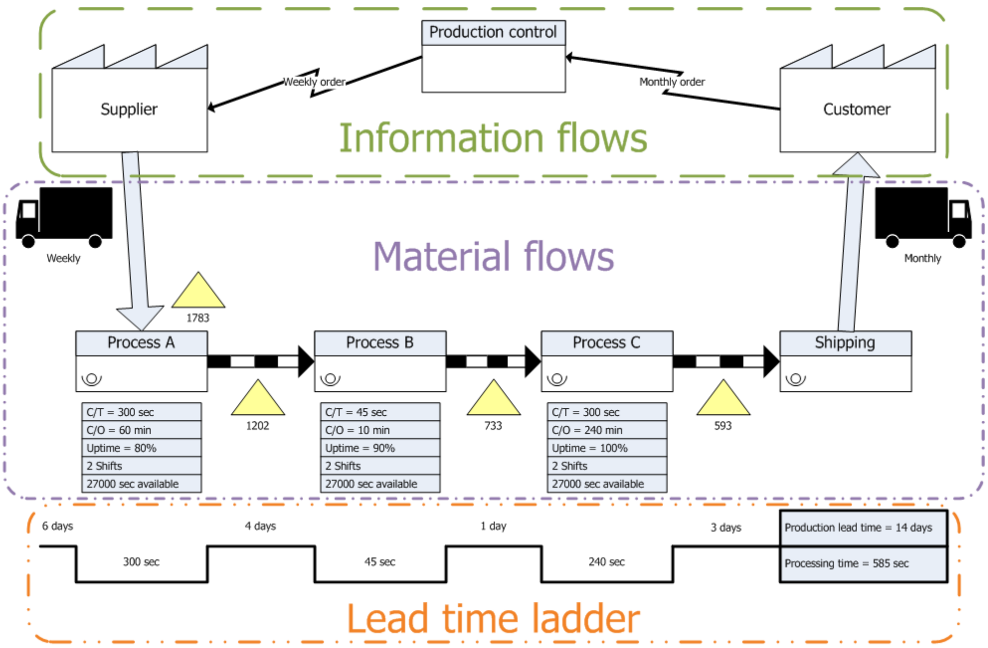
Drawing an activity diagram of the as-is process also brings all workers together in the same room. They may exchange views on the process itself and make it smoother and more efficient for everyone. Often people have no idea who provides their inputs or who their outputs are delivered to. Thus, they have no opportunity to ask suppliers to change inputs and format them in a more convenient shape. Nor they know if the customer would be more satisfied with an output made in such way it even requires less effort. Transparency in process redesign will increase workers' awareness, proactiveness and acceptance for change.

An expansion of the activity diagram is the cross-functional diagram. It follows the same rules and symbology, but it categorizes activities depending on their belonging to the company's functions. See Picture 18. This diagram provides more information and allows to visualize the function that has the majority of workload. It also shows the number of times the process flow crosses function as this may lead to time consumption due to motion.



Picture 18. Cross-functional diagram.

A value stream map (VSM) is a tool that helps mapping material and information flow from supplier to customer and visualizing value-added process steps. First, the overview of the process is drawn from the customer to the supplier using the SIPOC diagram: suppliers, inputs, process steps, outputs, customers. The scope is also defined by marking the boundaries of the process. Second, the visualization of the rest of the value and information stream is drawn: transportation, inventories, scrap and rework, type of material flow, order from supplier and deliver to customer information, and value timeline or lead time ladder. The value timeline shows each step's duration, distinguishing between value-added processing activities and non-value-added waiting stocks. The following Picture 19 shows a template of VSM.



Picture 19. Template of value stream map. [26]

Another tool for process visualization is the spaghetti diagram and it concentrates on motion of material and people. It is built by drawing the plant layout and, with the use of a pen, all motions of people and material around processing stations. The simplest way to perform this activity is to follow operators or material, stop when they are stocked, and walk as they move from a place to another. Having all motions drawn, congestion evaluation is possible, effectiveness of the plant layout and whether motion is a problem's cause can be assessed.

After process visualization, process analysis is made feasible. Process analysis aims at measuring the process. Value analysis is the computation of value-added and non-value-added activities. In performing such analysis, the team must take the customer's point of view. Value added activities are those activities the customer is willing to pay for as they directly impact the product production. Non-value-added activities are those activities that do not add any value to the product. They may be required for secondary company's processes but have no impact on the product. They should be eliminated or minimized. A third class of activities may also be identified: value-enablers activities directly support value-added one, but do not add value per se. They should also be minimized. Evaluation of activities requires a knowledge of the company's core competence [2]. The sum of the durations of all activities is defined as the process lead time. The process efficiency is then computed as follows:

$$process\ efficiency = \frac{value\ added\ activities}{process\ lead\ time}$$

Process efficiency allows to identify improvement opportunities by benchmarking the current activity with the should-be one or with other companies in the industry. In categorizing activities care must be put in employees' feelings. Seeing one's own work marked as non-value-added might be counterproductive. It is important to clarify the aim of this analysis at the beginning of the workshop this tool will be employed.

Another kind of analysis is about process throughput rate and takt rate. The average process throughput rate for stable-state processes is defined as the number of items exiting the process per time unit. Takt rate is, instead, the exit rate the process should guarantee to fulfill demand:

$$takt\ rate\ [item/time] = \frac{customer\ demand\ \ [item]}{available\ production\ time\ [time]}$$

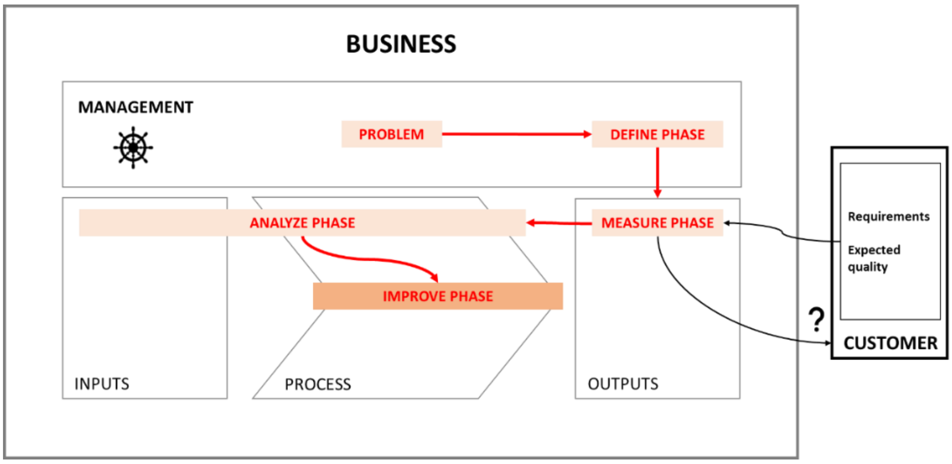
From their comparison it is possible to identify the bottlenecks of the process and prioritize improvement effort.

When all process steps seem to fulfill requirements on average, the cause of problems may be variability. Variability should at this point be computed and analyzed. Every process has two types of variability: a structural variability and a natural variability. The former one is due to some failure happening and must be fixed and eliminated. This kind of failures affects all items processed and results in a process' mean shift. The latter one is, instead, intrinsic in all processes, it may be minimized and controlled but it cannot be eliminated. Natural variability builds up around the process' true mean value. Variability of a process step cascades down and amplifies on the following steps. This has the effect of increasing safety inventories and costs. Understanding variability and its causes is accomplished through statistical methods as hypothesis tests, analysis of variance tools (ANOVA), or regression tools. Hypothesis tests allow to assess the validity of an assumption made about the population. ANOVA and regression are models that enable computation of statistical influence of one or more independent factors (input) on the considered dependent variable (output). Thus, it is possible to understand how much of the output's variance is explained by the input factor. If the factor explains enough output's variance it is likely to be a problem's cause. If not, different assumptions must be made.

5.5. Improve phase

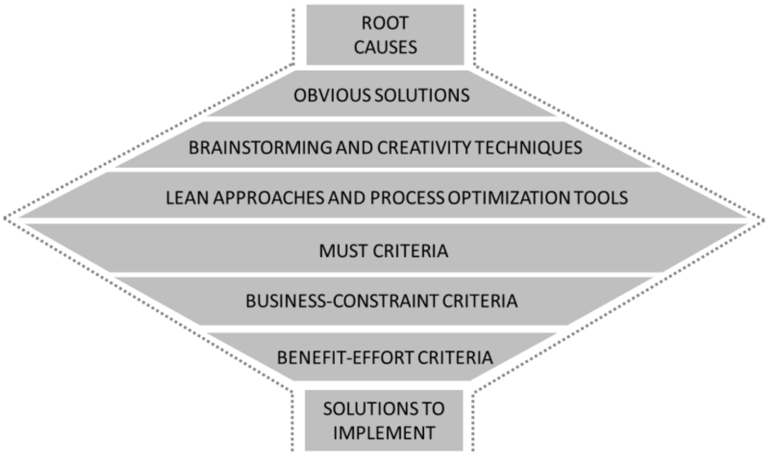
Objective

Improve phase has the target of fixing causes and solving the problem. Starting from designing solutions, the team has the task of selecting the most promising ones and finally implement them. Solutions address the root causes that have been identified during analyze phase and must be sustainable over time to avoid the process to fall back into its original state. To check on their effectiveness, outputs must continuously be supervised. See Picture 20.



Picture 20. Improve phase.

The funnel of potential solutions (Picture 21) first widens to include all ideas and later narrows down to the selection of the most impactful ones.

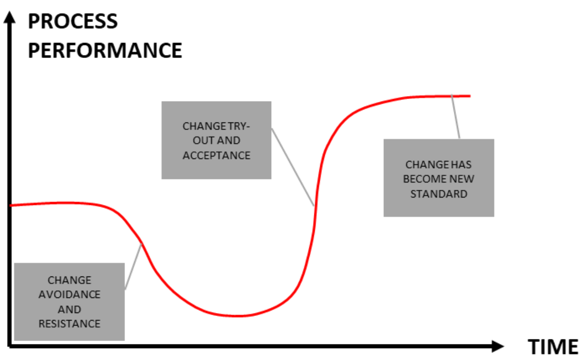


Picture 21. Solutions funnel.

Having well identified and understood root causes, a brainstorming session for each cause takes place. All potential solutions are collected, including trivial ones and complex ones. The team is asked to be creative and suggest any possible element that could fix the root cause. In case of a bad structured process, a more efficient structure can be designed. In case people don't follow procedures, new procedure can be written making sure to involve them into the redesign workshop. As people's habits and way to work have been questioned and are going to be tackled and changed, involving people into solution designing and brainstorming is critical to make them sustainable and accepted.

Process optimization actions should create a standard. They are necessary to overcome variability and reach a stable and smooth process. There are two reasons behind that. The first one is that as the process changes, new tasks, roles, and procedures must be well defined and communicated. Workers must know what their scope of work is and what is under their responsibility. The second one is that a process sustains a stable state and minimizes his variability if the procedure is fixed and followed each time the same way.

Solutions must be tailored to the company's environment. The organization's culture and the people's culture must be taken into consideration to design successful solutions. Effectiveness of change depends on two factors: quality and acceptance. Therefore, designing high quality solutions, that will not only improve the process' outputs but workers' jobs as well, is critical. The outcome of this effort is though lowered when acceptance is low. Communication and involvement of people is the most effective tool to overcome resistance. There are three types of resistance when trying to change people's habits: technical, political, and cultural. The first one is when a person responds with sentences like, "I cannot do that". Technical resistance is addressed through training. The second one will have people say, "I am not allowed to do that". This kind of resistance will solve as soon as that person's boss gives him the new task. The last one is about will: "I don't want to do that; I do not feel comfortable". People will change habits only if they see some degree of payoff. Motives that make people change habits are prestige, gain, comfort, and safety. By addressing these four elements personally for each worker, improving and later sustaining processes is smoother. Picture 22 shows the performance curve of a process when improvement is implemented correctly.



Picture 22. Process' performance curve when improvement is implemented.

Selection of solutions starts from reminding the project's problem and goal. Solutions must achieve the goal. They must reach the output-variables' desired values that have been stated during measure phase. Their effectiveness is thus evaluated based on their impact on process outputs. If output variables have been well designed and chosen, their maximization will fulfill customer requirements as well. Other criteria for selection are cost and effort, scheduling, technical feasibility. There usually are some must criteria to respect also, as general company rules and national law. Solutions that lower service or quality level of the customer should not be taken into consideration. After prioritization a decision must be taken. A *solution statement* is a sentence that clearly describes a proposed improvement [1]. The solution that has been chosen must be clear to everyone to enable effort to be put in that direction consistently. There are two reasons behind this need. On one side, implementation does usually not take short. Everyone must understand and accept his new role or task fully and stick to it. On the other side, the project lead would lose credibility and support if it changes mind and opts for another solution making effort put become useless.

