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Final Project

APPLICATION OF WCM METHODOLOGIES FOR FIRST TIME QUALITY IMPROVEMENT

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Chapter 1 - Introduction

Nowadays, each market requires fierce competition between firms, clients are more and more demanding. High customization and frequent innovations are necessary to sustain profits over the years. An accurate plan is fundamental, so Companies invest a lot on defining strategic targets that could lead to potential advantages against competitors. In addition, globalization and Digital age have increase the importance of rapid evolutions of products, and consequently on working environments. This continuous evolution is accompanied by a reduction of volumes, if once a model was manufactured identical for many year, today even ancient products require continuous improvement to compete with equivalent products available in the market. High customization has increased manufacturing costs, changing completely the industry from past times. If once the target was to fill the market with the more products possible, today companies perform Marketing analysis to forecast Sales volumes and consequently produce the strict necessary to avoid costly unnecessary stocks. In addition to avoiding unnecessary production, modern Companies cover required high investments with intense cost reduction. Each aspect of a Plant is analyzed in order to find and erase all sources of waste, to save money and at the same time improve product, process and working environment. This continuous improvement must involve the entire Organization, and to be performed correctly, it needs an easy and effective Methodology. It is for this reason that around the 2000s Japanese professor H. Yamashina theorized World Class Manufacturing (WCM) Model, which became the standard approach in many Successful Companies, as FCA Group. This Project aims to introduce this set of standards from a theoretical point of view, before their application in a sophisticated and advanced working reality, as FCA Powertrain plant in Mirafiori (TO), Italy, who adopted WCM methodologies to improve its product: a transmission for A and B segment cars. In particular, the target of this work is to help the plant to achieve 100% of production without the need of a repair before shipping. Production process is complex and divided in numerous operations and subassemblies. Components are purchased as row material and machined, heat treated before their final assembly on the transmission, and finally this product is tested. Quality standards of the Company require that each transmission must satisfy certain quality requirements, to guarantee Customer satisfaction. However, in present situation some defects are detected on a small fraction of the production, during these final quality tests. Non-compliant products can still reach requirements, but they first require a repair or a rework, but this represents a waste for the company. To avoid these additional repairing costs is important to increase the number of products respecting standards at the “first time”, and for this purpose WCM monitors a dedicated Indicator denominated First Time Quality (FTQ). This project aims to apply WCM methodologies to improve FTQ of Mirafiori Plant, which represents the fraction of products with defects to be repaired. First chapter will present World Class Manufacturing as a temple sustained by pillars, its history starting from first production system adopted in the past to achieve operational excellence, the targets of WCM and finally its structure. Second chapter will give a specific focus on all the tools available for Quality, which is one of the pillars of WCM temple. These tools will be explained from a theoretical point of view before their application during the applied part of the project. Third chapter will contain a brief presentation of Mirafiori Plant, and its transmission, which was introduced in the 90s and continuously improved to be competitive in the market. Chapter will also include specific mechanical notions about manual transmissions and metrology for gear wheels, helpful to better understand activities and achieved results. Next chapters will describe the phases of the analysis for FTQ improvement, following a "Kaizen" problem solving scheme: "Plan", "Do", "Check", "Act", starting from the identification of the main problems affecting first time quality, represented by noise detected during transmissions functionality test generated by an inadequate contact among gears.

Chapter 2 WCM

World Class Manufacturing (WCM) is a structured, rigorous and integrated production methodology adopted by FCA plants worldwide, which involves the entire organization, from safety to environment, maintenance, logistics and quality. The primary objective of WCM is continuous improvement in all areas of production in order to guarantee the quality of final product and meet customer expectations. Projects developed under the WCM methodology – which rely on a high level of employee involvement – target the elimination of all forms of waste and loss with the ultimate objective of achieving zero accidents, zero waste, zero breakdowns and zero inventory.

WCM is a production system where:

- *Safety is a basic value*
- *Customer expectations are heard within the plant*
- *Leaders apply standards with method*
- *Waste and loss are not accepted*
- *Methods are applied with rigor*
- *All anomalies are made visible*
- *People involvement is the engine of change*

From https://wcm.fcagroup.com/

2.1 Origins

Theory of management techniques for improving the efficiency of work processes in a scientific way was first introduced by the American engineer Frederick Winslow Taylor in "The Principles of Scientific Management",1911. His pioneering work in applying engineering principles to factory production led to the development of what is now known as Industrial engineering.

A significant improvement were made between 1945 and 1971 in Japan, where Taiichi Ohno, adopting concepts of Just in Time (JIT), Waste Reduction and Pull System, developed Toyota Production System (TPS).

"*All we are doing is looking at the time line, from the moment the customer gives us an order to the point when we collect the cash. And we are reducing that time line by removing the non-value-added wastes.*"

- Taiichi Ohno

TPS also inspired creation of the term "Lean Manufacturing", or "Lean Production" , which was introduced for the first time in 1988 by John F. Krafcik in his article "Triumph of the Lean Production System", which contains theories and methods theorized by Ohno for Toyota. This term is now widespread thank to the best seller published by James P. Wolmack, Daniel T. Jones and Daniel Roos in 1990: "The Machine that changed the World". Lean Manufacturing means managing operations by continuously reducing wastes to maximize the Value/Cost ratio. A process is considered "Lean" if it uses the minimum required amount of resources while keeping required quality and respecting schedules.

Many Western Companies adopted Japanese methods, and started to develop their own models of “Operational Excellence”. One of the firsts was Total Quality Management (TQM) adopted in the late 1970s by several U.S. Government organizations. This theory, developed firstly by William Edwards Deming who published “Out of the Crisis” in 1982. TQM methods are Client oriented and promote high involvement of people using systematic approaches. Many other models of “X-Production System” were developed. One of them is World Class Manufacturing.

The term “World Class Manufacturing” was first used in 1986 by Richard Schonberger, in his “World Class Manufacturing: The Lessons of Simplicity Applied”, in which he collected his experience of companies who adopted “Kaizen” methods for continuous improvement with the target of reaching the Excellence in production. Lately this term was adopted by Japanese professor Haijime Yamashina to identify his new Model of Operational Excellence theorized in the U.S. around 2000 and now adopted by several Firms leaders in their market.

2.2 Mission

WCM is a structured production system finalized to eliminate all types of wastes and losses by applying standardized methods for long lasting improvements. The model aims to Customer satisfaction and creation of value, involving the entire organization to increase people awareness and participation for increasing knowledge and sense of responsibility. WCM Association, to enforce competition and participation of each plant and verify the achieved targets, uses a system of Audits, which evaluate different performance levels following a schematic objective procedure. These Audit give a score to tested plants called Methodology Implementation Index (MII). WCM structure is divided in 10 Technical Pillars and related 10 Managerial Pillars; each Pillar after the audit receives a score from 0 to 5 as function of level of implementation of methodology:

- Score 0: No activity made
- Score 1: Reactive approach
- Score 2: Preventive approach in few model areas
- Score 3: Preventive approach extended to all important areas
- Score 4: Proactive approach in few model areas
- Score 5: Proactive approach extended to all important areas

The sum of the Score of each Pillar gives the MII and represent the Plant Score (from 0 to 100). WCM divide plants in five levels of Methodology application:

- 0 – 49: Method application still at base conditions
- 50 – 59: Bronze Medal
- 60 – 69: Silver Medal
- 70 – 84: Gold Medal
- 85 – 100: World Class

The goal of each plant is to achieve World Class level, this is possible when each Pillar rigidly applies standard methods in all important areas with a proactive approach in order to have “Zero” problems.

2.3 Structure

WCM is a guide to the Total simplification of all activities, an idea based on Total Quality Management finalized to obtain zero: It uses methods of Total Industrial Engineering (TIE), Total Quality Control (TQC), Total Productive Maintenance (TPM) and Just in Time (JIT) to achieve zero waste, zero defects, zero breakdowns and zero stocks.

Total Industrial Engineering (TIE): A system of methods for maximizing performance of labor trough reduction of *Muri* (unnatural and complicated operations), *Mura* (incorrect operations), *Muda* (non-value added operations) . Standard operations must be applied correctly to ensure quality, this is guaranteed by introducing controls and continuously improving the processes. Final goal is to achieve zero wastes

Total Quality Control (TQC): System for optimizing production to guarantee customer satisfaction and zero defects. It is based on various techniques involving both workers and managers to improve and optimize quality and productivity, including close monitoring of the market and client feedbacks with great importance given to customer service.

Total Productive Maintenance (TPM): Global approach to a maintenance system aimed to maximize machine capabilities maintaining equilibrium between efficiency and maintenance costs. These methods attack all possible production wastes due to machine lacks, as stops, leaks, speed reduction to obtain zero breakdowns.

Just in Time (JIT): A guide model for logistics based on *Pull* system, which aims to produce exactly what the market needs avoiding overproduction typical of Push systems. Final product and materials during manufacturing processes are delivered when required in a precise quantity. JIT target are Zero stock, and reduction of lead time.

PDCA: also called Deming Cycle, it is ann iterative four steps management method for problem solving adopted for Kaizen procedure:

- **Plan:** Phase of identification and analysis of the problem, finalized to find the root cause and an effective countermeasure to avoid it to reappear in the future.
- **Do:** Application of countermeasures identified during Plan phase.
- **Check:** Period of monitoring to verify the effectiveness of proposed solutions.
- **Act:** If the solution seems effective and strong during check phase, the problem Is considered solved. Modifications introduced becomes standard and are applied also to similar cases.

These methods retrieved from TQM are included inside World Class Manufacturing structure which can be seen as a temple sustained by 10 Technical Pillars standing on 10 Managerial Pillars.

10 Technical Pillars	10 Managerial Pillars
Guide the activities of continuous improvement	Guide improvement with correct decisional process and integration among technical pillars
Safety (SAF)	Management Commitment
Cost Deployment (CD)	Clarity of Objectives
Focus Improvement (FI)	Route Map of WCM
Autonomous Activities (AM & WO)	Allocation of Highly qualified people
Professional Maintenance (PM)	Commitment of Organization
Quality Control (QC)	Competence of Organization
Logistics & Customer Service (LOG)	Time and Budget
Early Equipment Management (EEM & EPM)	Level of Detail
People Development (PD)	Level of Expansion
Environment (ENV)	Motivation of Operators

2.3.0.1 WCM Pillars

Each pillar is focused on a specific aspect of the Plant, owns defined targets and it is guided with dedicated methods and a common structure divided in 7 steps. Each step identifies a phase and the area of application of the methods. WCM is first applied in few selected areas and then extended to important areas and finally to all the plant. The method applied is first reactive to problems, then is preventive and finally Proactive.

2.3.1 Technical Pillars

First ten pillars are called technical as they act directly for continuous improvement. Activities are strictly connected to the area of interest of the pillar, but with a proactive and cooperative view, for a better integration of other pillars. The role of each pillar will be presented shortly by identifiying the main targets and activities, together with a schematization of the expected 7 steps to follow.

Safety (SAF)

Safety first. In WCM Temple, the first Pillar is represented by Safety. A model based on people involvement and customer satisfaction must give priority to Safety and Health of workers. This Pillar takes care of all the risks actuating procedures and supplying equipment to guarantee an adequate level of protection to avoid accidents.