To avoid impediments during implementation, an execution plan should be arranged. Specifically, implementation steps and timeline must be defined and communicated in such way people know when improvements are due and what tasks and milestones are under their responsibility. Risk prevention and mitigation plans are also useful to clarify who is responsible for deviation in the process when circumstances will request it. During solutions testing and implementation measuring the effect of changes is a must. Without this measurement if would not be possible to say whether the problem has been solved. A *pilot plan* is a trial solution implementation when outcomes are not forecastable with enough degree of confidence. The team might decide to go for a trial and see how it works. After having measured outputs, if they in fact have the potential of fulfilling the goal, the team finalizes them and makes them official. Otherwise, the solution might in part change or be discarded.

The champion's decision is usually requested before starting to implement a solution. As it takes time and resources, solutions might be discarded or delayed by the champion due to current lack of available resources.

Tools

Creativity techniques to brainstorm potential solutions are brainstorming, anti-solution brainstorming and benchmarking method. These techniques are helpful to the team when it comes to suggesting improvement ideas that are known to bring change into the process and might not be welcomed by all. The team leader takes the role of workshop facilitator and collects potential solutions from the team and using sticky notes makes them visual on a board. The keys to brainstorm ideas are the following [1]:

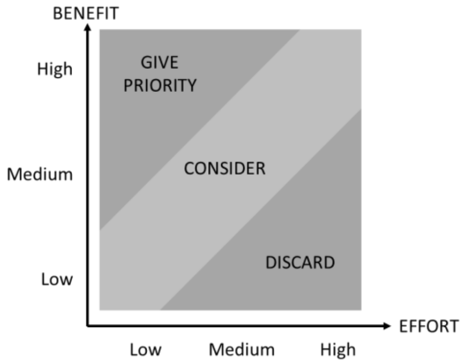
- no comment and criticism are allowed: people must feel free and unjudged of suggesting; otherwise, they will no longer feel comfortable with sharing,
- the objective of the session (the cause that is being tackled) must be clear to avoid non-pertinent ideas,
- people must listen and put focus on each idea to enable building on the ideas of others,
- define a "quantity" and "quality" objective for the session: a time frame and a target number of ideas to come up with; this way the brainstorming may be boosted,
- abandon assumptions to avoid thinking the way it has been done till now; Six Sigma requests out-of-the-box thinking.

Brainstorming may also be done handing out sheets of paper to each participant to have everybody participating. This method also works when the task is to be carried out online as it does not need simultaneous participation of team members. The anti-solution technique may be employed when the team is particularly averse to the project. It consists in asking how the performance may be worsened. People get more creative in making things run worse. Those ideas may then be reversed to reach a potential solution. The benchmarking method or analogy method consists in studying different industries and try to understand how they solve problems. This helps creativity and out-of-the-box thinking. In any case, the disclosure of the idea development and selection process by the team leader before the starting of the brainstorming session will help people feel more comfortable.

Most process improvement tools aim at process standardization and come from Lean Manufacturing System. Among them I will present 5S and Poka Yoke. 5S method takes his name from the five steps that are to be carried out (from Japanese: Seiri, Seiton, Seiso, Seiketsu, Shitsuke). This method aims at standardizing a process by spotting causes for failures and variance. The first step is *sort*, and it refers to working tools and equipment used at the workstation. All elements that are superfluous to the execution of the job are to be eliminated. This way the probability the worker misuses equipment or does not find those he needs are lowered. Sorting is done using two boxes: one collects waste equipment, the other one collects necessary tools. The second step is *set in order* and has the objective of arranging equipment the simplest way they can be employed and found at the right moment during the execution of the job. A shadow board is a toolset board that identifies fixed spots for each working tool through drawings (the “shadows”) of their shapes. This board has two advantages. The first one is the worker always knows where to find tools and where to put them back. The second one is the object of the third S: spotting variance. When it is possible to see a shadow on the board, the correspondent tool is not present. Either the operator is using it, or it is missing. Setting things in orders allows to spot variation that can potentially lead to failures. For example, not finding a tool because of mess, will increase the product cycle time and customer dissatisfaction. When these three steps are done, the fourth is setting up a *standard*. This means to solve all obstacles and sources of potential variance that came up during sorting, setting in order and spotting variance. Last, the standard must be *sustained*. The 5S is not a one-way through process, it is a cycle of sustaining and improving a standard. The most challenging part of 5S is sustaining results: keeping things organized to enable the spotting of new source of failures that may arise.

Poka Yoke means *failure proof*. This method aims at setting up mechanisms that stop processes and machines as soon as a failure is spotted without the need of human supervision. Preventive maintenance is indeed much cheaper than failure fixing. When the process and the machines are designed in such way failure cannot happen or are immediately spotted, the cost of quality check and product fix is minimized. This is especially true when production is organized in batches. The probability of finding a defect and spotting the failure late is very high and it will have affected the whole batch. The aim of poka yoke is to have the process stop and alarm as soon as a failure happened. Workers will have the task of fixing failures and restart the process.

Selection and prioritization of solutions is carried out using either the N/3 method, an effort-benefit chart, or a criteria-based tool. The N/3 method consists in distributing to each team member an amount of votes that is one third of the total number of possible solutions. Each member assigns his votes to solutions he considers most performing. The most voted solutions will be the ones to be given priority in implementation. It is a good practice to vote secretly to avoid influential members to influence the team. The effort-benefit chart is shown in Picture 23. Each solution is given a benefit and effort ranking. It may be qualitative or linked to a variable such as payoff, cost, time, resources needed. Then, solutions are plotted on a benefit vs effort chart. Those solutions that present a high benefit and a low effort will be prioritized.



Picture 23. Effort-benefit chart.

The multicriteria-based method is based on the identification of multiple criteria on which basis solutions will be chosen. First, criteria for selection are chosen and a scale is defined. Values on that scale may refer to qualitative expressions. Second, criteria are prioritized assigning values of relative importance to each. Third, solutions are given ranks for each criterion depending on the defined scale. At this point, each ranking is weighted by the respective criterion's importance and a score is obtained. Finally, summing up scores for each single solution, a preferred solution is found. Picture 24 shows the multicriteria matrix.

	Criterion 1	Criterion 2	Scores	Priority
importance	30%	70%		
Solution 1	5	5	5*30%+5*70%=5	1
Solution 2	3	1	3*30%+1*70%=1.6	3
Solution 3	1	5	1*30%+5*70%=3.8	2
...				

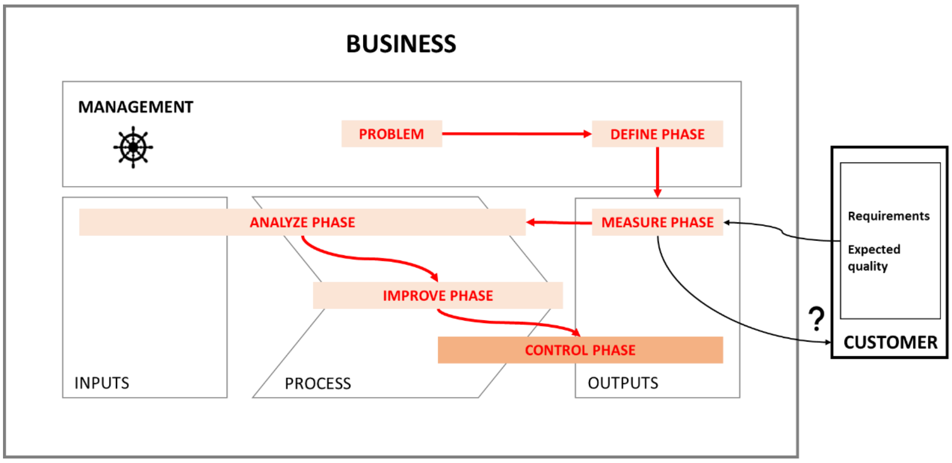
1 = Does not respect the criterion	*2 = Barely respects the criterion*	*3 = Broadly respects the criterion*	*5 = Fulfils the criterion*

Picture 24. Multicriteria method for prioritization of solutions.

5.6. Control phase

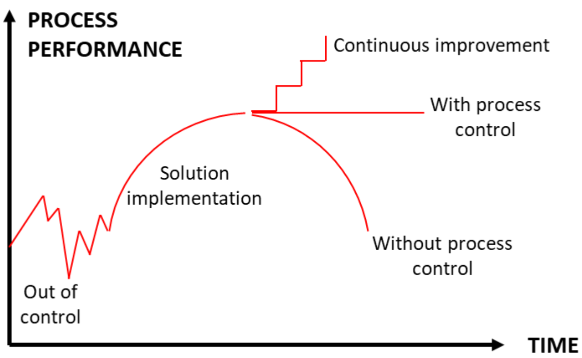
Objective

Control phase ensures the solution stays in place over time. Its importance must not be underestimated. Its aim is to set in place mechanisms that make the solution sustainable, respected by all, and avoids the process to fall back into the previous routine. This phase is about measuring outputs, Ys, and monitoring the process. See Picture 25. Without a careful and constant attention during this phase, the work done so far would result in a loss of time and effort and expected economical results will not be met.



Picture 25. Control phase.

One of Six Sigma visions is that of process continuous improvement. As shown in Picture 26 control phase may take up the challenge of putting more effort into process improvement. This can be achieved through minor enhancements or major one. Minor improvements can be carried out by the process owner himself. Major ones may need a new DMAIC project.



Picture 26. Process performance curve with and without process controlling.

Control phase consists in 4 activities:

- creation of project documentation,
- process monitoring,
- creation of a risk response plan, and

- handover to business.

Documentation is fundamental to leave track of work done, decisions taken and reasons behind them. The project leader is about to step out of the process control. The team breaks up as no longer needed. People change roles and are repositioned within the company. Things are likely to get out of control as none of them will no longer oversee the process performance. A well done and easily accessible documentation reduces this risk. Documentation includes the should-be process structure and expected performance, a description of the initial situation (the reason the project was started) and a description of the main decision taken (the reasons and context that led to those decisions). Documenting the new process structure is cardinal to sustainability, as those who will run the process do not have an overview and those who will control it were probably not part of the team at the time the project was executed. Moreover, the reader may understand why some causes have not been taken into considerations and why some solutions have been discarded or did not work as expected to. Documentation avoids redoing past mistakes in the future and enables continuous improvements by leaving a list of secondary causes found but not considered (for example because of low impact at the time).

Having concluded improve phase, change is only halfway through. Time and effort have been put into solving the problem. The project's goal is achieved at the end of improve phase in terms operational results, i.e., of reaching the desired value of output variables. Though, economical results are usually computed on a longer time span. Without sustaining solutions, economical results will not be met. Additional time and effort must be put into monitoring the new process is sustained. As processes and people's habits are tackled, time is needed to have everyone on board, making sure they understand their new set of tasks and proactively stick to it. Control is carried out by constantly measuring outputs (mean value and its stability), process quality and capability in terms of defects, and monitoring inputs for some time as well. These activities are done by the project leader together with the process owner in such way the latter one may get in control of the new process, understands it, and may later sustain it.

A response plan is a document that lists and analyzes likely risks and problems that may happen in the future based on the acquired experience and knowledge about the process. Its output are pre-defined actions that should be taken to mitigate or solve those situations. They are very specific and guide step by step to the solution of the problem. The idea is that people who did not deal with the project still know how to act quickly and effectively. In case major problems arise, a team member needs to be questioned or a new causes analysis carried out. A response plan tells, for example, what secondary variables to constantly check and their control limits, and what actions to undertake in case a negative trend is detected.

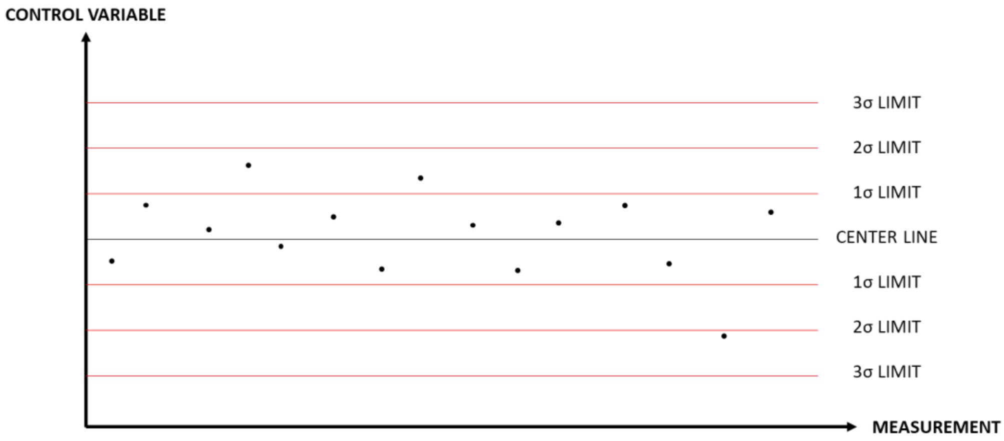
The last activity is the handover of process responsibility from the project leader to the process owner. See Picture 27. It is a good practice to involve the process owner as early as possible, best during improve phase already. Form this moment on, the project leader has finished his tasks.

Picture 27. Process responsibility.