Targets:

- Prevent accidents and minimize all potential risks
- Improve working conditions trough ergonomics and sustainability
- Support the idea of prevention to avoid health and safety issues
- Development of people competencies in matter of safety

Activities:

- Reactive analysis of occurred accidents for root cause identification and introduction of corrective countermeasures
- Evaluation of all potential risks
- Technical improvements on machines and workplace
- Training of people
- Periodical internal Audit to evaluate safety of equipment

2.3.1.1 7 Steps of SAF

Cost Deployment (CD)

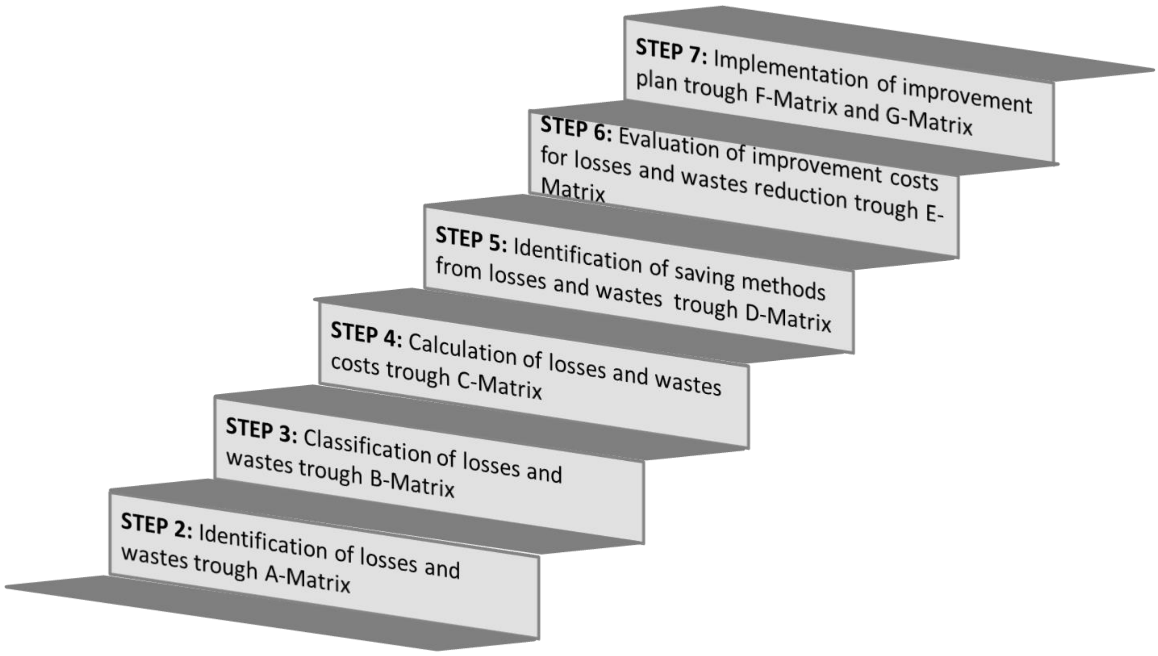
World Class Manufacturing is based on the idea of reducing to zero all wastes and costs. So, after Safety, the Second Pillar is Cost Deployment. It is a systematic method of cost reduction that involves both production and management. CD classifies in a scientific way the costs of losses and wastes and define a priority for reduction plans .

Targets:

- Identify and classify all losses and wastes of the production system
- Plan and monitor cost reduction following a schematic order of priority
- Find the root causes of all losses and wastes for application of corrective actions

Activities:

- Define relations between each process and all possible losses and wastes
- Identify the root cause of losses and wastes
- Prioritize losses and wastes as function of their costs
- Define methods to be applied for a cost reduction plan
- Evaluate benefits/costs of improvement plans for cost reduction
- Integrate cost reduction plans with plant budget to improve cost reduction effectiveness



2.3.1.2 7 Steps of CD

Focus Improvement (FI)

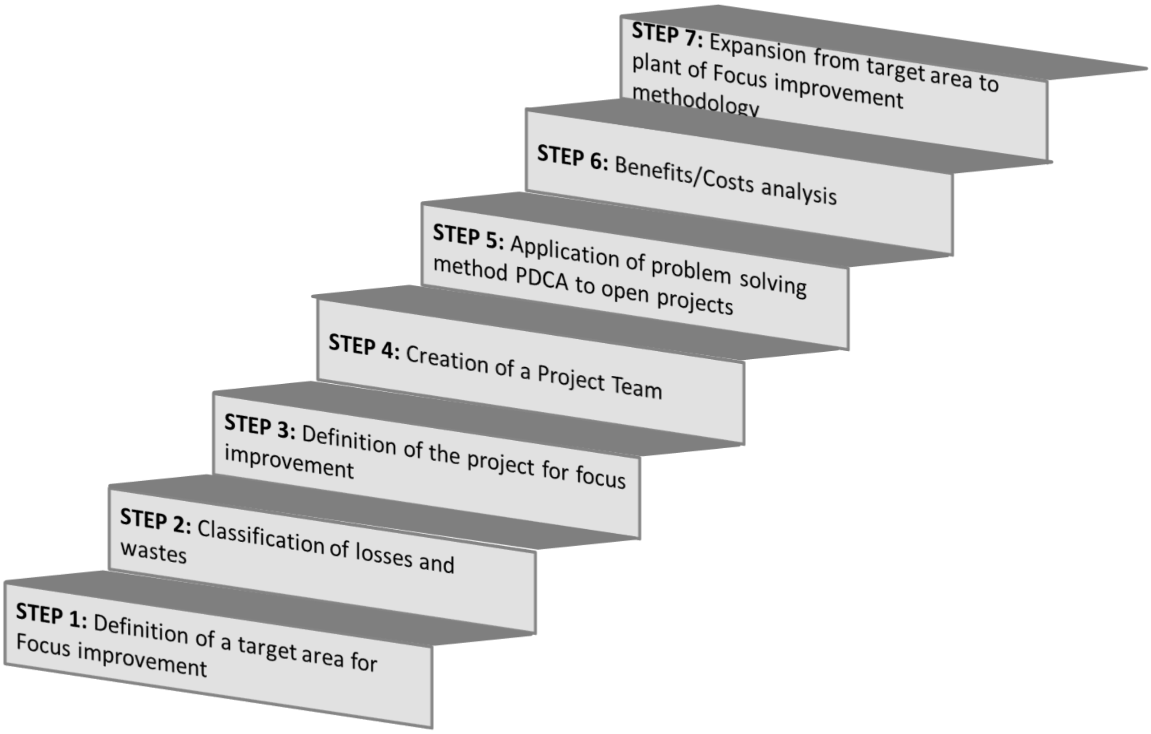
Cost Deployment define the sources of losses and wastes. Focus Improvement pillar works on cost reduction plans defined by CD and starts projects to eliminate losses and wastes starting from the top problems. CD helps FI avoid focus on problems that does not represent priorities. The main tool of FI is the Kaizen approach PDCA.

Targets:

- Eliminate losses and wastes following the priority scheme defined by CD
- Improve processes by eliminating inefficiencies and avoiding non-added value operations
- Obtain a reduction of costs after FI activities
- Develop competencies of problem solving involving workers at all company levels

Activities:

- Identify of team members for each project of cost reduction plan
- Apply problem solving methods (Kaizen, PDCA) to find corrective actions
- Monitor the status of each project from the start to the verification of corrective actions
- Training of people for a better involvement in problem solving activities



2.3.1.3 7 Steps of FI

Autonomous Activities

As said before, WCM is based on people involvement. Great importance is given to increase responsibilities and awareness of workers. A technical pillar is then dedicated to Autonomous activities, which is divided in: Autonomous Maintenance (AM) and Workplace Organization (WO).

Autonomous Maintenance (AM)

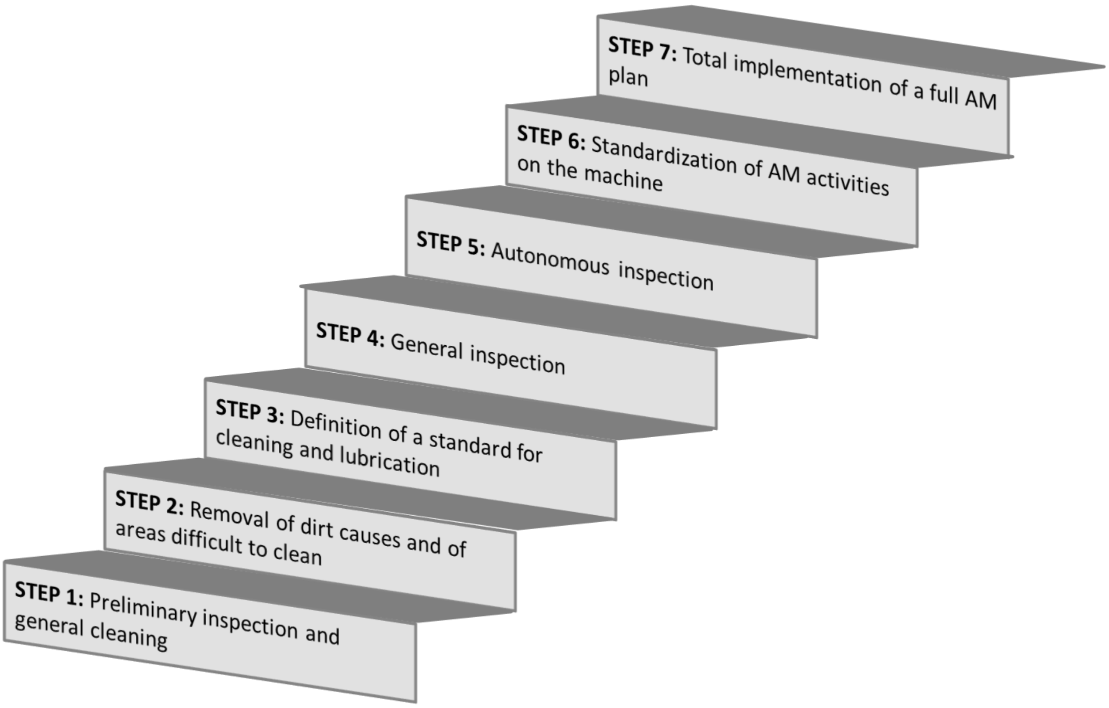
Autonomous Maintenance activities are performed by operator working in production, and not by professional maintainers. These activities concern preventive maintenance on machines, as scheduled inspections, cleaning, functional controls, substitution of defined components and small repairs. The base principle of Autonomous Maintenance is to enhance and guarantee the product quality trough the involvement of people on a good utilization and preservation of the machines.

Targets:

- Avoid machine degradation to guarantee product quality and increase machine lifetime
- Involve production workers to maintain and retrieval of machine basic conditions
- Realize a global management system for all AM operations
- Improve efficiency of plant trough adequate preventive maintenance
- Guarantee a total cooperation between production and Maintenance

Activities:

- Define AM Activities and adequate training to production workers
- Clean machines from important components to the ones difficult to reach
- Eliminate dirt acting on its generating causes and improve ergonomic to reach all parts
- Periodical checks or component substitution to avoid machine degradation
- Monitor and check leakages and unexpected machine behaviors to help finding a solution
- Improve inspection quality by increasing competencies of workers



2.3.1.4a 7 Steps of AM

Workplace Organization (WO)

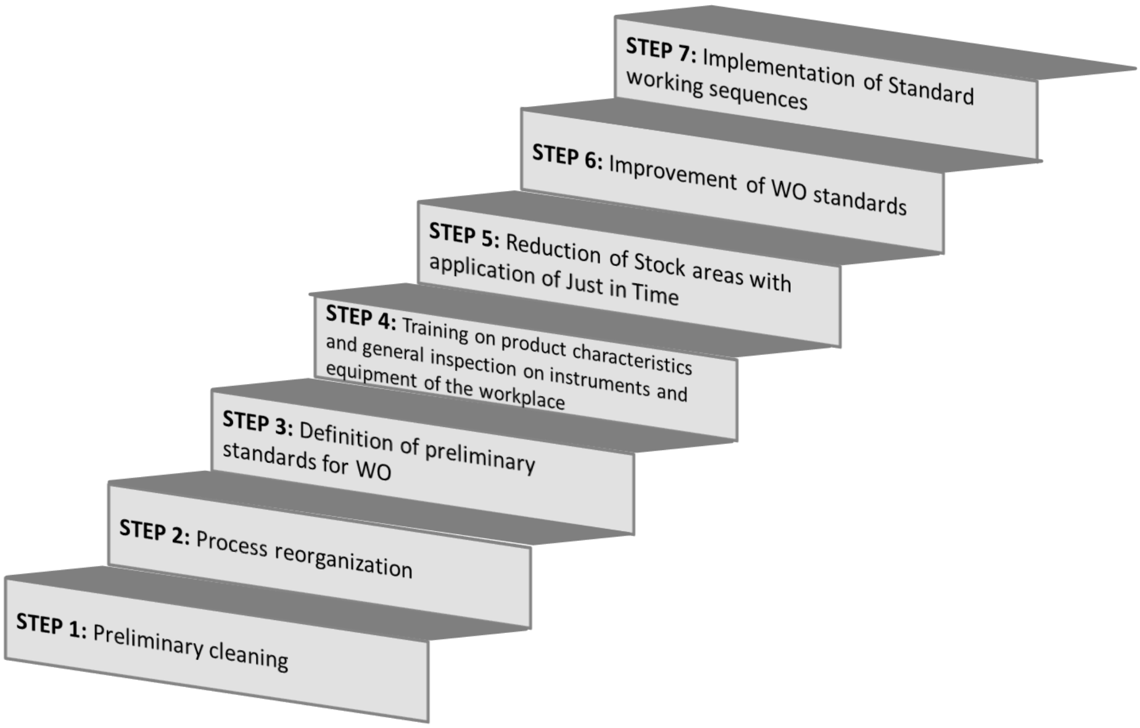
Workplace Organization activities are performed to obtain a better workplace, safe, clean and ergonomic, which can improve working condition and reduce stress and labor effort for the operators. A Better organized workplace also helps avoiding mistakes and non-value added operations. These activities are guided by technical criteria, methods and instruments that allow to retrieve and maintain workplace clean, in order and without useless instruments or stock areas. WO creates standards for the behavior of workers in order to guarantee process capability.

Targets:

- Improve Safety and Ergonomics of the workplace
- Avoid inefficiencies due to an unorganized and dirty workplace
- Involve production workers to maintain and retrieval workplace basic conditions
- Improve technical knowledge of workers about the product and their workplace
- Define standard activities to improve efficiency and avoid errors and non-added operations
- Reduce stock areas adopting a just in time strategy
- Improve logistics and avoid operational mistakes trough a well-organized workplace

Activities:

- Define WO Activities and adequate training to production workers
- Clean the workplace removing useless material
- Identify a place for each important material, equipment and instrument
- Apply periodically WO activities to maintain adequate conditions
- Improve standard working cycles by increasing technical competencies of workers



2.3.1.4b 7 Steps of WO

Professional Maintenance (PM)

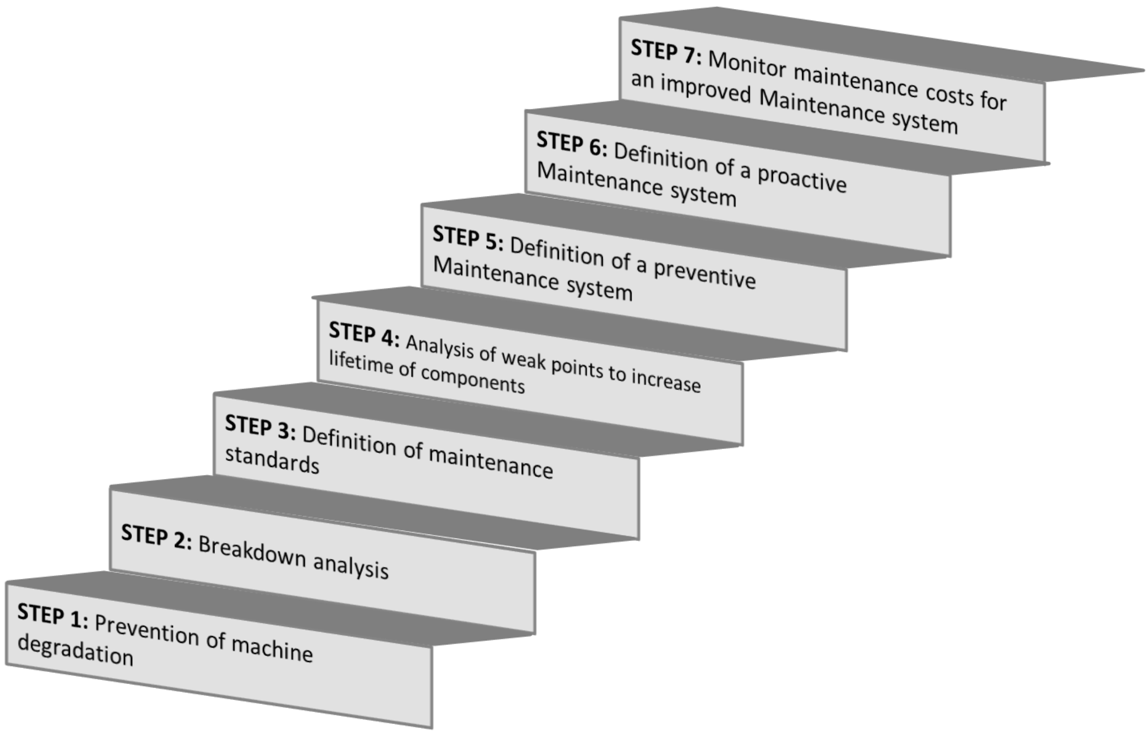
Aoutonomous activities can help avoiding degradation of machines and working equipment but major competencies are required in case of major failures. For this reason, Professional Maintenance represents another technical Pillar of WCM temple. With the cooperation of AM and Focus Improvement, Professional Maintenance attacks the breakdowns with a reactive approach. The main target is to develop a preventive system to avoid failures and increase machine useful life. PM organizes maintenance activities to increase duration of components and defines standard to guarantee a proper functioning preventing the degradation with time.

Targets:

- Avoid all kind of machine stops due to failures
- Increase machine reliability and efficiency through breakdown control and analysis
- Guarantee the cooperation between PM and AM to avoid machine degradations
- Reduce breakdowns and increase of Mean Time To Failure MTTF and MTTR
- Focus maintenance activities from a reactive to a proactive approach
- Improve maintenance system by reducing costs related to PM activities

Activities:

- Breakdown control and analysis
- Define and continuously improve Maintenance standards
- Follow a convenient maintenance plan, considering the possibility of a purchase in place of an excessively expensive maintenanceImprove standard working cycles by increasing technical competencies of workers



2.3.1.5 7 Steps of PM

Quality Control (QC)

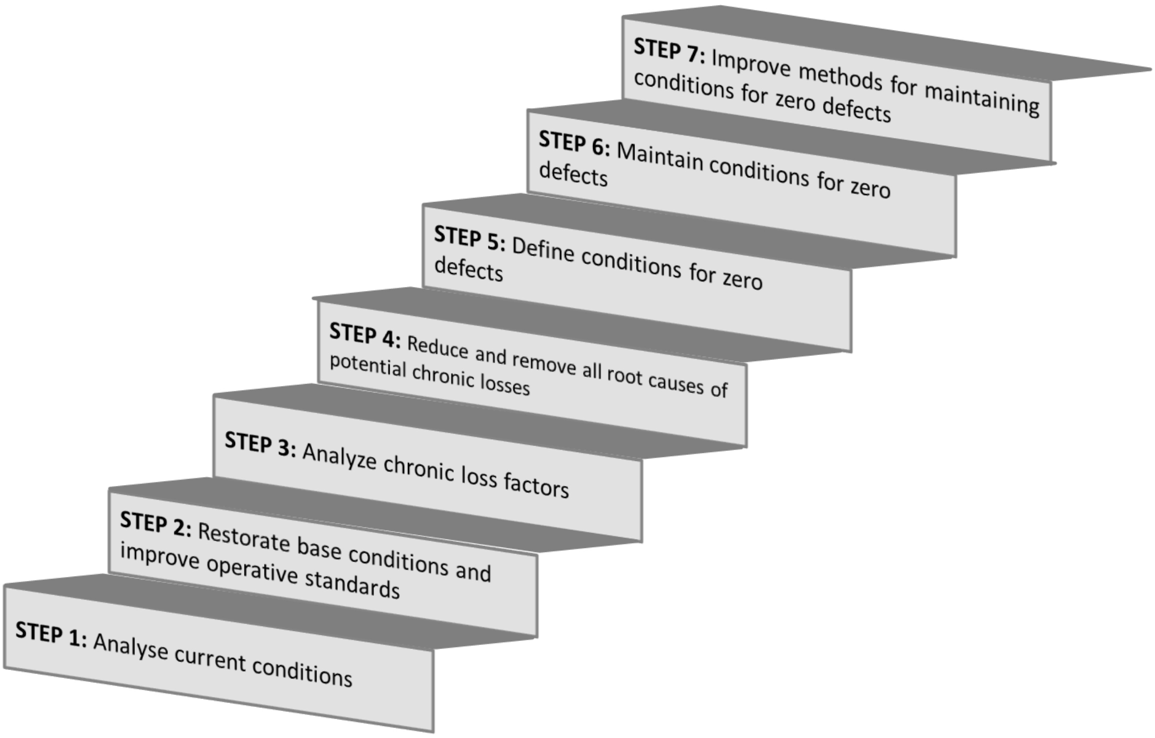
QC pillar has the main target of guaranteeing Customer Satisfaction, as it is one of the fundamental principles on which is based the entire WCM. Quality Control attack quality issues to find their root cause and apply adequate countermeasures. The aim is to monitor the production identifying non-compliances and avoid their reappearing. QC is not based on controls of production but on solutions that help avoid controls, as they are non-added value operations. As a consequence, Quality Control also helps to reduce costs related to reworks and scraps.