Control phase virtually never ends. The process needs continuous and infinite monitoring to ensure its stability. Habits of workers change over time if they are not monitored. This happens because the reasons behind newly established routines (why tasks are carried out the way they are being) are forgotten over time and people tend to change the way they work to fulfill their own wills instead of constantly serving of the customer and making the interest of the business.

Tools

A control chart (Picture 28) is effective in monitoring the process and recognize structural failures with the final aim to keep it in control.



Picture 28. Control chart.

This tool is built by measuring the variable of interest (choosing a sample if necessary) with respect to time. The average $\bar{X}$ and standard deviation σ of the variable are computed. $\bar{X} + 3 * \sigma$ is called *upper control limit* (UCL). $\bar{X} - 3 * \sigma$ is called *lower control limit* (LCL). The idea is that the process should always stay within the two control limits. Values beyond control limits are called *outliers*. They can have two different natures: they either are due to natural variability or to some failure in the process. Being the control limits at $3 * \sigma$ distance from the center value, the probability of this event is just 0,27%. Otherwise, a failure happened, and causes must be investigated. The Western Electric rules suggest a way to recognize a sequence of events that can make think of a failure happening in the process. W.E. rules are found in Table 7. When building the chart, each time some outlier is present and its cause understood and solved, that information may be taken out from the database and a new chart built using the new values of average and standard deviation based on the smaller sample. This way all structural variability is taken out from the database and natural variability is left. Having this chart ready simplifies the comprehension of the process each time a new measurement of the variable is computed.

Table 7. Western Electric rules for out-of-control process recognition.

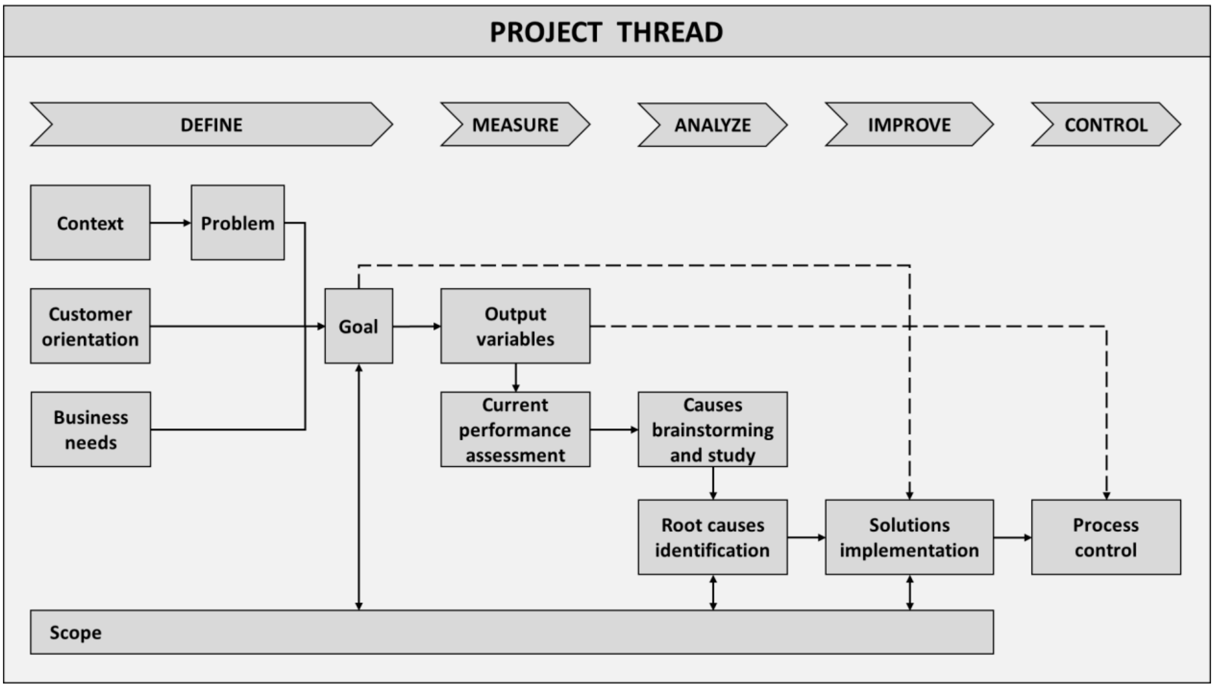
W.E. Rules	
Either:	
	A point plots outside the 3σ control limits.
	Two out of three consecutive points plot beyond the 2σ warning limits.
	Four out of five consecutive points plot beyond the 1σ limits.
Or:	
	Eight consecutive points plot on one side of the center line.

6. INDUSTRIAL STUDY CASE OF DMAIC CYCLE

Note*: all number and figures have been scaled therefore they do not show real values.*

The following study case originates from a project I have been assigned to with the role of project manager by the plant manager. The project has been opened due to the fact the annual performance target on a production line has not been reached. The indicator utilized to assess it is the *Overall Equipment Effectiveness* (OEE). Being the problem's causes not clear, it has been decided to use the DMAIC approach. Thus, tackling the problem started with problem and goal definition and project scoping. Process measuring followed and output variables have been identified and measured. Once the problem's frame was clear, causes exploration and study has been carried out with the aim of identifying the root causes that most impacted the process making the problem arise.

The following Picture 29 shows the project logical thread.



Picture 29. Project logical thread.

6.1. Company context, production line, definition of the problem

Henkel is a German-based multinational company operating in the chemical industry. It owns many and different brands sold to both end customers and B2B. Casarile plant is part of the adhesives division, and its products have industrial application in lots of industries. Here, tens of different resins are produces and shipped to other businesses.

The polyamides production process consists in mixing raw materials, processing the product, and bagging it. First, raw materials (ammines, amino acids, and additives) are mixed into reactors at high temperatures. Second, when the desired level of chemical specifications is met, the liquid product is pulled out of the reactor and cut into small spherical balls that are immediately cooled down and solidified. Last, balls are bagged and shipped.

Casarile plant produces polyamides on five production lines divided into two different buildings. The production is organized in batches because production times are very high and variable: 20 to 40 hours. For this same reason, work is organized in shifts including nights and weekends. Raw material mixing into reactors can take up to 20 hours due to setup times, processing time, quality tests and, when needed, correction of the chemical mix. When the product is within specification limits, the reactor's discharging valve is opened and the liquid product flows out into a supply line that feeds the cutting machine. At this point, the production becomes continuous, as the batch inside the reactor is made flown out continuously. The product is hereby cut into spheres that end up into a cold-water flow. Spheres are then transported to a drier to remove water and to a sieving machine. This machine separates non-conformities and powders from finished product that is transported to the bagging machine where bulks are created and shipped out. Cutting machines can be fed by more than one reactor (not simultaneously). As cutting machines represent the line's bottleneck, the line's efficiency is computed on the continuous part of the process: from the cutting machine to the bagging machine.

As anticipated, the process' effectiveness is measure by the OEE indicator. The average OEE of the line year to date September was 32%. Target for end 2022 was 40%. For this reason, the project's goal is to reach 40% OEE on the line.

The definition of supplier and customer of the process starts from considering the project's goal. The increase of the OEE is a direct business interest. The problem posed is not about product quality and it did not start from customer dissatisfaction. The problem is internal to the business; thus, the focus is to be put on company's requirements. Customer orientation is well known and currently respected. Indeed, quality tests are out of scope, the product's quality is assessed by the quality laboratory and are not affected by the product cutting activity. A second quality check is the shape of the balls produced. Those that are not conform are selected and separated by the sieving machine. On some products a granulometry check is executed by operators. On others, a visual check is executed by operators at the beginning of the process to assess balls are all the same size and shape. These kinds of checks are out of scope and the process cannot affect their evaluation. Tool 1 has been used to understand business' needs. See Table 8. A higher OEE means to increase the efficiency of the line, i.e., increasing the volumes the line can manufacture per time unit. The supplier, instead, is the reactor as it supplies the material to the cutting machine.

Table 8. Tool 1.

	Voice of business	Business' need	Critical To Business
Tool 1	Higher line OEE.	Increase line efficiency	Increase volumes of finished product per time unit.
			Decrease scraps volume.

The project's scope has been defined with the team during the project's kick-off meeting. For scope definition, a in-out frame has been employed. Elements to be classified are workforce, shift arrangement, machine parameters, procedures, work instructions and manuals, quality tests, and trainings. The following Table 9 classifies elements into three categories: in-scope, out-of-scope, and nice-to-have. Elements that are put out of scope will not be addressed and changed to reach the project's goal. Unless root causes are found to be part of out-of-scope elements, these elements will not be tackled during the project. Otherwise, a change in scope would be necessary. In scope elements are those factors that the team will explore and study in search for problem's causes. Therefore, solutions to causes will stay within these boundaries. Nice-to-have elements are elements the team does not currently consider to be hindering from reaching the project's target, thus will not be prioritized. Their innovation might be interesting in the future as well. Nice-to-have element will be moved in scope in the scenario their enhancement has an impact higher than expected. Classification is done by the project's team considering the current OEE measurement system.

Table 9. Scope definition.

Element	Classification	Comments
Workforce	Out	Hiring and firing personnel is not in the scope of the project.

Shift arrangement	In	Re-arranging shifts means to move operators from a shift to another one.
Machine parameters	Nice-to-have	Creating a database of reliable data to set the optimal instant machine parameters.
Procedures, work instructions and manuals	In	Create, update, and standardize procedures. Review and update work instruction and manuals.
Quality tests	Out	Chemical quality is assessed by the laboratory.
Trainings	In	Educate new operators.

When stating the goal, an assumption has been made; different product can individually reach the target OEE or, if not, they will allow an 8% OEE increase on average. This assumption translates in constant product mix each month. Not all products yield the same efficiency while processing. The assessment of process' efficiency should be product-based. The current computation of the OEE by the company has been kept as is as external-to-project requirement and to allow the comparison with available data.

The company computes the OEE on monthly total values of finished product and processing time of each batch. It does not distinguish between different products, and it is not an average value of the OEEs of each single batch. Thus, equipment's overall effectiveness will be computed this way:

$$OEE_m\ [\%] = \frac{FP_m}{potential\ FP_m} = \frac{\sum_b FP_{m,b}}{\sum_b potential\ FP_{m,b}}$$

where $FP = finished\ product\ [kg]$, $m = month\ of\ reference\ [1{,}12]$, $b = batch\ manufactured$.

Potential FP is the amount of FP that could have been produced in the scenario of machine running at maximum speed, no scrap production, and no downtime. This value refers to the processing time spent during the same month. So,

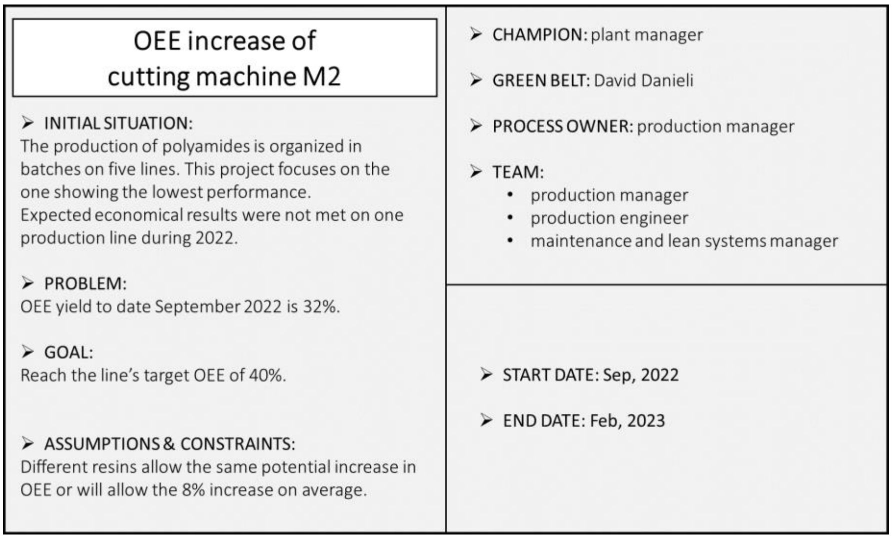
$$potential\ FP_b = maximum\ speed * processing\ time$$

The maximum speed the machine can run at is 900 kg/h. It is a value set by the manufactured based on some tests and on machine capacity. This number is a constant as its change would entail a change in machine or technology which is out of the scope of the project. The processing time is the total time taken to discharge, from the moment the machine starts running stably to the point the process has ended, i.e., the reactor is empty. This time includes downtimes.

As a timeframe, the project is expected to last five months up to the full implementation of improvements. Control phase may then start, from the end of February.

Early expectations of the team were that the low OEE was due to machine speed setting and excessive scrap production. On one side, it was a common comment from operators that increasing the machine speed setting would make the process more unstable, increase machine stops and consequently downtime. On the other side, employees commented that this was just a perception. The team suggested to put the focus on the machine speed setting and understand what was happening. Data had already been collected starting from January. Scrap production tracking has also been prompted by the team as a useful activity. Indeed, as part of the scrap is recycled, there was the worry operators did not try to minimize scrap production.

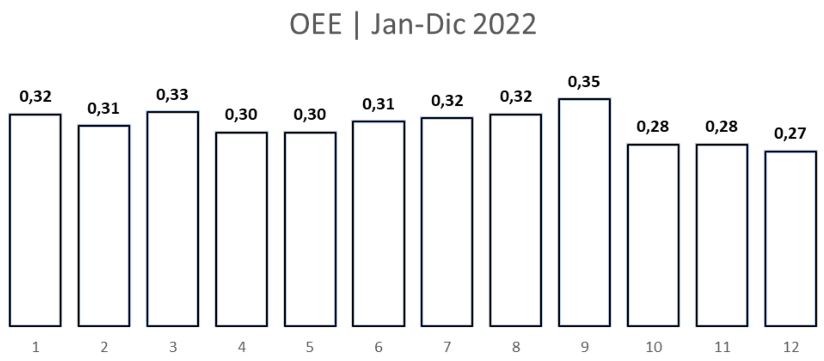
Picture 30 is the project charter and it summarizes information about the project.



Picture 30. Project charter.

6.2. Measuring the problem

First step toward problem solving is problem measuring. The following Picture 31 shows the OEE per month in year 2022 from January to September. It is possible to see that the OEE has never reached its target and has varied between 30% and 35%, which is a maximum of 9% deviation from the average of 32%. The graph also shows the OEE information about months October, November and December as this information were made available during project execution. The last three months have registered a great and relevant decrease in OEE. The average OEE on the whole year is 31%.



Picture 31. OEE per month.

This paragraph will concentrate on finding the correct output variables to assess the process' performance anytime during the project and after project completion (during control phase). These variables will first be employed to assess the current performance. This information will drive process and cause analysis. Second, variable's target values will be computed. Target values of output variables are those the company aims at reaching. They will drive analysis phase and the designing of solutions.

The OEE formula can be extended as follows:

$$OEE_m = \frac{\sum_b(volume\ batch_{m,b} - scrap_{m,b})}{900\ kg/h * \sum_b(run\ time_{m,b} + downtime_{m,b})}$$

where $volume\ batch$ is the size of the batch [kg] processed and it is the sum of finished product and scrap; $run\ time$ is the time [h] the machine is running; it either is producing scrap or finished product. Processing time is the sum of run time and downtime.

The OEE indirectly depends on three factors: scrap volumes, line run time, and line downtime. An increase in scrap production leads to a reduction of the OEE. There are two types of scrap produced. These two types will later be explained in more detail. Instead, an increase in run time or downtime leads to a decrease of the OEE. Run time of a batch depends on the flow parameter set on the machine while operated. The monthly run time also depends on the number of batches processes. On a monthly basis, run time does not lead to a relevant information unless it is related to the volumes processed (batches are not all the same size, thus the run time cannot be related to the number of batches manufactured). Downtime depends on how fast the process and operators can recover from a machine stop. Tool 2 (see Table 9) has been employed to determine and define output variables.

Table 9. Tool 2.

Tool 2		Output variable			
		Run time	Downtime	Scrap type 1 volume	Scrap type 2 volume
CTB	Decrease scraps volume	\	△	●	●
	Increase volumes of finished product per time unit	●	●	△	△
Data collection plan	Operational definition	It is the time the machine run net of downtime (per month), i.e., the time the machine was producing product.	It is the total downtime (per month).	It is the percentage total volume of scrap type 1 (no product distinction) divided by the total processed volume (per month).	It is the percentage total volume of scrap type 2 (no product distinction) divided by the total processed volume (per month).
	Unit of measurement	h	h	%	%
	Measurement instrument	Clock.	Clock.	Scale.	Scale.
	Measurement method	For each batch: the collector writes down the time of machine start, the collector writes down the time of process end. The difference is then computed.	For each batch: the collector writes down the time of machine failure, the collector writes down the time of process recovery.	For each batch, at the end of the process, the weight of boxes filled with scrap type 1 is measured on a scale and written on the batch report.	For each batch, at the end of the process, the weight of boxes filled with scrap type 2 is measured on a scale and written on the batch report.

			The difference is then computed.		
	Data type	Continuous.	Continuous.	Continuous.	Continuous.
	Responsible for collection	Operators.	Operators.	Operators.	Operators.
	Sampling strategy	None needed.	None needed.	None needed.	None needed.
	Criteria for decision	N/A.	N/A	N/A.	N/A.
Meaning		It is a measure of the average flow parameter set during processing.	It is a measure of the time lost due to line stops.	It is a measure of scrap type 1 production.	It is a measure of scrap type 2 production.

Symbol	Meaning
╲	No relationship
△	Weak degree of relationship
○	Medium degree of relationship
●	Strong degree of relationship

Tool 2 relates output variables to the critical to business elements. Output variables "scrap type 1" and "scrap type 2" have a strong relationship with the CTB "decrease scraps volume" as they directly measure it. The same is valid for "run time" and "downtime" with respect to "increase volumes of finished product per time unit". The symbols of weak relationship stand for the degree of impact scraps have on downtime and on the share finished product produced per time unit. Machine stops, indeed, increase downtime and scrap production.

Having output variables defined, it is possible to compute the current process performance and the desired process performance that allows the achievement of the project's goal. Due to constraint in time for project completion and the fact past data was already available within the company, output measurements have not been collected ex *novo*. Data starting from January 2022 to December 2022 have been processed. The current situation in terms of OEE does not give much information about how to steer the project. It only suggests something has happened in October as the OEE seems to decrease structurally. A deeper insight about scrap volumes and process productivity is needed. Average scrap type 1 and 2 values are given as the average of the monthly cumulated values of scrap in percentage to the monthly cumulated batches volumes:

$$average\ scrap\ type\ S = \frac{1}{12}\sum_{m=Jan}^{Dec} scrap\ type\ S_m$$

with $scrap\ type\ S_m = \sum_b scrap\ type\ S_{m,b}\ ; S = 1{,}2$.

The same is valid for average downtime:

$$average\ downtime = \frac{1}{12}\sum_{m=Jan}^{Dec} downtime_m$$

with $downtime_m = \sum_b downtime_{m,b}$.

To interpret the variable “run time”, as anticipated, it is needed to compare it to the volumes manufactured as each month volumes processed, and batches’ sizes vary. Dividing monthly cumulated volumes to monthly cumulated run time, we get a speed measure. Average speed [kg/h] is computed as follows:

$$average\ speed = \frac{1}{12}\sum_{m=Jan}^{Dec} speed_m$$

with $speed_m = \frac{\sum_b volume\ batch_{m,b}}{\sum_b run\ time_{m,b}}$.

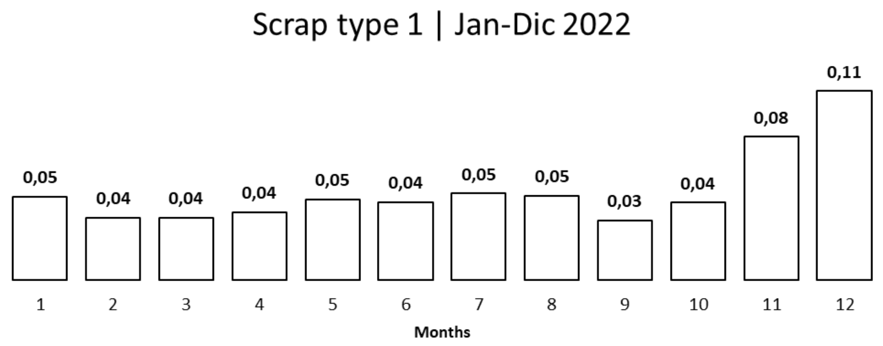
Table 10 summarizes these measurements.

Table 10. Current performance.

Measurement	Current performance Jan-Dec 2022	
	Average	Standard deviation
Scrap type 1	5%	41%
Scrap type 2	7%	23%
Downtime	10%	40%
Speed	348 kg/h	6%

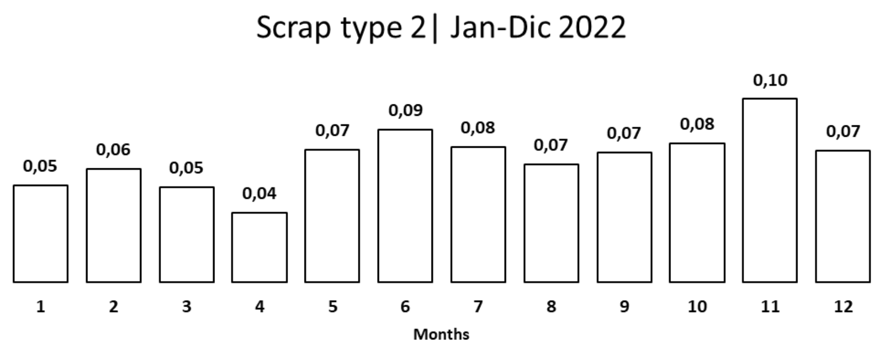
The table shows scrap production is currently 12% of total processed volumes and it has a very high variability. Scrap type 1 has a standard deviation that is 41% of the average value. Downtime's standard deviation is also high.

A further analysis on scrap type 1 shows (see Picture 32) that during months November and December amounts heavily increased. The average on the time span January to October is 4% and the standard deviation 14%. The two values related to November and December are thus responsible for most of the variability.



Picture 32. Percentage scrap type 1 per month.

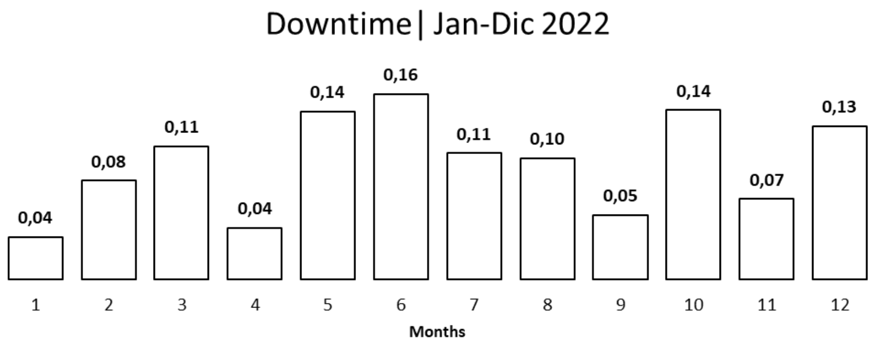
Concerning scrap type 2, Picture 33 shows that average value is increasing while variability seems to be quite constant.



Picture 33. Percentage scrap type 2 per month.

Run time depends on the number of batches manufactured and the machine speed settings. The number of batches manufactured monthly depends on the production schedule and does not affect the OEE. The machine flow parameter setting is an input parameter and will later be studied during analyze phase.

Picture 34 shows monthly values of downtime. For data privacy reasons, downtime will be displayed as percentage of the total processing time. Variability is very high, and it varies from 4% to 16% of the total processing time.



Picture 34. Downtimes per month as percentage of total processing time.

The desired values of scrap and downtime by the business are zero. The aim is to minimize these measures. Aggregate information about the nature of downtime is not available within the company.

Average speed has a very low variability. This means that the average machine flow parameter setting is constant. Data can tell some more information through the creation of a productivity index that relates the amount of manufactured product to the total time taken, i.e., processing time. The productivity index is the following:

$$productivity\ index_m = \frac{FP_m}{processing\ time_m}$$

It assesses the volume of sold product over the time taken to process the whole batch. Its current average value on time span January-December is $average\ productivity\ index = \frac{1}{12}\sum_m productivity\ index_m = 276\ kg/h$.

OEE and productivity index are this way related to each other:

$$OEE_m = \frac{productivity\ index_m}{900\ kg/h}$$

The desired value of productivity to achieve an OEE of 40% is $desired\ productivity\ index = 40\% * 900\ kg/h = 360\ kg/h$.

By including scrap production and excluding downtime in the productivity index it is possible to see the distance between the current process performance and its desired level. So, by including scraps at the numerator and excluding downtime in the denominator of the productivity index we get the same calculation as for the speed variable. The gross productivity index is:

$$average\ gross\ productivity\ index_m = 348\ kg/h$$

This index represents the line productivity in the scenario of no scrap produced, i.e., the scrap is considered as finished product, and of no downtime, i.e., as no downtime happened. These values tell that the machine speed setting should be set at 360 kg/h if scrap and downtime were zero. The problem drivers are scrap production and downtime. Indeed, the gap between total average productivity index and average productivity index is of $360\ kg/h - 348\ kg/h = 12\ kg/h$. This loss of productivity is due to machine flow parameter settings. This is confirmed by the computation of the speed variable. The reduction of scrap and downtime increases the productivity index. In case scrap and downtime are necessary to the process and cannot be eliminated completely, the productivity index will never reach the desired value unless the machine flow parameter setting is increased to a point it compensates for scrap and downtime. The process is not known in detail at this stage of the project, it is therefore not possible to compute target values of scrap, run time and downtime. The only target value that is possible to compute is the desired productivity index value if 360 kg/h, that must by achieved by minimizing scrap and downtime and by compensating them through the setting of the machine flow parameter higher than 360 kg/h. If the current scenario was already at the process' optimum point of scrap production and downtime, the required gross productivity index, i.e., the flow parameter to be set on the machine, should be

$compensating\ average\ gross\ productivity\ index = \frac{average\ gross\ productivity\ index * target\ OEE}{current\ OEE} = \frac{348\ kg/h * 40\%}{31\%} = 455\ kg/h$.