Targets:

- Guarantee quality of product and customer satisfaction
- Maintain the required capability for each process in the production system to avoid non conformities
- Reduce defects and rewkorks, and the number of controls without affecting the quality of products

Activities:

- Define a QA Matrix to list defects in order of priority
- Analyze defects to find the root cause using QA Matrix priority sequence
- Apply countermeasures, also to similar cases and monitor the results to guarantee the effectiveness of solutions
- Help AM and PM measuring process capability and supplying guidance for evaluations related to product and process quality
- Train production workers to understand a defect and to avoid mistakes that can cause its appearing



2.3.1.6 7 Steps of QC

Logistic / Customer Service (LOG)

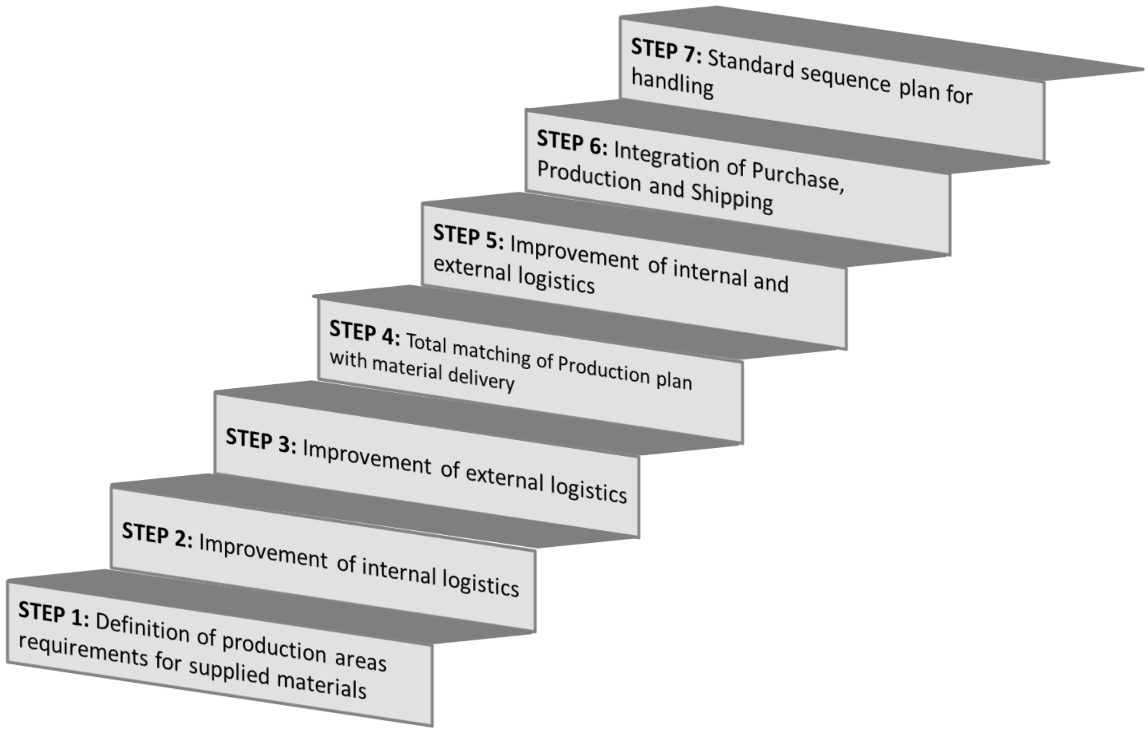
Another Pillar of WCM Temple is represented by Logistics, which controls all material flows inside and outside the Plant. The main goal is to apply JIT to all areas, in order to maintain an efficient control of all materials, supplying each production process with required material just when it is required. This is done to limit stocks which represent a great cost for the Company, and to help production to avoid mistakes. This can be possible through an accurate analysis and control of the demand, as material supply rigidly follow the production plan with a pull logic. Material flows are optimized and reduced, to avoid both financial costs related to stocks, and risk of material damaging or degradation.

Targets:

- Supply material to production areas strictly following production plans
- Improve flows inside and outside the plant to limit material handling and its related risks and costs
- Reduce stocks and avoid material obsolescence
- Deliver the right material just in time in each production area

Activities:

- Analyze flows to find losses and opportunities of improvement
- Apply material distribution strategies like JIT, KANBAN, FIFO to improve production process and reduce logistics related costs
- Improve layout of stock areas, material flows and the shape of containers



2.3.1.7 7 Steps of LOG

Early Equipment Management / Early Product Management (EEM / EPM)

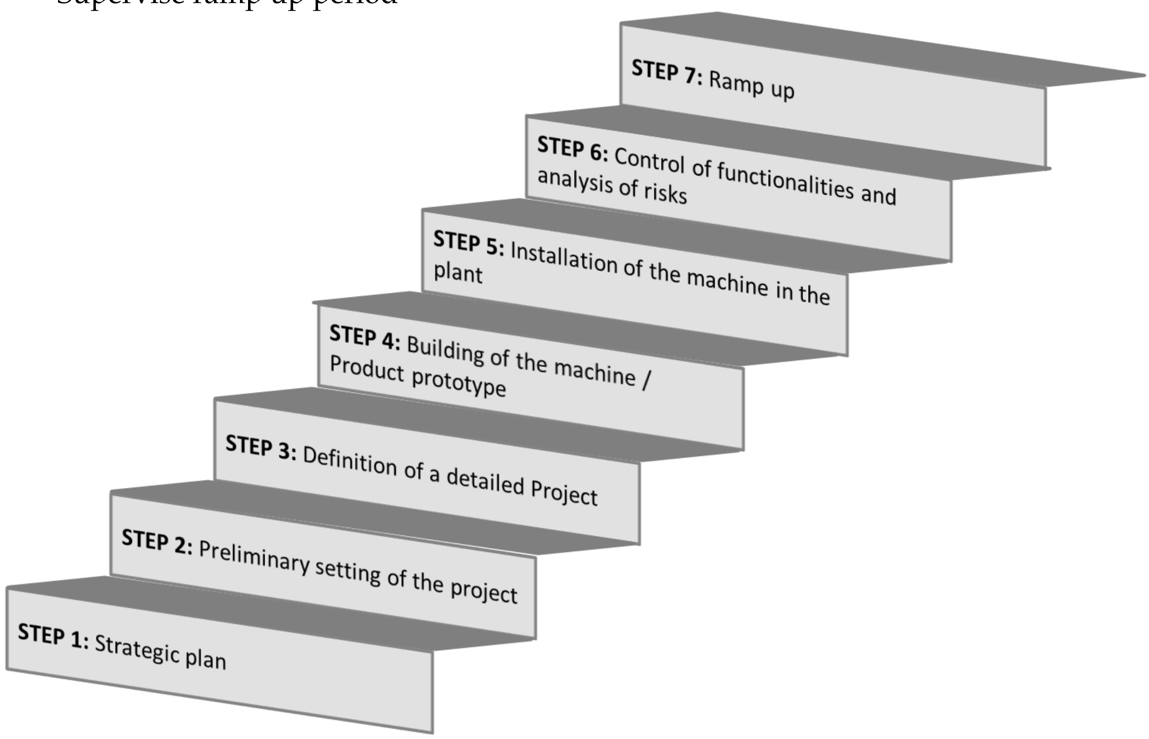
This pillar is dedicated to the introduction of new machines /products in the production system. It cooperates with Suppliers of the machines and Product Development up to the Ramp up phase, to improve both machine and process reliability, and to avoid future costs caused by an ineffective proactive analysis of all potential problems related to the new machine / product. The aim of the pillar is to reduce costs and time required for new introductions in production process. The role of Early Equipment Management and Early Product Management is similar, but EEM refers to introduction of new Machines and equipment, while EPM is dedicated to new products.

Targets:

- High reliability of the machines and quality of the product
- Follow the schedule and allocated budget
- avoid extra costs after introduction in production process
- Guarantee a fast and effective ramp up and preventive maintenance cycles
- Reduce life cycle costs
- Introduce machines with fast setups and easily accessible for maintenance and inspection

Activities:

- Guide introduction of new machines / products respecting schedule and planned costs
- Define schedule for the new introduction
- Monitor construction of the machine / development of the product
- Monitor the installation of the machine in the plant
- Verify functionalities and define preventive maintenance plans
- Evaluate risks to avoid extra costs due to failures or production wastes
- Supervise ramp up period



2.3.1.7 8 Steps of EEM / EPM

People Development (PD)

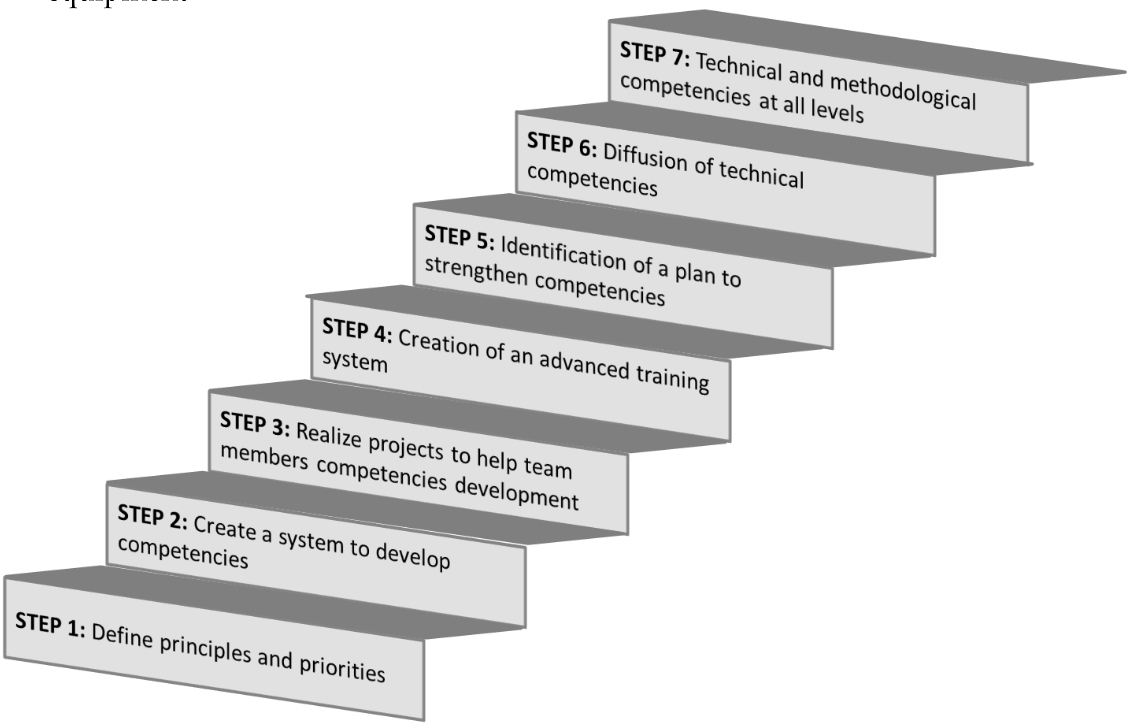
Humans represents the most important factor influencing the Success of a Company. A Pillar of the WCM Temple is then represented by People Development. Its role concerns people and their technical development, it provides trainings to improve worker competencies on Autonomous Activities or application of QC procedures, but especially on WCM methods. World Class Manufacturing is based on people involvement, this pillar has the task of increase the feeling of responsibility and the proactive attitude of all workers, in a form compatible with WCM to help the continuous improvement of the plant.