Conclusions

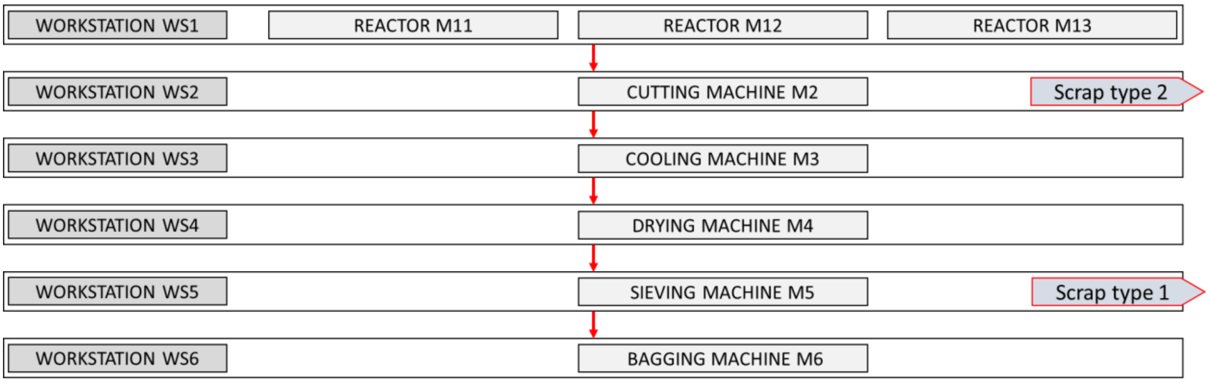
Looking at OEE and scrap type 1 graphs (respectively Table 31 and Table 32) it seems something structural happened at the end of October or starting of November 2022. The heavy decrease of the OEE and the doubling of the production of scrap type 1 suggest the process got out of control and is facing a structural change. The high downtime variability suggests the process of recovering from breakdowns is not controlled or not given priority to by workers, or that different kinds of breakdowns characterized by different degrees of impact happen and are solved reactively. The main drivers of the under target-OEE are scraps and downtime as the machine speed setting is near to the should-be value of the best-case scenario. Reducing scraps and downtime to zero would request a speed setting equal to the desired productivity value, 360 kg/h. If, instead, scrap and downtime are at their lowest possible level, machine speed setting must be increased up to 455 kg/h to compensate.

6.3. Analyzing the problem

Analyze phase concentrates on process inputs and process structure. Inputs to the process consist in the material supplied, the parameters set on the cutting machine, and the process overall structure. Product is supplied by reactors and the discharge starts after chemical quality check is passed. Being reactors and the chemical tests out of scope, they will not be addressed by the analysis. Machine parameters and process structure will be the objects of cause analysis. The aim is to find the root causes of the problem starting from the output measurements. This entails answering the questions "why is the process productivity not at the desired level of 360 kg/h?". This question brings three punctual questions: "why does the process produce scraps and why are they at this level?", "why are there downtimes and why are they highly variable?", and "why does not run time compensate scrap and downtime?".

The first step of analyze phase is process structure description. Second, brainstorming of causes with both project's team and line operators is performed. Causes are then questioned, and root causes classified and prioritized.

The line consists in four workstations laid out as shown in Picture 35. Machines M11, M12, and M13 are reactors. They are parallel to each other and form workstation 1. M2, M3, M4, M5 and M6 are respectively the cutting machine, the cooling machine, the drying machine, the sieving machine, and the bagging machine. They are in sequence, and each is part of a different workstation. The batch is created in the reactors (that have different capacities) where input materials are mixed and processed. Once the product is polymerized and a chemical test on it is performed and validated, the discharging of the product is a continuous process. The product flows through supply pipes to the cutting machine's die plate. The cutting machine cuts the flowing product into spheres that are cooled down using water and transported to a drying machine through a pipe. Then, they go through a sieving machine that selects those with the correct diameter only (as requested by the business' customers). Those that are conform to customer's specification are bagged and shipped. There are two types of scraps produced along the line: scrap type 1 produced by M5, and scrap type 2 produced by M2. They can both be minimized but not eliminated as the technology requests the production of some during machine setup and to recover from machine stops. Scrap type 1 is being recycled as raw material; scrap type 2 is being recycled depending on the product as a new recycling technology has been installed in October.



Picture 35. Production line.

When starting the process, a sequence of actions is undertaken to prepare the line. Line set up include the preparing of the line as cleaning and heating up, and the setting of cutting parameters, temperature of the product in the reactor, temperature of the cooling machine and of the drier, sift size put in the sieving machine. Operators are given processing parameters as a range within which they may find the optimal combination of them that produces the highest quality of finished product and the most stable cutting process. Each product has its own optimum parameters, and they depend on the single batch's physical characteristic as well. The current measurement system does not allow a reactive set up of parameters based on the fed product's instant characteristic.

To brainstorm causes a meeting has been organized with the project team and operators and shift leaders have been involved. The collection of causes from operators and shift leaders has been deployed through interviews on the shopfloor and using an A3 sheet put on the working table next to the cutting machine. This sheet has been left there for ten consecutive days and gave the opportunity to operators to note down problems as they came to their mind and to involve night and weekend shifts. The suggested causes by them have then been reorganized in a second A3 sheet that asked to rank each cause. Table 11 and Table 12 summarize the brainstormed causes by the team and by operators and shift leaders respectively. Picture 36 shows the rank assigned by operators to their suggested causes.

Table 11. Brainstormed causes by project's team.

Causes brainstormed by the team	
(a)	Machine flow parameter is often set under capability.
(b)	Each batch has a different behavior when processed. Parameters to set must be adapted to the instant product and process characteristic. Lack of clear know how.
(c)	Lack of effective communication among shifts.
(d)	Shift leaders allow deviation from procedures.
(e)	Operators work based on their own experience: each operator uses a different set of machine parameters and does not share it with other.
(f)	Low sense of responsibility by operators and shift leaders.

The production manager stressed on the fact shift leaders do not perform their job well. They are often not in control of what happens on the shopfloor as they stay in their office. They do not effectively communicate facts to the next shift to help them take over their work and the ongoing processes. The production manager often receives calls right after shift changes and needs to give an update on the advancement of processes. A comprehensive and real overview of processes' status is often missing. Shift leaders do not organize operator's time and tasks efficiently. In addition, they are not proactive in problem solving. The overall shopfloor culture is of *laissez faire* and low engagement. When asked for the reason of some decision or some element not properly working, operators and shift leaders do not take their responsibility and do not suggest improvements; they always address the cause of problems to other shifts and to the maintenance team.

To support brainstormed cause (a), processing data analysis has been carried out. While the cutting process is going on, operators write down on a sheet of paper the instant processing parameters read by machine's sensors. This happens at a constant rate of about two hours. Data collected during year 2022 from January to September has been analyzed. As data processing entailed digitalization of it, it has been upfront decided together with the champion to concentrate on those products that yielded 70% of manufactured volumes. In this case, product P1, P2, and P3. Their cumulated volume accounts for 67% of total volumes and creates a solid basis for such analysis. The measurement of material flow parameter set for each product on average over the period January-September 2022 has been executed by taking the average of monthly values of material flow parameter set on average for each batch:

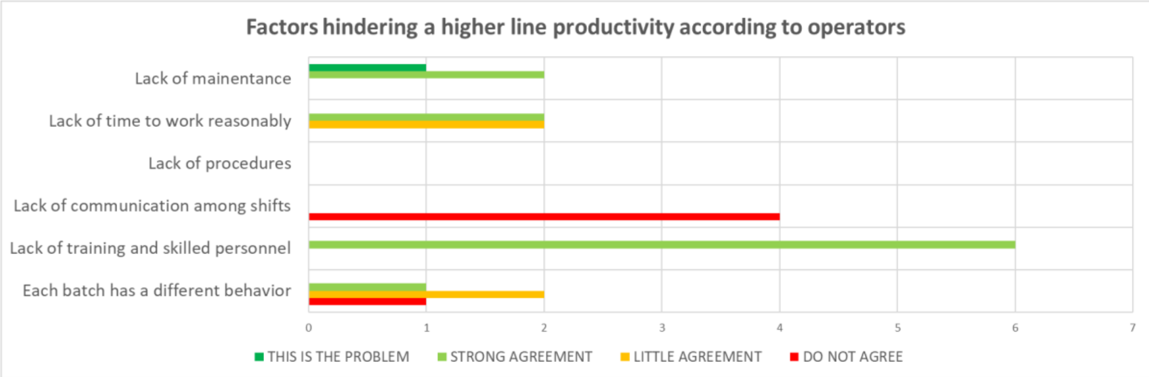
$$average\ flow\ setting_{product\ j} = \frac{1}{9}\sum_{m=Jan}^{Sep}\left(\frac{1}{B}\sum_{batch\ b} average\ flow\ setting_{j,b,m}\right)$$

The result of this analysis is all three products have been processed setting the machine's flow parameter at a lower level than the machine's capability. Moreover, these flows are not able to compensate for the current production of scrap and downtimes. Although the project's goal is to reach an OEE 40%, it is the interest of the business to maximize the material flow values to increase efficiency and volumes (by increasing the number of batches manufactured in a month). This additional requirement by the company will be kept into consideration during solutions designing. P1 has been processed at 69% of the given flow setting. P2 has been processed at 70%. P3 has been processed at 65%. Moreover, the analysis showed that:

- parameters given by the procedure are not respected by all operators,
- often, as the shift changes, the flow set on the machine decreases, and
- instant processing parameters are not always written down although requested.

Table 12. Brainstormed causes by operators and shift leaders. Reported below is their voice.

Causes brainstormed by operators and shift leaders	
(a)	Lack of maintenance of machines.
(b)	Lack of time to work reasonably.
(c)	Lack of procedures.
(d)	Lack of communication among shifts.
(e)	Lack of training and skilled personnel.
(f)	Each batch has a different behavior.



Picture 36. Questionnaire results about causes suggested by line operators and shift leaders. The x-axis represents the number of answers collected related to each cause.

Operators attribute the reason of the low productivity mainly to the lack of trained personnel. They must follow the advancement of different processes within the factory at the same time. The large amount of tasks to perform, operators claim, do not allow them to think enough time and act with meaning. When skilled personnel are working at different machines, they cannot be fully present at the cutting machine M2. This cause affects the whole production, thus the cutting machine as well. The lack of maintenance is also pointed out by operators as cause of machine breakdowns. Insufficient maintenance does not allow the machine to work correctly. The lack of procedures is not perceived as a cause of the problem. Probably, this is because those who answered the questionnaire are those who are familiar with the line. Communication among shifts is not perceived as a problem at all; this result is opposite to production manager's view.

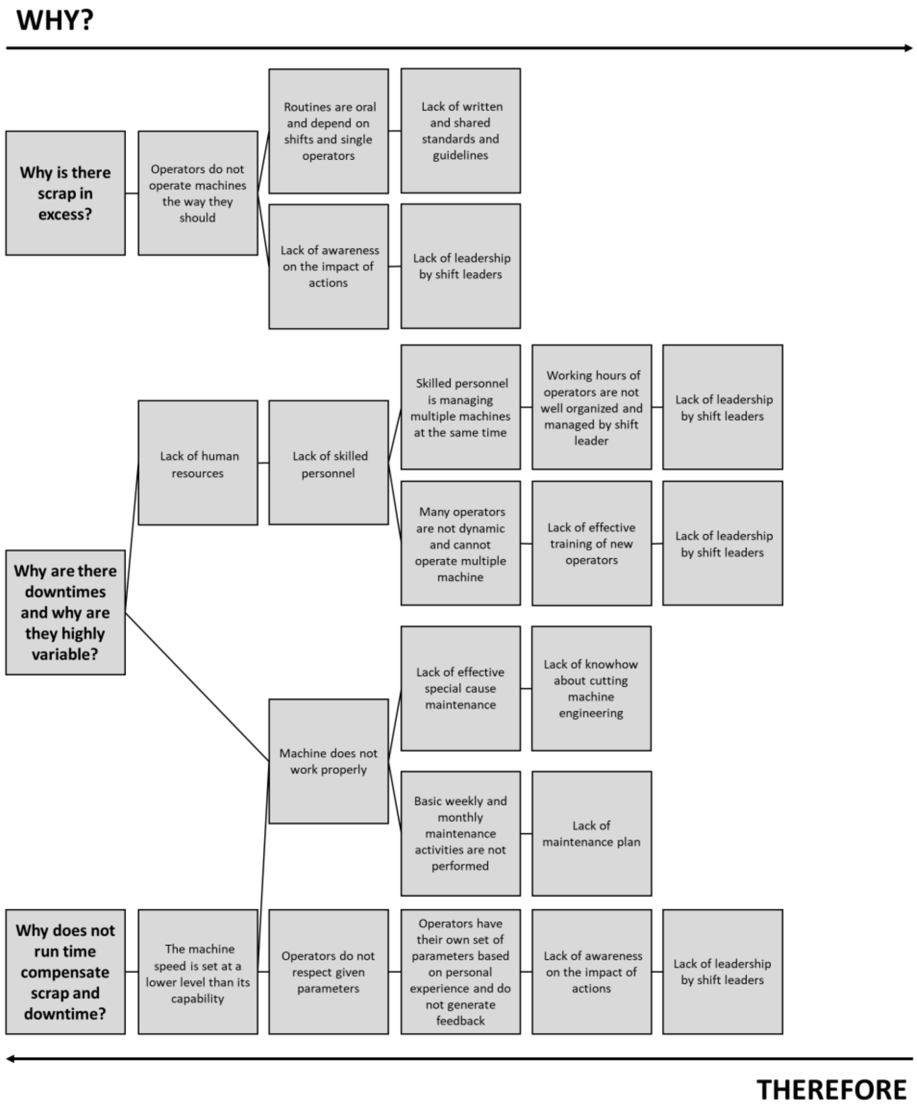
Additional observations made and comments collected on the shopfloor are the following.