Targets:

- Avoid accidents caused by inexperience or lack of knowledge of the performed operations
- Guarantee adequate skills and competencies to every worker of the plant
- Train every worker to WCM for a faster continuous improvement of the plant
- Reduce human errors introducing Poka Yoke
- Gain performances from a higher satisfaction and technical knowledge of the workers
- Apply correctly Quality Control on processes and products in all areas

Activities:

- Define competencies and skills required for each role
- Plan adequate training session in predisposed Training Centers
- Train Quality workers on application of QC procedures to guarantee quality of products
- Train PM workers competencies to repair Machines in any failure conditions
- Train technicians to be able to solve problem related to their areas
- Guarantee that Trained personnel can transmit to workers their knowledge
- Train production workers on autonomous activities and on use of workplace equipment



2.3.1.9 7 Steps of PD

Environment (ENV)

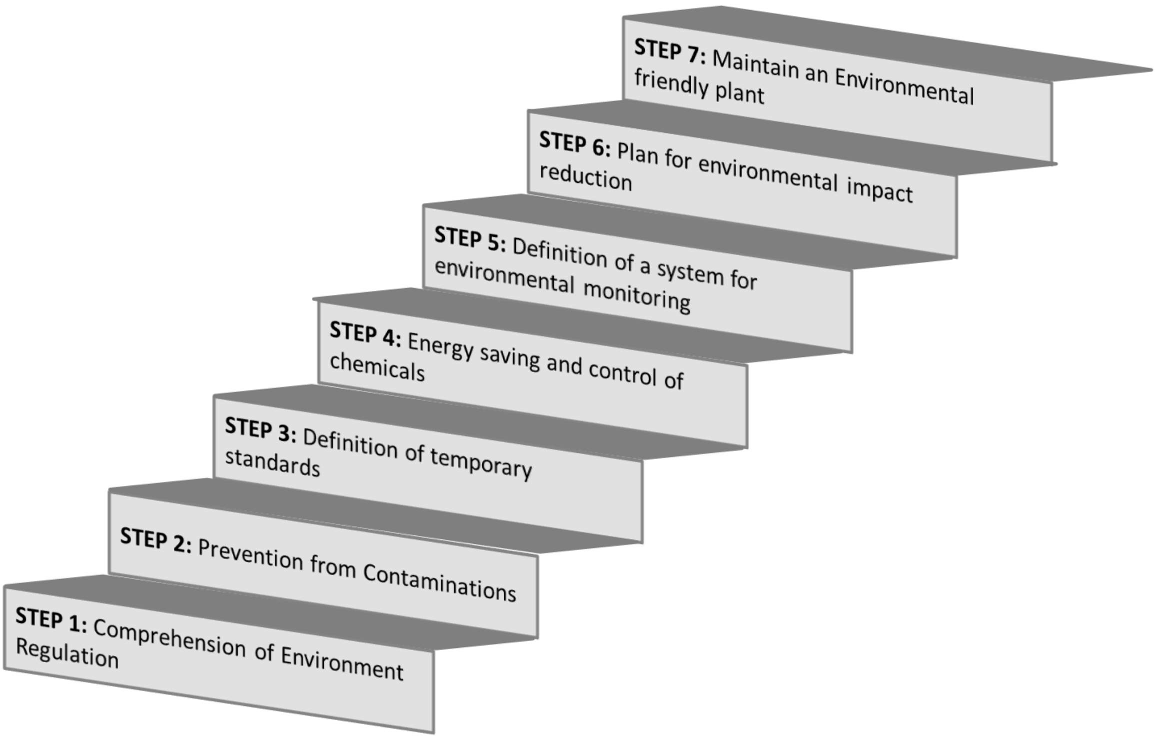
Last Technical Pillar of WCM Temple is dedicated to Environment. Its main concern is the evaluation of the impact of Plant activities on the environment, considering both immediate and long term. It is an instrument to monitor the performances related to resource consumption.

Targets:

- Avoid environmental accidents
- Observe regulations concerning environment
- Develop the idea of prevention to preserve the environment
- Continuously improve working conditions from the environmental point of view
- Improve machine utilization to reduce leakages and energy consumptions
- Reduce energy consumption and generation of pollution agents
- Reduce noise in the workplace
- Give importance to sustainability and recycle materials

Activities:

- Identify and prevent risks
- Guarantee application of ISO Regulations
- Maintain and control environment through periodical internal audits
- Guide improvements on machines to reduce their consumptions



2.3.1.10 7 Steps of ENV

2.3.2 Managerial Pillars

WCM introduces ten managerial pillars strictly connected to the technical pillars, as a support for work and continuous improvement. They are related to aspects as planning, organization, leadership and motivation which are fundamental for the success of technical activities. It follows a brief explanation of the main roles of each pillar:

1) Management Commitment:
This Pillar is responsible for the beginning of the shake-up. It opens a discussion about actual conditions to analyze possibilities of improvement trough changes. It represents the main sponsor for the mutation of present activities and habits, it has to convince the entire organization that a change is necessary. Management Commitment pillar transforms strategical objectives in operative objectives, runs Transversal meetings to guarantee the coherence of daily activities with the organization targets and assign activities to correct resources, guiding the Company toward change.

2) Clarity of Objectives:
As suggests the name of this Pillar, its role is to Define Objectives in a simple and clare way to prevent any kind of incomprehension. Objectives must also be quantified to avoid subjective interpretations, and diffused to every interested person in the Organization. As WCM is based on reduction of losses, Cost Deployment indicates for each pillar an Objective which is translated in KPIs, which is the main instrument of diffusion of the Objective. KPIs are first defined, then diffused and calculated, and after application of corrective actions in case of need they are monitored.

3) Route Map to WCM:
This pillar is based on two factors: Customer Aspectatives and the Mission / Vision of the Company. Starting from these factors it is defined a "Route Map" to follow, a definition of Targets, a strategic pianification of the future of the Company comprehensive of all Plants. This is the base point for the Pillar of a Plant, which target is to develop several "route maps" starting from the "general rout map" evaluating the medium-long period and define proper targets. The following responsibility is to guarantee that all pillars, both technical and managerial, know and follow in the same direction the Route map, with a proactive attitude and a strong cooperation. The increase of motivation and involvment are important factors required to succeed on bringing together all pillars and satisfy required targets without delays from schedule

4) Allocation of Highly Qualified People to Model Areas:
WCM as said before is based on people involvment. The main role of this Pillar is to guide the beginning of Method implementation. Starting from model Areas, Some Experts are in charge of transmitting their Knowledge about methods, procedures and ideas. These competencies must be absorbed by workers of that area and then, the method must be "self-managed". The role of the Pillar leader is to evaluate performances and effective application of learnt methods, to guarantee a proper advance toward the direction planned with the Route Map. The pillar evaluations are based on KPIs, property of adoption of Methods and instruments, and Team competencies gained trough People Development.

5) Commitment of the Organization:
A part from the Management, a relevant role is given to Organization, this pillar represents a guide for each activity of improvement, acting against tendencies of relying on habits and avoid admitting existing problems, or solving them in an incorrect way. A correct organization teaches people to act against problems with a propositive attitude, helps people to find the solution of a problem starting from their technical knowledge and the method. A good way to improve organization is to involve more people in many projects, for a wider point of view which could be helpful in certain situations, rather than focusing few people in few projects at a time. The organizational guide starts from the pillar leader, to the team, and finally to the entire organization, in which everyone should be trained on WCM and its methodologies.

6) Competence of Organization toward Improvement:
World Class Manufacturing, to reduce losses and wastes exploit several methods and stragegies, which should be objective and systematic, so equal for each similar situation. This pillar evaluate and monitor trough a database the effectiveness of the organizational aspects related to a problem in each aspect, from the method, to related economical requirements. It is important to use the correct instrument offered by WCM in each situation, for example simple problems should be analyzing with Quick Kaizens, it is not correct to open a Major Kaizen, because it would be an unprofitable waste of time. This Managerial pillar is a guide to help the correct choice of the instrument to be used to solve a problem, other than a source of knowledge about the history of projects, both completed and still running. For simpler problem basic instruments should be used, while for project related to situation more and more complex, the instruments suggested get sofisticated and more advanced.

7) Time and Budget:
This pillar develop specific plans to evaluate and monitor times and costs. An average project in WCM has a duration of 3 / 4 months, it is then important to define budget and expected time required for each project, in accordance to Plant annual budget. Time and Budget pillar helps the management of project guaranteeing the required budget and dividing the time of the resources available, to prioritize fast solution projects in order to focus attention afterwards to more complicated ones which give a smaller benefit. This system allows to easily monitor all the costs of the plant and to prevent dangerous delays that can cause extra expenses.

8) Level of Detail:
This Managerial Pillar has the task to analyze the processes deeply in the details losses and wastes after their elimination, in order to find their real root cause. This approach allows to remove definitively the problem avoidinding a potential reappearing in the future.

9) Level of Expansion:
World Class Manufacturing is based on expansion. Each activity it is firstly introduced in a selected area, then it expands until reaching the total plant. Management must follow a Detailed plan of WCM expansion, accompained by a great number of parallel projects defined starting from guidance of Cost Deployment, starting from processes of class AA, A, B up to the entire Plant, and eventually even to external suppliers.

10) Motivation of Operators:

This pillar aims to increase the motivation among operators, as they are the base of the production system and the most determinant members of the organization, as they are directly acting on the product and on the machines, and so their knowledge is relevant even for their eventually limited areas of experteese. Workers must be involved in WCM and trained to application of methodologies to let them exploit their direct technical experience to help the solution of plant problems. This is possible if the worker is satisfied and motivated to add other activities to the basic ones that he is used to perform. This pillar organize teams for small projects among operators with Kaizen used as a guide procedure for all activities finalized to the solution of a problem. To avoid absenteeism and low engagement, Management must involve workers, give them the importance they deserve, and inform them of the achieved results as they are part of the Organization. The Pillar also suggest incentives for good application of the methods and for proactive attitude of workers, and promote training sessions and guidance in case of low quality of the proposed solution for a given problem.

Chapter 3 QC Quality Control

The Vision of Quality Control is "Full Customer Satisfaction trough Excellence in Quality". This pillar is entrusted of the responsibility of guaranteeing Quality and Compliance of products, with the target of Zero Defects, reachable with the help of WCM tools and methods.Continuous improvement in Quality is based on the reduction of costs related to defects and non-value added activities, like controls. The starting point is a final control of product quality, which should be able to detect all defects generated in the production system and avoid that defective products enter the market. The improvement advances looking backward in the production process, identifying the root cause of a defect and adopting countermeasures to avoid its generation and not just finding a way to intercept it. This pass trough a constant monitoring and refinement of processes to enforce their capability and repeatibility. As any other Pillar of WCM, Quality Control is first introduced in a selected area of the plant, to offer a fast and effective reaction to problems, then trough method and discipline it expands, providing solutions to root causes, for finally being able to prevent problems adopting countermeasures with a proactive approach. Effectiveness of Quality Control is constantly tracked trough proper indicators based on customers feedbacks or data within the production system. These indicators, which are based on defects and customer satisfaction, define QC targets for the continuous reduction of costs related to Quality.