- When machines have a problem, the cause does not get fixed, nor the problem is effectively communicated. Shift leaders and operators put a "patch" on the problem even when this fact will have other cascade effects. Shift leaders' level of collaboration is low.
- Operators' perception about making the machine run faster is that this will increase the number of machine breakdown and downtime, which requires more cleaning effort by them.
- Operators do not trust experts and given parameters to be set on the machine. They only work based on personal experience and do not entirely follow given procedures. Many of them keep their personal parameters and will not share them with others. Shift leaders have low supervision on parameters set and do not enforce the respect of given procedures.
- Procedures are routines based on oral knowledge.

- Some operators do not accept to clean material that has been left unsettled by the previous shift. They do not clean the workplace as they should at the end of a task. They claim negligence is the way most people act.
- The way operators justify breakdowns and deviation from the procedure does not always reflect reality. Their time is not well managed by the shift leader, and they act without supervision and clear tasks assigned.
- In January 2023 the cutting machine broke. Operators claim the problem existed in the past two months already but nobody intervened.

In conclusion, it is possible to say that the variability in scrap production is given by differences in procedures. Temporary changes in context lead to changes in procedures that, yet, never go back to the standard. The slight increase in scrap type 2 production in due to the new scrap-type-2 recycling system that lightens the sense of waste by operators when they operate the machine. The heavy increase in scrap type 1 production is probably due to the cutting machine bad functioning and the lack of immediate maintenance. The high variability in downtimes is given by the bad management of operators' time and work and the lack of preventive maintenance. The system does not allow to classify downtimes and intervene in advance of a failure. In addition to these elements, there is the shopfloor culture that tends to low proactiveness and low engagement.

The following Picture 37 will explore causes for each output variable's current performance using the 5Ws tool, arranging and giving a logical order to the above causes found and observations made.



Picture 37. 5Ws tool.

From the above considerations, cultural, organizational, and maintenance causes are at the basis of problems arising on the shopfloor. Cultural problems arise from the lack of leadership of shift leaders and the low level of awareness about the impact decisions and actions have on the line's performance. Shift leaders do not have the situation in control and do not communicate with each other efficiently. They allow deviations from procedures without reasoning such behaviors. This lack of reasonings does not generate the correct loop of feedback of information that allows an efficient management of the current situation by the next shift and does not generate alarms to the production manager and the maintenance team about upcoming breakdowns. This behavior hinders from preventive maintenance and makes deviations from routines a daily business. Organizational problems come from the people's culture and feed low proactiveness and dynamisms of workers.

Shift leaders cannot efficiently organize operators' tasks. The result is that there are peaks of work and moments in which no task needs to be performed. This element is present throughout all processes and impacts the availability of human resources on the considered line. Organizational problems also exist at a procedure level. Procedures and routines are oral and allow therefore deviations easily. This fact also impacts new operators employed who cannot work autonomously without close supervision. Both from cultural and organizational causes, the lack of effective training of new employees also arises and later becomes a cause for the lack of skilled workers. The last root cause is maintenance. Due to a low level of knowhow about the machine, a reduced maintenance team, and the lack of a preventive and monthly maintenance plans the probability of machine breakdown and of scrap production increases.

The four root causes exist by themselves but also influence each other creating a cause-effect loop and frustration among people who loose proactiveness and optimism in implementing and sustain improvements. Root causes have been prioritized as shown in Table 13.

Table 13. Root causes prioritization.

Root cause	Nature of the cause	Impact / Priority
Lack of leadership by shift leaders.	Cultural, organizational	HIGH
Lack of written and shared standards and guidelines.	Organizational	MEDIUM
Lack of maintenance plan.	Organizational, maintenance	MEDIUM
Lack of knowhow about cutting machine engineering.	Maintenance	HIGH

The four root causes have all a medium-high priority and, after the above considerations made, they must be addressed simultaneously to ensure their individual effectiveness. The lack of knowhow about the engineering of the cutting machine is responsibility of the maintenance team and is out of the scope of the project, thus, will be addressed by the maintenance team. The lack of a maintenance plan is, instead, cross functional as some frequent maintenance activities may be controlled and performed by operators as well. The generation of a plan will be supported by the project team, but its detailing and action plan is responsibility of the maintenance team.

6.4. Designing and implementing solutions, controlling the process, and future development opportunities

Improve phase designs and tests solutions. Solutions that yield the greatest impact will be implemented and made sustainable over time. This phase may overlap with analyze phase as while causes are explored and root causes identified, some solutions are implemented quickly, and the attention is rapidly moved to some other cause that had not been considered or that come up later thanks to improvement implemented.

Root causes to address are:

- lack of leadership by shift leaders,
- lack of written and shared standards and guidelines, and
- lack of maintenance plan.

Solutions brainstorming generated the ideas shown in the below Table 14. The same table also summarizes the effect each solution is expected to have, the priority, or impact, assigned by the team and effort needed.

Table 14. Brainstormed solutions.

Solutions brainstormed	Comments	Priority / Impact	Effort / Cost
Performing periodic meetings with operators.	Periodic meetings strengthen the sense of belonging to a team and create a space for open discussion of general problems and of reflection of improvements implemented and to be implemented.	MEDIUM	MEDIUM
Creating a OEE panel to track batches' OEE on the shopfloor.	Allows to have visual feedback of past performance for all shifts.	LOW	LOW
Setting up a faster and more efficient OEE feedback system.	Allows to track OEE with a higher frequency than the current one.	MEDIUM	HIGH
Involving shift leaders in monthly OEE assessments.	Increases awareness of the importance of tracking and meeting targets.	HIGH	MEDIUM

Reviewing procedures, discovering differences in operating between shifts and creating a best-practice procedure.	Allows the creation of a standard way to work that is at the same time the best one and well accepted and shared by all operators.	MEDIUM	LOW
Applying Lean manufacturing approaches to lower downtime due to organizational issues.	Decreases downtime by organizing the workspace efficiently and spotting variation more easily.	LOW	MEDIUM
Creating tools to help shift leaders to better organize operators' time.	Empowers shift leaders and strengthen their leadership.	HIGH	MEDIUM
Creating a preventive maintenance plan and schedule activities.	This plan must be agreed and validated with maintenance team and its execution controlled.	HIGH	MEDIUM

Among these solutions, the team chose to start with those with a medium-high or high impact and medium-low or low effort needed. The action plan is showed in Table 15.

Table 15. Brainstormed solutions action plan.

Solutions brainstormed	Responsible for design and execution	Time plan
Performing periodic meetings with operators.	Production manager	Starting January 2023, biannually
Involving shift leaders in monthly OEE assessment.	Lean engineer, green belt	Starting February 2023, monthly
Reviewing procedures, discovering differences in operating between shifts and creating a best-practice procedure.	Project manager (Green Belt)	February 2023
Creating tools to help shift leaders to better organize operators' time.	Production manager, green belt	February 2023
Creating a preventive maintenance plan and schedule activities.	Production manager, maintenance team	March 2023

Meeting with operators and shift leaders have the aim of increase the awareness about what the OEE is, how it is computed, what factors influence it. Operators have been reminded to decrease the production of scrap as much as possible, and to notify issues arising. Shift leaders have been asked to organize trainings to unskilled operators in such way to increase the availability of skilled labor. The tool provided to shift leaders to better organize operators' work time is showed in Picture 38. This tool helps shift leaders in assigning tasks to operators and tracking work advancement. The end of a task will show the availability of the correspondent operator and allows an efficient scheduling of activities to do.

Operator / working hours	1	2	3	4	5	6	7	8
Operator 1	Activity 1	Activity 1	Activity 2	Activity 3	Lunch	Activity 4	Activity 4	Activity 4
Operator 1	...				Lunch			
...					Lunch			

Picture 38. Work time organization tool provided to shift leaders.

The maintenance plan will list all activities to be performed. Each activity will have a responsible, a frequency of performance, and a label to check its status (last intervention date, next-due date). Daily maintenance activities to be performed by production (autonomous maintenance) will not be displayed into the maintenance plan but will be included into the process procedure. Picture 39 shows the template of the maintenance plan. The production manager, i.e., the process owner, has the responsibility of checking activities are performed.

Activity	Responsible	Frequency	Last intervention	Next due intervention
Activity 1	Production / Maintenance team	Weekly / monthly / every x days / ...	dd/mm/yyyy	dd/mm/yyyy
Activity 2				
...				

Picture 39. Maintenance plan.

During February, the project manager also collected information and knowledge from experts and shared it with operators. This knowledge made it possible to increase the flow parameter setting during production without destabilizing the process. The increase in flow parameter resulted in an increase of the productivity index and the OEE.

Being it a behavioral and organizational issue, time needed for change is great. The key players to ensure the implementation of solutions are shift leaders, who supervise the processes during the whole production time.

Early evidence of improving is given by the OEE assessment of February and March. Data available has been split into three time-buckets: first and second half of February, and fist half of March. Table 16 shows output variables and OEE. The variable downtime has been computed based on the baseline run time before solutions implementation. This computation is due to the increase in machine flow parameter, which was an unexpected solution when output variables have been selected and which lowered the monthly run time.

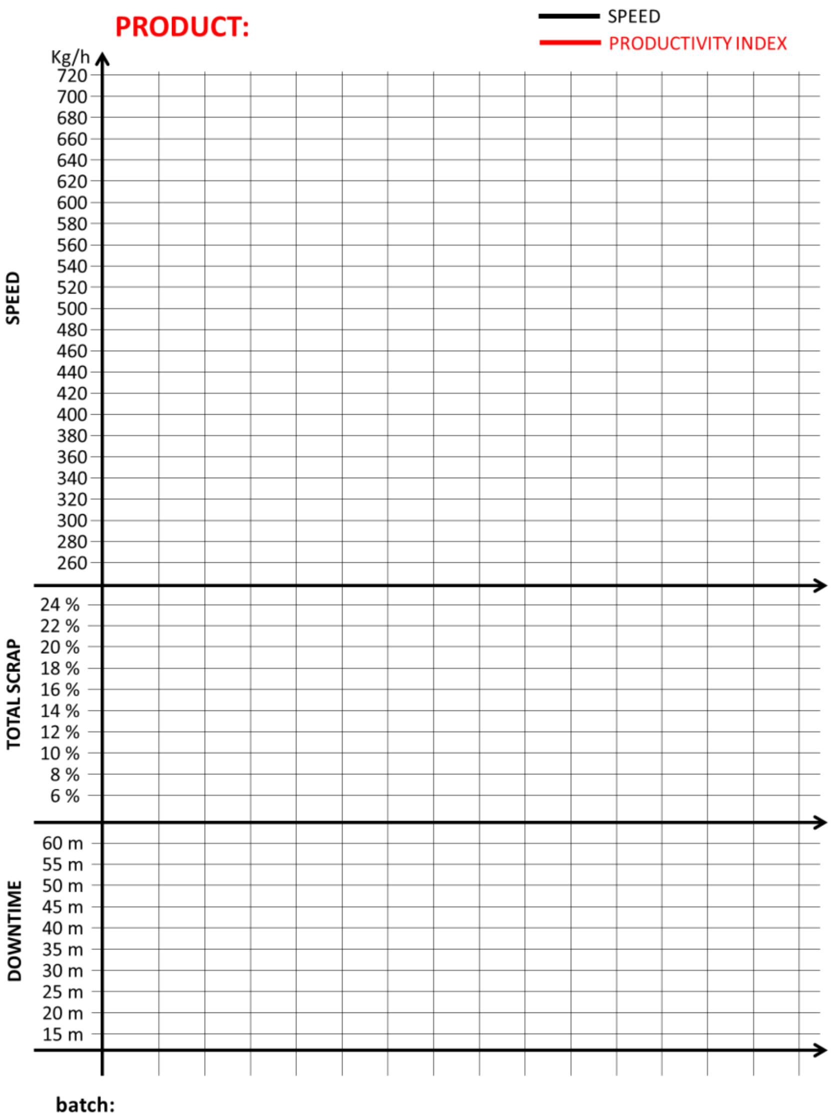
Table 16. Brainstormed solutions action plan.