3.1 QC Indicators: Each WCM pillar monitors specific Indicators, which are characterized by a common base structure and a specific purpose. All those indicators are divided two typologies:

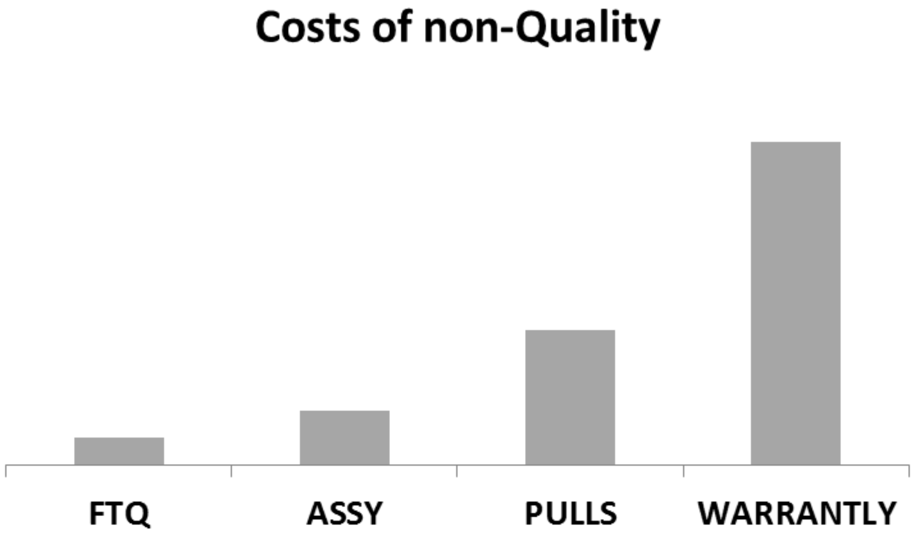
- [KPI] Key Performance Indicators: Evaluate and numerically quantify performances with an objective and systemic approach
- [KAI] Key Activity Indicators: Evaluate and numerically quantify performed activities with an objective and systemic approach

It follows an explanation of indicators of Quality Control in the automotive field:

KPIs:

- **Warranty C/1000:** Defined as the number of cases of Warranty after 3 - 12 Months of utilization every 1000 vehicles sold. It is the most importantindicator as it quantifies the cases of non quality with an higher impact on costs and customer satisfaction.
- **Quality Tracking:** It represents the percentage of customer unsatisfaction, based on questionaries with fixed multiple choice questions to evaluate customer feeling about the main features of the product.
- **NCBs:** It also represents the percentage of customer unsatisfaction, New Car Buyers differs from Quality Tracking as the questionaries are managed by External Institutions which evaluate in the same way all manufacturers, offering a good tool to evaluate and compare competitors.
- **Pulls:** Measure in ppm the number of defects which require a substitution of the product, found by intermediate clients. These defects does not reach the final Customer, but still represent unsatisfaction of clients manufacturers. The impact on costs is high, as the defective product must be substituted and repaired.

- **Assy:** Measure in ppm the number of defects which do not require a substitution of the product, found by intermediate clients. As pulls respresent unsatisfaction client manufacturers, but with lower related costs
- **FTQ:** Measure the percentage of products respecting quality standards at first time among the entire production. First Time Quality is an internal indicator for the plant, whose purpose is to monitor the quantity of defective products intercepted by final quality tests on production.



3.1.0.1 Costs of non-quality

KAIs

- **N. of Poka Yoke and Error Proofing:** Counts the number of devices introduced in the production system for sistematically avoiding generation of defects (Poka Yoke) and for sistematically intercept and block defects trough automatic checks (Error Proofing).
- **N. of Kaizen:** Counts the number of problems solved trough Kaizen PDCA methodology, differentiating Quick Kaizens, Standard Kaizens, Major Kaizens or Process Point Analysis (PPA) and Design of Experiments (DOE).
- **N. of SOP and OPL:** Counts the number of Standard Operating Procedures and One Point Lessons introduced in production to help workers to prevent wrong actions that can cause defects.

3.2 WCM Tools for QC

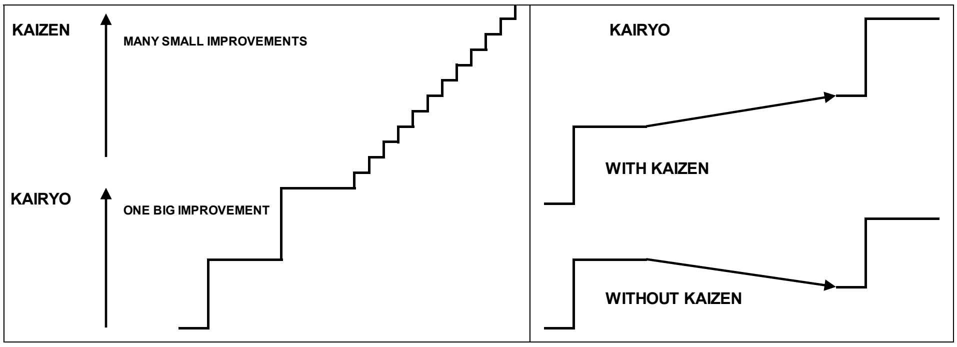
Quality Control activity consists in detecting defects, isolate them from the production and lead the analysis to find a solution for the root causes. This is a process which could be schematized and standardized to obtain with low efforts the best results. For this purpose, WCM offers to Quality Control a set of tools for identify, prioritize, find root causes and related solution for each Quality problem of the plant.

QA Matrix: Before deploying resources on certain activities, it is fundamental to have a wide vision of all the problems for being able to give priority for the most important ones, avoiding to waste time and effort on themes that could reveal themselves as marginal. QA Matrix is a tool that guides QC to chose correctly the problems to face first. It correlates defects to the production process in which they are generated or identifiead. It is then defined for each defect a priority index, product of different weight factors concerning Frequency, costs, detection and gravity. This priority number allows a classification of defects, from the most serious mostly related to safety or final Customer unsatisfaction, to the marginal ones related to productivity and reduction of number of defects inside the plant. Higher priority is given to Warranty cases, defective products that reached the final customer causing a malfunctioning of the vehicle requiring a repair within the first year of utilization. A part from detection, high priority is given to defects with a high gravity factor obtained from the FMEA.

$$PRIORITY\ INDEX = Frequency\ \times (Material\ Costs + Labour\ Costs) \times Detection \times Gravity$$

Starting from the top of the list, following Priority Index guidance, for each defect should be applied the problem solving procedure of Kaizen, to determine the root cause and apply the appropriate countermeasures. This tool does not apply only with a reactive approach to happened defects, it can also be developed thinking with a preventive approach, starting from the FMEA. Other than classifying defects, QA Matrix also helps classifying processes to identify the ones that required the higher effort for improvement. Finally, as QA Matrix keep track of the status of advance of Kaizen activity with PDCA phases, it is useful to keep history of defects to verify that they does not occur again after reaching the Act phase, as a proof of the correctness of the solution applied.

KAIZEN: An approach of problem solving based on Deming cycle PDCA and continuous improvement step by step. It is the opposite concept with respect to Kairyo, representing few big improvements. Kaizen is a good approach as it is systematic and continuous, useful to prevent degradation with time of introduced solutios. If few big improvements are introduced after great time delays, previous improvement become less important and it is easier to lose effectiveness, while with Kaizen approach this is not possible with a correct application.

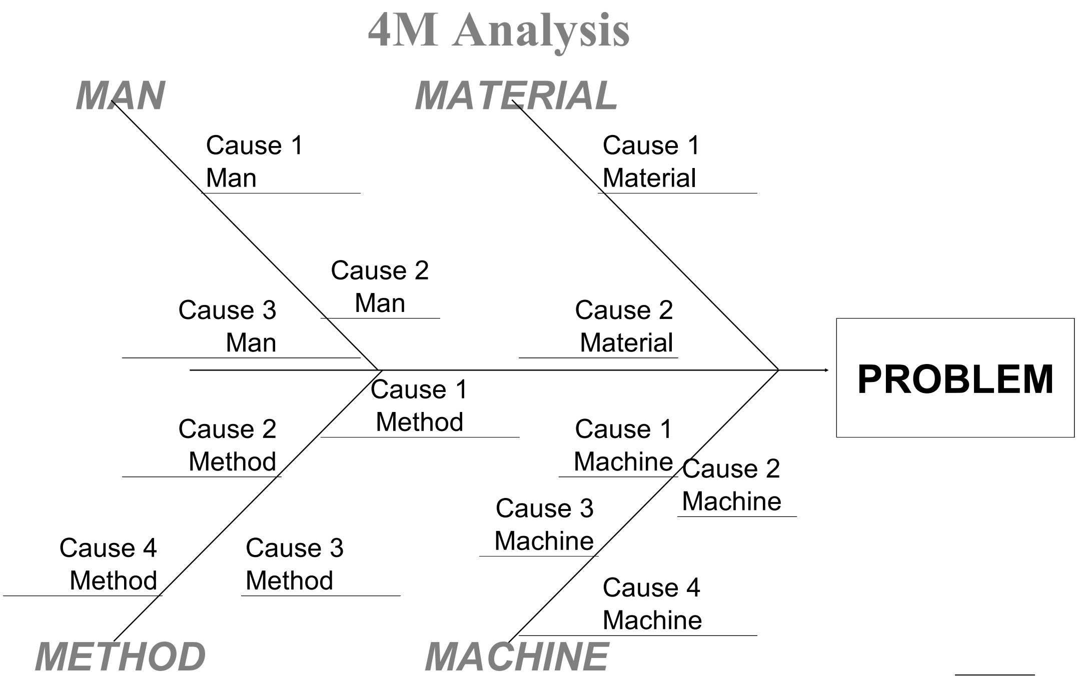


3.2.0.1 Kaizen approach

4M Analysis: Method integrated inside Kaizen procedure to identify the correct origin of a problem and its solution. Common Quality issues can be usually riconduced to a root cause connected to Machines, Men, Methods and Materials. 4M Analysis is tool finalized to help finding the origin of a defect, starting from the problem and going backward identifiyng all possible causes dividing them among 4M:

- **Man:** Causes associated to human errors
- **Machine:** Causes associated to wrong functioning of machines
- **Method:** Causes associated to a wrong operative procedure
- **Material:** Causes associated to defects or non-compliants on purchased material

All identified potential causes are listed in the Ishikawa diagram, which represents a visual help to connect root causes to their consequences with a fishbone scheme. All causes are then analyzed and verified, removing the ones which result irrelevant for the analyzed problem. The goal is to identify a Root cause and associate it to one of the 4M to start the effective problem solving procedure.



3.2.0.2 4M Analysis Ishikawa diagram

For each of the 4M, WCM offers a procedure for identifying the root cause and correctly find a solution. The scheme in the figure X divides the 4M and define the tools suggested by WCM to finally being able of answer to the 5 Questions for zero defects. If the result is positive, the solution is strong and the problem is solved, otherwise the process should be reiterated reconsidering steps made or other root causes not yet analized. WCM also suggests to use Kaizen to solve problems, but in case it does not lead to good results, it is required a deeper study with Process Point Analysis, to go deep into the details accepting major efforts and higher costs. 4M Analysis can be applied with different approaches:

- **Reactive:** Problems are faced after they happened
- **Preventive:** Expected Problems are identified and countermeasures are applied before it can happen. This approach is mostly based on past experience on similar cases.
- **Proactive:** Final stage of problem solving in which situations are analyzed deeply, thinking of potential problems that could arise in order to find and apply countermeasures

Machine: Once it is established from the Ishikawa diagram that the root cause of a certain problem is M for Machine, 7 Steps of Quality Maintenance should be iterated until an adequate and strong solution is found:

- **Step 1:** Analyse Base conditions of the machine and working procedures
    - **Tools:** PFMEA, Machine prescriptions
- **Step 2:** Restorate machine base conditions and improvement of operative standards
    - **Tools:** 5W1H, Standard Kaizen
- **Step 3:** Analyse Chronic loss factors. If Standard Kaizen does not lead to results a deeper analysis is required.
    - **Tools:** Process Point Analysis
- **Step 4:** Reduce and Remove all root causes of potential chronic losses identified during PPA
    - **Tools:** Process Point Analysis
- **Step 5:** Define conditions for zero defects. Define a correlation between defect modes, measured parameters, machine parameters and teir values which should be monitor and kept in a secure range to guarantee product quality trough process quality. This steps comes after step 3 if Standard Kaizen is adequate, or after Steps 4 and 5 if a PPA is required.
    - **Tools:** X Matrix
- **Step 6:** Maintain conditions for Zero defects by introducing periodical inspections on machine parameters identified with X Matrix. For each inspection 5QFZD Should be performed to certify the good state of the machine and the quality of the process.
    - **Tools:** QM Matrix, 5QFZD
- **Step 7:** Improve methods for maintaining conditions for zero defects. The final stage aims for a fast and efficient check of machine conditions
    - **Tools:** 5QFZD

PFMEA: Process Failure Modes and Effects Analysis is a preventive tool for a deep process analysis finalized to consider every possible risk and define strong countermeasures to avoid their effective insurgence.

5W1H: Simple tool that helps identifying a problem in a short time. It consists on answering to six questions: What? When? Where? Who? Which? How? The idea is to focus just on important informations, avoiding to waste time on finding the words to present a problem.

5 WHYS: Logical tool used to identify a root cause. It consist on answering five times to the a question "Why?" once the cause of a problem is identified. The purpose is to reach the root cause, starting from the most superficial cause.

PPA: Process Point Analysis could be considered a form of advanced Kaizen used to analyze a process deeply in the details, going into a machine component after component and measure the effect of each parameter in order to find root causes to problems that are not effectively solved trough standard kaizens.

X Matrix: It is a useful WCM tool dedicated to correlate defect modes to acceptable values of machine parameters which directly influence the insurgence of the defect. A square is in the middle of the X Matrix, each side represents in sequence:
Defect modes →Phisical phenomena → Machine components → Machine parameters
For each side a list is written, while on the corners it is required to evaluate interactions. First of all defect modes with all physical phenomena, then of physical phenomena and machine components and finally of machine components and machine parameters. This give a direct correlation that allows to define tollerancies for machine parameters that guarantee avoidance of defect modes analyzed.

QM Matrix: A riepilogative table containing for all machine parameters identified as cause of a defect mode trough X Matrix their nominal value, a control system, a frequency for checks and a person in charge for the controls. The target of QM Matrix is to guarantee an effective Process, avoiding degradation of machine to conditions that potentially can generate a defect. QM Matrix is introduced in periodical controls of AM and PM, Pillars directly correlated to machine maintenance.

5QFZD: 5 Questions for Zero Defects is a tool offered by WCM to understand if the solution identified is strong enough to consider the problem solved. It Consists on 5 questions, specific for each M, to be answered with a score. If The score result of the five questions is high enough, the solution is correct and reliable, otherwise the problem solving process should be iterated to find a new solution.

#	Machine	ANSWER		
		1	3	5
1	Are the settings defined?	The settings are defined and shared.	A method to check the settings is defined.	The settings are easy to see without special access or tools.
2	Is the machine easy to adjust to return to specified settings?	Difficult to adjust/set.	Easy to adjust/set.	Adjustment is automatic.
3	Are the equipment outputs varying outside the specification range?	During operation.	Only at set-up.	Varies only by exception.
4	Is the equipment variation of output detectable?	Low probability of seeing it.	The periodic inspection system is able to detect the variation.	Continuous monitoring ensuring immediate alert.
5	Is it easy to bring the equipment output back into specification?	Difficult, requiring specialized technical skills and high downtime.	Easy, once a person is qualified	Automatic adjustment (closed loop)

3.2.0.4 Five questions for zero defects Machine

Man: Once it is established from the Ishikawa diagram that the root cause of a certain problem is M for Man, WCM suggests to proceed with interviews to operators that were working in the moment in which the problem happened. These interview, called TWTTP, are composed by standard questions which allow to determine if the cause of the error is the lack of competence. After interviewing the operators, the team fills out a form, called HERCA, to determine if the root cause of the human error was not the lack of knowledge and finally proceeds with another interview with the same form of the previous one, as a check of the considerations emerged during the analysis. In the end, when the root cause is found, the countermeasures applied are evaluated trough 5QFZD. If the solution is robust, 5QFZD should give an high score and the problem is considered solved, otherwise the analysis should start again to find a new countermeasure for the problem.

TWTTP: The Way To Teach People, a tool in the form of a simple and standard questionaire finalized to to determine if the human error is caused by the lack of competence. Together with HERCA allows to determine the root cause of any human error.

HERCA: Human Error Root Cause Analysis, a standard form to be filled out by the workteam to determine ifthe root cause is not the lack of competence of the operator.

5QFZD: Follows the same scheme of Machine 5QFZD, but with specific questions for human errors

#	Man	ANSWER		
		1	3	5
1	Is the needed training/competence defined to complete operation correctly?	Training/competence is not defined.	Training/competence is defined but could be clearer.	Training/competence is clearly defined and training/competence gaps are easily identifiable. (exe. Radar Chart).
2	How is the training/competence gap covered?	Only class room training.	More class room training than training on the job/MTS.	More training on the job (including MTS) than class room training.
3	Can the operator follow the standard (i.e. VSOP, SWI/OPL,...)	The standards are not followed.	The standards are often followed.	The standards are always followed.
4	Is the human error detectable?	Most of human errors will not be detected.	A method to detect exists, but it is not robust (exe. Downstream visual check, push/pull/push).	All human errors are detected and analyzed (Example Q gate/Error/Mistake/ Alarming).
5	Is there an on-going training system?	Refresher training is not done.	The training is refreshed periodically to avoid forgetfulness (especially after shutdown periods) (exe. LPA).	There is a real-time (QA Network / Q gate / Sequential Inspection or machine) feedback to maintain skill levels.

3.2.0.5 Five questions for zero defects Man

Method: Once it is established from the Ishikawa diagram that the root cause of a certain problem is M for Method, the solution is identified following a simple scheme which helps identifying the “failure mode” of the method. Root causes could be associated to methods if a work standard is missing, or if it is not followed strictly because it is uncorrect or difficult to apply or comprehend.

Once it is defined a correction for the defective method, the effectivenes of the solution is verified trough the 5QFZD for method. If the new Standard reaches a good score it is implemented, otherwise the analysis should start again grom the scheme in FIGURE X to find a new scheme.

#	Method	ANSWER		
		1	3	5
1	Is the standard (work instructions) clearly defined?	There is no standard.	A standard exists, but lacks detail and it’s not visual yet.	There is a detailed VSOP (the document is at least 80% Visual) that all operators should find easy to understand.
2	It is possible to follow the standard as described?	It is not possible.	It is possible, but difficult.	It's easy to follow .
3	Is the standard effective?	It is non sufficient, high risk of error.	It is effective, but a margin of error still exists.	In 100% of cases, the quality is guaranteed.
4	Where is the standard located?	Standard is available, but not visible from work station.	Standard is in work station and visible, but not in line of sight of the operator.	Standard is in work station, is clearly visible, and is in line of sight of the operator when performing their job.
5	Is the operator involved in standard definition?	Operator at work station not involved with generation of standard.	Operator at work station reviewed and approved the work instruction .	Operator was directly involved with the content of the standard and approved the document.

3.2.0.6 Five questions for zero defects Method

Material: Once it is established from the Ishikawa diagram that the root cause of a certain problem is M for Material, the work team should proceed with the 8 steps of incoming material. To verify the effectiveness of the actions, 4M analysis is concluded with the 5QFZD.

8 steps for incoming material: When a certain insourced material has quality problem, the supplier is classified stage zero. To avoid defective materials, the company should inspect the products to verify if the standards are satisfied. The controls move then toward the source, first the inspection department of the company, then the supplier. The final step is reached when the suppliers obtain a controlled process which allows to avoid inspections on the production, with a cost reduction for both the supplier and the company.

5QFZD: Follows the same scheme of Machine 5QFZD, but with specific questions for material problems

#	Material/8Stage	ANSWER		
		1	3	5
1	Is the definition of a good versus a bad part clear in the suppliers process?	Quality Standards are defined but are not at the work station.	Quality standards are defined and at the work station, but are not clear and visible.	The standards are clear and and visible at the work station.
2	Are defects identified close to point of generation?	Defects are found at the using plant	All scrap for the characteristic is found within the suppliers facility but is found as far as their final line	The supplier relies on process control and does not use visual inspection to guarantee quality.
3	Is the supplier's capability sufficient?	Cpk is too low, and there are many problems with the supplier.	Sporadic problems 1<Cpk<1.33 Not Safety 1.33< Cpk< 1.67 Safety	No Problems Cpk>1.33 Not Safety Cpk >1.67 Safety
4	Is variation in the suppliers process visible?	Low probability of seeing variation.	The periodic inspection system is able to detect.	Continuous monitoring ensuring immediate alert.
5	Difficulty to bring the process back in control?	Requires a specialist/Technician.	the operator can make the adjustment.	Easy, the process is automated to compensate.

3.2.0.7 Five questions for zero defects Material

Kaizen structures: WCM divides Kaizen method in different levels corrisponding to the complexity of a problem:

- **Quick Kaizen:** In matter of simple cases, the procedure to be used is simplified, it is sufficient to correctly define a problem to think fast a proper countermeasure, so a full implementation of Kaizen method is not required. In this case, the standard to be followed is called Quick Kaizen.
- **Standard Kaizen:** In other cases, when the defined problem is not easy to solve, all steps of kaizen are required, starting from the Plan phase with 5W1H, passing trough the 4M analysis and five whys to identify the root cause and related countermeasure, up to the verification with 5QFZD.
- **PPA:** When a problem is particularly complex and countermeasures identified trough standard Kaizen are not effective, it is required a deeper analysis. The

Method is the Process Point Analysis, also called Major Kaizen. It consists on a detailed analysis trough all the production process to verify all aspects of involved methods, men, materials and machines, questioning machine parameters and components to understand their influence on product quality. The purpose of the analysis is to detect the real root cause and introduce a robust countermeasure.

- **DOE:** When a process is not controllable and the standard are respected, but a problem still remains, it is required an Experimental analysis. Design of Experiments is a method to redesign a production process after analyzing the results of dedicated experiments. It is required when other Kaizen procedures result not effective.

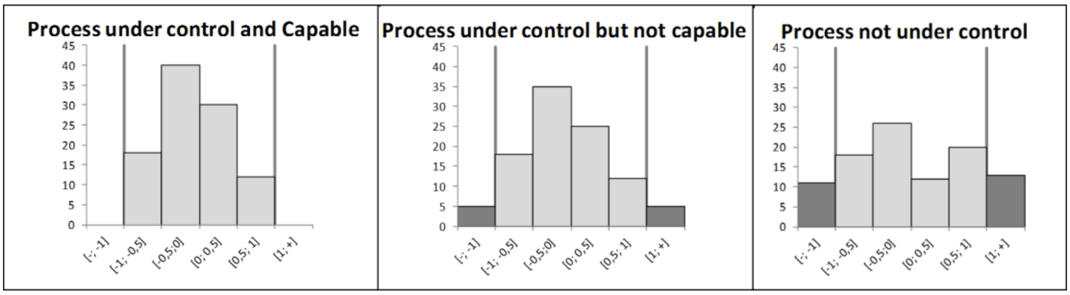
3.3 Statistical Process Control

To guarantee Product quality it is possible to inspect 100% of production, but this would represent an unnecessary cost and an high number of non-added value operations. Best choice is to guarantee the effectiveness of the processes, if a process Is capable of generating a good product, an inspection on the product itself becomes not necessary. In the real word it is not possible to perform ripetitive operations successfully without variations infinite times. Each itaration can be different from de previous one, depending on the work of the operator if it is a manual operation, or on the state of the machine tools if it is automatic. The goal is to obtain a process with high ripetibility, with a precision sufficiently high to reduce the probability of errors to a level acceptable for the production volumes. Statistics becomes a fundamental help to verify process capabilities, in order to understand if they are statistically capable of guarantee a number of repetitions high enough to cover the production with a number of defective operation lower then the company target, which is zero for companies aiming to operational excellence.