Measurement	Performance				
	Average Jan-Dec 2022	Average, Jan 2023	Average, Feb 1st half, 2023	Average, Feb 2nd half, 2023	Average, Mar 1st half, 2023
Scrap type 1	5%	5%	8%	3%	3%
Scrap type 2	7%	10%	4%	5%	5%
Downtime	10%	17%	9,5%	7,2%	6,7%
Speed	348 kg/h	223 kg/h	329 kg/h	414 kg/h	446 kg/h
OEE	**31 %**	**17 %**	**28 %**	**35 %**	**40 %**

From the above data, it is possible to recognize the consistent drop in speed and efficiency of January 2023 due to the engine breakdown. Starting from February 2023, trainings, meetings, and focus put on the line show an increasing speed and a decrease of scrap and downtime. Comparing the initial situation September 2022 and the first half of March 2023, it is possible to see that scrap volumes decreased, downtime decreased, and the OEE reached the target. The decrease in scrap volume is due to an enhanced awareness by operators and shift leaders of the impact of scrap production. During machine startup phase they produce an amount of scrap that is strictly necessary to the process to work, avoiding wastes. The decrease in downtime is due to two factors. The first factor is organizational: training a higher number of operators allows quicker response in case of machine stops. The second factor is technical. As soon as the machine flow has been increased, some maintenance problems arose and have been readily solved. For example, the cutting tool head has been changed with a one that causes less machine stops. As expected, the speed is higher than the target productivity index of 360 kg/h as it must compensate residual downtime and scrap production. DMAIC cycle facilitated causes identification and analysis and the design of solutions able to reach the project target. Scraps still present show new causes of low efficiency arising on the line as speed increases and scrap production is closely looked at and minimized. These causes are linked to special maintenance of the sieving machine, which is responsible for scrap type 1. The resolution of these new causes will enable a further increase in OEE. New problems arising on the line as the identified root causes get solved, are the base for continuous improvement.

Following improve phase, the enhanced process needs to be controlled to avoid people to get back to the previous inefficient routine and habits. Sustaining the enhanced process is crucial. The team decided to develop process control tools to help shift leaders in their job, to allow the quick and effective communication of information and to control the performance of the process instantly. Control tools and clear procedures also allow to spot deviations and causes for variability more easily and intervene on problems arising preventively. The control tool is a performance frame. It will collect values of output variables daily per each product. Each deviation from the expected values will require a justification. The nature of downtime is an information that must be digitalized to enable quick access and interpretation. In addition, missed maintenance activities and bad-performed procedures will also be considered deviations from the standard, thus a process defect.

The following Picture 40 shows the adopted controlling tool. It will be displayed in the shift leader office and updated daily.



Picture 40. Control tool.

The performance frame consists in three graphs: the first one shows speed and productivity index, the second one scrap production and the last one downtime. The choice to represent downtimes in minutes is to improve visualization. The speed value easily delivers the information about machine speed parameter setting to the reader. The productivity index also takes into consideration scrap production and downtimes. Each vertical line identifies a batch. The advantage of this tool is also to keep track of recent batches and give to all shifts an overview of the performance referred to batches they did not see being processed.

An element that has not been taken into consideration by the analysis and represent an additional improvement opportunity for further project development is the creation of a machine parameter database of instant parameters set on the machine and read by machine's sensors. This database will allow an adaptive processing system based on instant product characteristics. In addition, operators experience will be extracted and put into data information.

7. INTERVIEWS

7.1. Interviewees and question asked

This chapter collects four interviews to managers who are or have been active Six Sigma leaders. The aim is to complete the study of Six Sigma through the answers they give to the proposed questions. Three interviewees are currently covering the role of Master Black Belts within manufacturing companies. Their role is to lead the Six Sigma program. They overview Six Sigma projects and coach project managers toward this approach. One interviewee has a different background; he experienced Six Sigma while working in a financial services company. The following Table 17 introduces the interviewees.

Table 17. Interviewees introduction.

Interviewee	Company and role
Bernd Bachert	Bernd Bachert is currently Senior Manager for Six Sigma transformation and strategic projects Europe at Henkel AG & Co. KGaA. He leads major Six Sigma projects and coaches Green Belts.
Alexander Eisenschink	Alexander Eisenschink is currently the leader of lean manufacturing and Six Sigma transformation for Serafin Unternehmensgruppe at corporation level. Serafin Unternehmensgruppe is a private equity that owns several industrial companies that are part of different industries and serve different segments. He leads a team of about five people established to bring Six Sigma approach into the acquired subsidiaries.
Jens Greving	Jens Greving is currently a Master Black Belt and leads the lean and Six Sigma program at Vorwerk Elektrowerke. Vorwerk Elektrowerke is an industrial company producing household appliances.
Alain Mimouni	Alain Mimouni has been CFO at GE Capital Europe between 1993 and 1997 when Six Sigma was implemented companywide.

Questions asked aim at understanding interviewees' points of view about Six Sigma and the point of view of their collaborators. As said in the previous chapters, the behavior of management, employees, and workers is critical in making Six Sigma successful. The aim of the questions is also to understand the feedback of people working in the organization when asked to implement Six Sigma.

Questions have been conceived by me, after having been trained on Six Sigma and while leading the green belt project presented in chapter 6. Table 18 lists and analyzes the questions asked.

Table 18. Questions.

Number	Question	Aim of the question
1	*What is Six Sigma for you?*	Interviewees will first be asked to frame Six Sigma at beginning of the interview. This question aims at creating an understanding of their point of view through their choice of words.
2	*Who are the key players and elements for a successful Six Sigma implementation?*	The aim of this question is to understand the main elements and roles which enable a successful implementation of Six Sigma company wide.
3	*Is Six Sigma a company choice or a personal choice?*	Does Six Sigma survive and reach expected results thanks to the company's initiative alone or does it also rely on employees' proactiveness and mindset? This question aims at understanding who sustains Six Sigma.
4	*Do people welcome Six Sigma approach? Do they consider it complex or simple?*	Six Sigma offers a logical and scientific approach. This requires much effort in defining and measuring before actual implementation of solutions. The challenge relies in following the cycle strictly. People may perceive measuring a waste of time as time could be used in improving the system. On the other side, the need to measure processes before analyzing them may seem trivial. The aim is to comprehend how employees and workers perceive the Six Sigma approach.
5	*Six Sigma is an ambitious program. Does this bring, in your experience, encouragement to people or sense of unreachable goals thus a waste of time and effort?*	The effort needed to bring change into a process, or an entire organization may lead people to discouragement. Especially, if a change in mindset is required. The aim of this question is to understand the feedback of employees and workers about such an ambitious program.
6	*How much, in your experience, is Six Sigma theory and how much is it practice?*	This question aims at understanding what the weight of theory and training and what the weight of practicing are to comprehend the Six Sigma approach and culture.
7	*How much does Six Sigma cost?*	What the costs of implementing Six Sigma are.

8	*What has been your first impression about Six Sigma? How did it evolve?*	What the first impression of interviewees was when first facing with Six Sigma themes and visions. And how it evolved as they implemented Six Sigma and put their own time and effort into it.

7.2. Answers and takeaways

1. What is Six Sigma for you?	
Bernd Bachert	Six Sigma is a tool to do projects and solve problems. Project and problem are synonym. The project only exists if a problem is faced. Otherwise, the action should simply be carried out. Lean and quality management are other tools, and they are all based on Deming's PDCA cycle. Six Sigma requires thinking before acting. The DMAIC cycle supports the thinking process; the team must take time to *think* about the process and problem's causes.
Alexander Eisenschink	Six Sigma is two things: project management, and statistics, data, and variation control. It is the approach of defining the problem, listening to customer need, and setting a target upfront, and then start measuring. Six Sigma is a tool for process control and design of experiments. It is not a shopfloor management tool. To manage the shopfloor Lean system is available. Six Sigma is used to get the insights of a problem and solve it. Lean system is about daily business.
Jens Greving	Six Sigma is a toolbox for problem solving. Both small and big problems. It may be applied depending on the problem faced. It is based on a S.M.A.R.T. goal formulation and on measurable requirements. It is also a tool to change mindset of people and for this reason it only works together with Lean system. Six Sigma is not a project management tool, as the project manager can choose the project management approach that best fits its team and still carry out a Six Sigma initiative.
Alain Mimouni	Six Sigma is a method to pass from a traditional way of problem solving to a frame able to solve any quality problem. It is a very precise frame and standard that enables the measuring of the initial situation before any analysis and improvement. Marketwise, Six Sigma creates a standard of quality assessment that is well recognized by different companies operating in the same supply

	chain. Customers expect the purchased products to be at six sigma level and introduce penalties in their procurement contracts.

Six Sigma is a frame and a toolbox to face and solve problems in a structured way. It provides a set of tools based on statistics that enables the control and improvement of process' quality and performance. It is based in the concept of measurement and customer needs: without the measurement of the initial situation there cannot be any improvement; knowing what the customer wants is necessary to deliver quality. Bernd Bachert underlines the importance of thinking: to effectively carry the improvement out, the team must comprehend causes. The DMAIC cycle supports this thinking process. Six Sigma is project-based and inherits projects' characteristics. The project manager can decide what management approach fits its team the best. Alexander Eisenschink and Jens Greving claim Six Sigma only works together with Lean Systems as there is the need for shopfloor daily management tools.

Alain Mimouni provides a marketwise perspective on Six Sigma. Six Sigma introduced a standard in quality assessment and problem solving for all companies on the supply chain. This fact brought to the introduction of penalties in procurement contracts from the side of customers, pushing all companies to adopt Six Sigma approach.

2. Who are the key players and elements for a successful Six Sigma implementation?	
Bernd Bachert	People and coaching are key when implementing Six Sigma. Managing human resources is the real complexity of a Six Sigma project. "Six Sigma will be different in each country"; national culture is a factor the project manager must take into consideration. When the people are ill, there is no project advancement. So, people need to be present and onboard. Coaching must be internal to the company as the coach must know the company's culture and routines, otherwise it is a loss of money. An external coach can only give technical knowledge, he does not comprehend the organizational culture and its routines.
Alexander Eisenschink	The Six Sigma effort must start from the CEO who gives the vision. There is a *span of control,* and a *span of support* management must have. The span of control is needed to steer the company. Management must design the right KPIs to assess problems' impact. Without measuring, it is not possible to tell if a problem is a constraint to the value chain. A *system* to track performance is a must because while projects end, controlling continues.

	The span of support refers to the supporting activity management has with respect to production. Delegating the achievement of goals to the shopfloor is a mistake. Management must support production. It must help to solve problems. If management is not convinced about Six Sigma approach, it will not give the right support. Management must ask the right questions and create cross-functional teams to efficiently solve problems.
Jens Greving	It is important to understand which tools to use depending on the context and the needs requires more experience than just learning the functioning. The project manager must handle change; thus, he is asked to have both soft and hard skills. The role of the Master Black Belt is fundamental especially during Six Sigma initiative build-up phase. He is the trainer and coach of other belts. He reports to the CEO directly. This ensures a good visibility to the initiative. Effort must start from the CEO to aim at establishing a Six Sigma organization. Six Sigma needs a vision.
Alain Mimouni	There are no key players. Everybody must be into Six Sigma. Otherwise, it does not work. It is important to ensure everybody follows this methodology. Companies can have managers overview the work of employees or create the role of Black Belts who ensure training is done and people follow Six Sigma. At the beginning of a Six Sigma effort, the key role is who starts and trains others. Afterward, it is the organization as a whole who makes Six Sigma sustainable.

All human resources are important to successfully developing Six Sigma within an organization. Bernd Bachert underlines that routines, habits, and national culture influence the interpretation of the Six Sigma approach and the outcome. Though, it is possible to detect a key role at the beginning of the Six Sigma program. The Master Black Belt oversees training and coaches project managers on the Six Sigma approach to problem solving. Alexander Eisenschink and Jens Greving point out the role played by management who must give visibility and commit to Six Sigma effort. Alexander Eisenschink explains the span of support management must provide. Employees and workers detect failures and suggest improvements. Management should facilitate solutions and provide the necessary resources to achieve goals. Delegating the implementation of the Six Sigma vision does not make it successful.

3. Is Six Sigma a company choice or a personal choice?

Bernd Bachert	Six Sigma is a tool that helps the project manager and the team in solving a problem. Therefore, it is a personal choice on a project execution level. Though, to start a Six Sigma initiative companywide, the input must be top down. The company invests in training and coaching its employees. Management benefits from Six Sigma in the long term as well as process performance assessment systems will be established, and projects documented.
Alexander Eisenschink	When the company distributes incentives, Six Sigma becomes a personal choice. To make it a personal choice by everybody, people must be communicated the plan and must be willing to improve and change processes. Those who are not willing to be proactive and do not feel comfortable in seeking improvements, can leave the company.
Jens Greving	Six Sigma is both top down and bottom up. On one side the project manager is convinced of the logical approach Six Sigma offers and finds it helpful. He will apply it by himself making it a personal choice. Companies though start up a Six Sigma initiative top down as education of people is needed first. People willing to use Six Sigma are scouted by the company.
Alain Mimouni	It is neither. The push toward a Six Sigma effort comes from the market. Customers started to put Six Sigma as a request to fulfil by contract, making Six Sigma a necessary standard to avoid contractual penalties. Effort toward reaching the desired six sigma level, became the premise to survive on the market. Supplier should adapt to this expectation by enhancing their processes and by asking their suppliers to supply quality raw materials. Six Sigma is a recognized frame of quality and improvement system that creates a standard on the market. This allows the comparison between companies' outputs, and the choice of the best company to do business with. Those who do not reach six sigma level will eventually exit the market.

The push toward becoming a Six Sigma organization comes from the market. As customers start to put penalties clauses into procurement contracts, the supplier must adapt its processes and deliver the desired level of quality. A Six Sigma effort is started by the company who organized trainings and coaching, and which distributes incentives based on Six sigma projects development. On a project execution level, it becomes a personal choice by the project manager who uses Six Sigma tools to achieve his goals.

4. *Do people welcome Six Sigma approach? Do they consider it complex or simple?*	
Bernd Bachert	Six Sigma is a tool that can or cannot be utilized. Perhaps people do better without. Incentives would not make sense.
Alexander Eisenschink	Companies link award, recognition, and certification to Six Sigma projects in order to incentivize project managers to use this approach. It is not easy to bring change, for this reason the support of management is fundamental.
Jens Greving	They do not find it simple. People often deviate from the DMAIC cycle and go for the so called DIDI approach (define-improve, define-improve) skipping measuring and analyzing steps. Moreover, the Six Sigma effort never ends.
Alain Mimouni	In the industrial world Six Sigma approach has been accepted more easily. As any new methodology introduction and change in habits, it has initially found some resistance from people, but benefits are expected. In the service world, instead, Six Sigma has found strong resistance as people could not initially see any application of it nor benefit from it. The measurement system did not fit well with service-based processes and activities. After measurement systems had been adapted to these processes, the objective became clearer, and people started working toward reaching them.

Six Sigma is a toolbox. The usage of it depends on the project's characteristics and on the preferences of the team. It is a choice. People do not find the Six Sigma approach simple. It is a common mistake to jump to solutions without a deep logical analysis of the problem's causes. Cause analysis requires time.

In the service world Six Sigma has been initially seen as not relevant. As it was coming from the manufacturing world, its measurement system did not seem to fit. Despite the resistance found at the beginning, Six Sigma proved positive results and people started to understand how to adapt it to service-based processes. GE Capital's managers, indeed, introduced the *define* phase of the DMAIC cycle [16]. This phase is crucial in defining the problem and the goal, which are less tangible in the service industry than in manufacturing and therefore request an extra effort to make them explicit.

5. *Six Sigma is an ambitious program. Does this bring, in your experience, encouragement to people or sense of unreachable goals thus a waste of effort?*

Bernd Bachert	It depends on the team lead. Six Sigma is a project-based approach. Therefore, it inherits all characteristics of projects. Projects must be on time, on quality, in cost. The project manager creates commitment toward the project among the team members. The success of a project depends on the effort, on the organization of time and resources, and on the leadership by the project manager. Project lead and clear targets are fundamental. Projects must be simple and well comprehended by the team.
Alexander Eisenschink	People will be incentivized when they know the goal and are involved into the change process. The shopfloor needs KPIs and designing them must be done involving workers. Otherwise, they will not give their support toward change. KPIs show performance only if information fed is correct. Therefrom, the need for workers involvement. The transformation to a Six Sigma culture will be completed when people are aware about performance, KPIs, strategies, impact of their actions. People must understand the problem in order to help out. Nobody is satisfied from making mistakes. On the shopfloor, S.M.A.R.T. targets are needed, not visions. There must be a strategy behind plans and actions and management can support with designing the strategy.
Jens Greving	It depends on the philosophy of the company. Having both high quality and low cost is a paradox. The question is not well stated. Ambitious goals exist without Six Sigma as well. Six Sigma is about measurable and reachable goal (S.M.A.R.T.). Resistance to change needs to be overcome. Many are convinced about doing things the best possible way already. But conclusions cannot be drawn without a reliable and relevant measurement system. In addition, people perceive change as a danger of losing their jobs. It is important to clarify the goal of a Six Sigma initiative upfront. Firing people is not the Lean-Six Sigma objective.
Alain Mimouni	At the beginning people had the perception of Six Sigma as something impossible to reach, its vision and goals were perceived as “too much”. Later, when its application started and its effectiveness and benefits had been demonstrated, it became reality. The initial push towards its application came after managers’ incentive system had been changed by including the achievement of Six Sigma projects into it.

Ambitious goals exist also outside Six Sigma organizations. As any project, success depends on the team lead. Bringing change is always challenging. It is important to set clear and measurable targets, to involve people and make sure they well comprehend the goal. The vision is needed to give a direction. The design of KPIs must be done including workers on the shopfloor as they need a tangible measurement system. Actions can only be taken having relevant measurements available.

The service world initially rejected the Six Sigma approach as its goals were perceived to be too ambitious. It was thought, benefits could not compensate the effort needed to be put into it. This situation changed as soon as the incentives system had been updated including Six Sigma projects' development, employees started to find a way to adapt the Six Sigma approach to their processes. Alain Mimouni underlines the importance of the market in Six Sigma tools deployment. The request of six sigma quality from customers through penalties in procurement contracts made the effort toward having the desired level of output quality a must.

6. How much, in your experience, is Six Sigma theory and how much is it practice?	
Bernd Bachert	Coaching and training enable Six Sigma. But coaching is more important, as it can be done without training and theory. The opposite, i.e., helping project managers with training only and no coaching, is not possible. More sophisticated and complex tools can be taught when necessary. Six Sigma is complex because it entails working with people. For this reason, internal coaching is important.
Alexander Eisenschink	Skills acquisition is 20-25%. The rest is effort toward changing mindset and behavior of people working in the organization to reach the vision. It takes one year to change awareness of workers.
Jens Greving	20% theory and 80% practice. The toolbox can be taught. But learning and understanding is done on the field. If more theory is needed, people can go back to theory. Practice consists in 50% education and 30% braveness in trying out solutions.
Alain Mimouni	At the beginning it is theory for as long as needed to learn the methodology and the tools. It quickly becomes practice as you need to reach results. Customers do not wait and expect high quality products.

At the beginning, Six Sigma is theory: it requires training about tools and methods. It soon becomes practice as results need to be achieved. Six Sigma is an operative approach. If the knowledge is not sufficient to overcome a certain problem, the team may go back to theory and acquire more tools.

7. How much does Six Sigma cost?	
Bernd Bachert	The cost of training and coaching. Projects are undertaken if they have a positive return on investment. Six Sigma is chosen as it provides effective tools to succeed.
Alexander Eisenschink	The company must establish a system to track costs and benefits. Costs are linked to training and coaching. In order to measure the benefit of Six Sigma, KPIs must be established. Benefits come from projects success and from the long-term advantage of the change in mindset.
Jens Greving	Educate people to be better problem solvers is a cost but will bring benefits on the long term. Training is external at the beginning. It can then be internalized, and its cost saved. Salaries are paid either using Six Sigma or not using it. Six Sigma is a toolbox to best organize cross functional teams to solve the problem efficiently and effectively.
Alain Mimouni	The cost of training is more than offset by the cost of penalties. Contractual penalties are put by customers to ensure the desired level of quality is delivered.

The main voices of costs linked to Six Sigma are training and coaching. Training is initially external to the company but can later be internalized and part of its costs saved. Projects should be undertaken when they have a positive net present value, which means Six Sigma projects provide a cost saving. Moreover, the set up of a process control system to sustain results is a long-term benefit from the deployment of Six Sigma. The team working on a Six Sigma project receives its salary both if it uses Six Sigma or not. Six Sigma provides structured tools to solve problems, thus it is convenient. An avoided cost from deploying Six Sigma comes from avoided contractual penalties put by customer on product quality.

8. What has your first impression been about Six Sigma? How has it evolved?

Bernd Bachert	Positive. The first time utilized, Bernd Bachert reports to have solved a big problem he was facing, and which traditional quality management tools did not solve.
Alexander Eisenschink	First approach with Six Sigma was purely Six Sigma and it was complex because of the big amount of numbers and statistics. Within six to ten years after starting to work with it, Eisenschink says to have reached a deeper understanding. He understood that the effort must come from management first and the preliminary step to make was to convince management about the mindset behind Six Sigma. Managers coach workers. The drawback of Six Sigma is that it operates through projects lasting around six to eight months. This time is shorter than the time needed to change people's mindset.
Jens Greving	It is a journey of learning. At the beginning Jens Greving was interested in learning to apply Six Sigma toolbox and now he can confirm that it has been useful. The challenging part is to work with people and extract information from them.
Alain Mimouni	At the beginning Six Sigma was perceived to be not relevant to services. The way quality had been thought of and measured could not be applied to service industry. As soon as the company based a percentage of managers' yearly incentives on Six Sigma projects, everybody started adapting and applying it and the desired results started to be obtained. From then on, the methodology started to be more and more accepted and useful, and Alain Mimouni says to have used it in different occasions later during his career.

All interviewees agree on the effectiveness of Six Sigma approach. A deep understanding and experience of the methodology and of its tools is important. They all have a positive first impression apart from Alain Mimouni who was working at a service-based company. He claims the methodology was initially rejected as not relevant and of no apparent use to the financial world. The mindset of the company changed, after Six Sigma implementation proved its effectiveness to the customers.

Conclusions

Interviewees complete the picture of Six Sigma. Six Sigma is a frame in which problem solving is facilitated through the use of standard tools and of a structured approach. Measurement is the key of the Six Sigma approach, i.e., the DMAIC cycle. This approach enables the standardization of the way quality is measured across the supply chain making Six Sigma the basis for quality assessment. Procurement contracts asking for a high level of product quality push suppliers to adopt the Six Sigma approach internally. The implementation of Six Sigma within a company is started by the CEO and the Master Black Belt. The former gives visibility and shows commitment toward the Six Sigma effort, the latter organized training and coaching to project managers. Yet, commitment by the whole team is needed to make Six Sigma effective and sustainable. Aside of Six Sigma and to support its implementation, Lean manufacturing tools are useful to ensure a relevant daily shopfloor management. The industrial world adopted Six Sigma more easily as quality can be better defined and measured. The service world had initially been reluctant about its effectiveness but proved benefits after Six Sigma tools had been adapted to the context.

8. CONCLUSIONS

Six Sigma is a toolset that effectively supports change, improvement, and control of processes through projects. It requires the involvement of all stakeholders and the support of management to yield results. Six Sigma is effective in solving problems with an unknown cause by applying the DMAIC cycle which is the structure Six Sigma projects adopt.

The DMAIC cycle provides a consistent and logic approach and tools that start from collecting and understanding customer requirements. The project goal is then defined, output variables identified, and the initial situation is measured. Through a cause analysis, the project team identifies the root causes of the problem and designs targeted solutions. The measuring of output variables and its comparison against the initial situation allows to prove enhancements and to end the project when the goal is reached. The most critical part is then the design of effective control tools that enable sustaining the new process. These tools also create a closed-looped system of information that enhances business steering and decision taking. To make Six Sigma effective, collaboration among the project team and support and commitment by management are needed. When this support and commitment are present, Six Sigma can become an organizational culture, in which all employees and workers act proactively toward process control and improvement.

The industrial use case shows the effectiveness of employing the DMAIC cycle as project thread to tackle a problem whose cause was initially unknown. The problem was the low performance of the production line in terms of OEE. Using tool 1 (customer orientation tool) and tool 2 (output variables definition table) the variables to measure process' outputs have been identified based on the customer's requirements. Such approach ensures process' quality is defined from the customer's perspective and improvement efforts are spent in the correct direction. The analysis of these variables, run time, downtime, and scrap production, brought the project team to deepen the analysis of the root causes for a low run time, a high downtime, and increasing production of scraps. Brainstorming session involving employees, shift leaders and operators led to the identification of possible causes. Using the 5Ws tool root causes have been identified to be lack of leadership of shift leaders, lack of knowhow about the main machine, and lack of a preventive maintenance plan. Actions undertaken included training to operators, writing of a shared procedure, organized maintenance. As these aspects improved during the improve phase, some other technical changes became necessary and confirmed a lack of precise technical knowhow about the production process.

These new problems of efficiency arising are the base for continuous improvement and further efficiency analysis.

The interviews made to managers of other companies enriched the understanding of Six Sigma and its perception by companies. They added and underlined three main concepts to the literature review made. The first concept is the need for critical thinking while applying Six Sigma methodology. Tools should not be utilized without concrete logic: they must be adapted to the faced needs and context. The second learning is that Six Sigma is often utilized along lean manufacturing which enables daily shopfloor management. The last concept is the push toward adopting Six Sigma comes from the market. As it establishes an output quality assessment recognized by all companies belonging to the supply chain, customers started to introduce penalties into procurement contracts. This led suppliers to adopt the Six Sigma approach for process control and improvement.

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