Capability Analysis:

1. To monitor the reliability of a process it is first necessary to define a parameter to be numerically measured and its range of tollerancy. If the measures remain within the limits of tollerances, the product quality respects the standards, otherwise it is considered defective.
2. Second step consists on gathering a significant number of process measurements.
3. In a reliable process, values should repeat themselves over time, while if the process is not capable there will be a wide range of values repeated few times. To analyze the process is then useful to group the measurements in a predefined number of value ranges, usually 6 to 10 depending on the number of available data, and then count the number of repetitions of the measurements that appear inside each range. This will lead to an istogram with a certain shape.
4. The shape of the istogram is a key factor to determine whether a process is stable and under control or if it is uncontrollable. In the first case, when the shape is similar to a gaussian plot, it is possible to proceed with the statistical analysis, while if the shape is randomic or in general non gaussian, the process is not stable

and it cannot be considered statistically determined as it requires first a direct action for improving the operations and guarantee the repeatability.



3.3.0.1 Process Capability and Stability

5. From measurements it is possible to determine an equivalent gaussian curve starting from two measures representing the entire population:

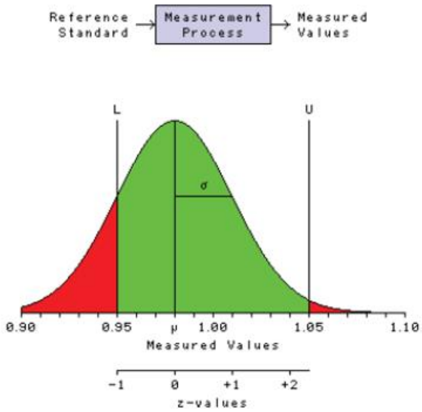
Average value μ: Represents the average value of population of N measurements x_i

$$\mu = \frac{\sum_{i=1}^{N} x_i}{N}$$

Standard Deviation σ: A measure to quantify the amount of dispersion of the population of measurements defined as:

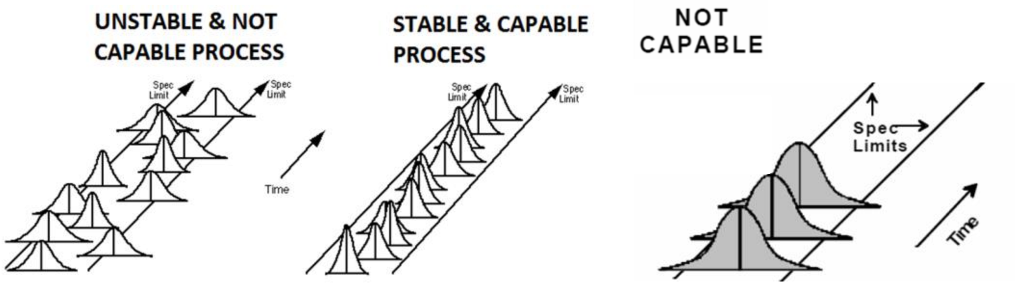
$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \mu)^2}{N-1}}$$

For any population Average value and Standard deviation can be determined, whether measurements come from a stable process or not, so it is possible to obtain always a gaussian. However, if the process is unstable, the gaussian will lead to mistakes, as it will be flat and wide as processes which are stable but not capable. Once lower limit L and upper limit U are defined, the area under the Gaussian out of the range defined by tollerance limits, coloured in red in the figure X, identifies an estimation of the percentage of defects of the entire production.



3.3.0.2 Process Statistical Gaussian distribution

6. To evaluate the stability of a process is useful to repeat the data gathering over time, to obtain several populations of measurements and their gaussians. If the gaussians repeat themselves over time, the process is Stable. If otherwise, in the process are present some causes that cause instability and low repeatability. When it is stable, the process is defined Capable if the Gaussians are contained within the 2 limits of tollerance range, or Not Capable if the Gaussian curve leaves outside of the tollerance range an area representing a faulty percentage higher than acceptable limit.



3.3.0.3 Process Capability and Stability over time

7. Once the process is Stable, it is useful to use statistics to determine its Capability. Two parameters are exploited to determine whether the process is sufficiently capable:

C_p: Evaluate the repeatability of a process independently from the position of the gaussian with respect to the range of tollerance. C_p correlates standard deviation of the process and the tollerance range, given USL (Upper Specification Limit), LSL (Lower Specification Limit), μ, σ:

$$C_p = \frac{USL - LSL}{6\sigma}$$

An high value of C_p guarantees the repeatability of the process but not its precision as C_p is not influenced by mean value. Usually the minimum acceptable value is $C_p = 1$, while the preferred is $C_p = 1.33$.

C_{pk}: Evaluate the precison of the process, as the mean value of the populations enters in the correlation between the dispersion and the tollerance range, so C_p affects the value of C_{pk} but C_{pk} does not affect C_p. Differently from C_p it can be negative when the average value μ is out of Specification range.

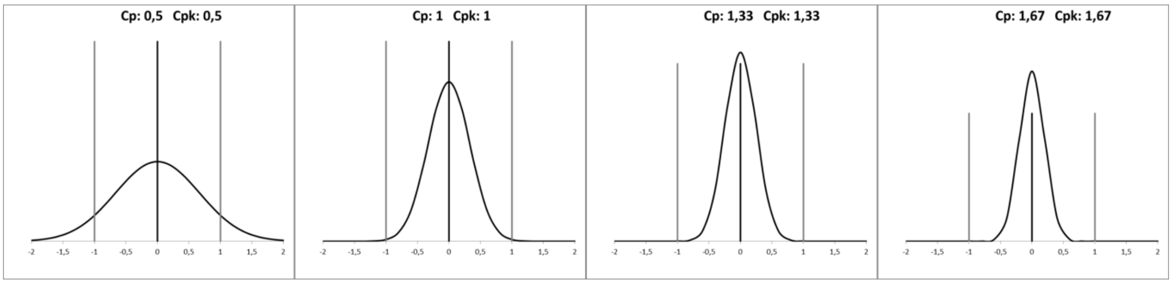
$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}\ ;\ \frac{\mu - LSL}{3\sigma}\right)$$

An high value of C_{pk} guarantees the repeatability and the precision of the process. Usually the minimum acceptable value is $C_{pk} = 1$, while the preferred is $C_{pk} = 1.33$.

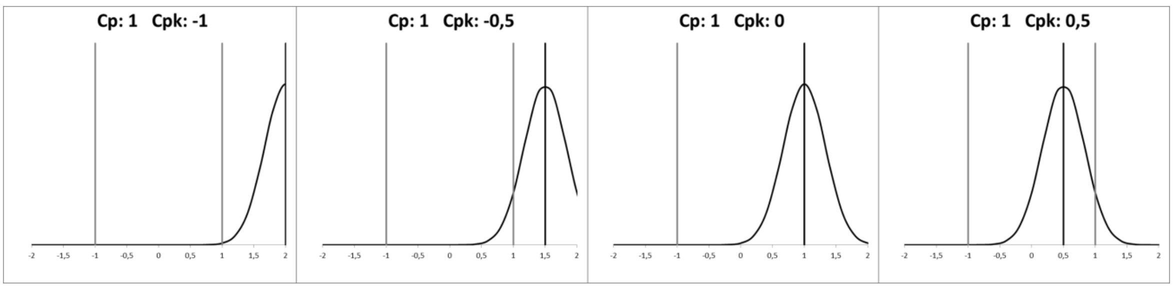
To guarantee a capable production process, C_p and C_{pk} must be monitored periodically. The frequencies of the inspection can be reduced with the increasing of C_{pk} while values too low require an analysis to evaluate whether is more costly to accept the risk of manufacturing products which not respect standards for quality, or improve the process to improve its capability.

Properties of C_p and C_{pk}

- $C_p = 1$ → 99.9% of population is able to remain within the specification range
- $C_{pk} = 1$ → 99.9% of population is within the specification range
- $C_{pk} = Cp$ → Population mean value is exately the nominal value in the middle of the specification range
- $C_{pk} = 0$ → The The population mean value is exately the USL or the LSL
- $C_{pk} < 0$ → The The population mean value is out of the Specification range
- $C_p = 1.33$ → 99.9994% of population is able to remain within the specification range
- $C_{pk} = 1.33$ → 99.9994% of population is within specification range, good process
- $C_{pk} < 1$ → The process is not capable of guaranteeing less defects than 0.1% of the population. It is required an analysis to improve process capability
- $C_{pk} > 1.67$ → percentage of measurements out of specification range is negligible so the number of inspections on the process can be reduced.



3.3.0.4 Variation of Cp with gaussian distribution



3.3.0.5 Variation of Cpk with gaussian distribution

Chapter 4 The plant and the Product

After a detailed explaination of World Class Manufacturing, with a Specific focus on the Technical Pillar of Quality Control, before entering in the matter of this Project it is useful to briefly introduce the Plant and the Product for which is performed the activity.

4.1 The Plant

Mirafiori FCA Powertrain Plant is equipped with tooling machines and automatic assembly lines built in the beginning of the '90s, to manufacture a transmission which is in the market with many variations since 1993. Internal production is divided between machining operations, Heat Treatments and assembly. For the purpose of this project it is important to mention some of the main operations during production process of principal components, which are the main shaft, the secondary shaft, and the couples of gears for each transmission speed:

- **Turning:** Starting from raw materials, this machining proces gives shape to the component on surfaces that does not require special finishing or surfaces that will require other operations.
- **Hobbing**: Machining Process for gears that removes material to generate the correct number of teeth to guarantee the selected gear ratio.
- **Shaving:** Finishing operation that determines the final shape of the teeth. The precision is high enough to permit a correct matching of the involute profiles and the helix
- **Carburization:** A Heat Treatment process of Carbon absorption for Steel, which is heated in an open chamber with a precisely monitored atmosphere rich of carbon. This operation is highly determinant on product quality as it causes deformations on finished components that does not allow a grinding operation in the following process steps.
- **Quenching:** Fast cooling of high temperature steel to avoid recrystallization of Austenitic Steel to form Martensite, increasing hardness of material. This is fundamental in case of transmission, as the gears, rotating at high speeds must withstand high stresses without deformation to avoid compromising performances.
- **Assembly:** Assembly process is characterized by a high level of automation. The main line is completely automatic, while some of the secondary lines for small assemblies still require manual operations. Automation guarantees high process capability, reduction of labour and costs of product, but also helps tracking errors when they happens. The line is full of devices called "Poka Yoke" that prevents operators working in manual stations from wrong installations, or "error proofing", usually cameras or sensors, that check the correctness of the assembly. This prevent most of the failure modes that can cause Quality Problems on the product.
- **Handling:** Performed by Automatic Guided Vehicles, shortly AGV, that automatically and safely bring components from a place to another guaranteeing the integrity of delicate parts, especially for machined pieces, that if damaged, the problem would be enhanced by heat treatment. Materials are brought in dedicated stock areas and contained in specific pallets for each component. Pallets does not allow a wrong placement and movements, helping the automatic picking of the robotized arms of automatic assembly lines and also the correct handling which prevents damages due to

contacts and unwanted movements of parts during their transportation from an area to another

4.2 The Product

The product is a manual transmission manufactured in different versions that could be grouped in 5-speed and 6-speed gearboxes. The purpose of a transmission, in a vehicle with an internal combustion engine, is to vary the ratio between the rotation speed of the vehicle wheels ω_w and the engine rotation speed at the crankshaft ω_e in order to exploit the range of maximum torque available from the Engine ad different speeds. The correlation between wheel and crankshaft rotation speeds is not direct as in vehicle also the differential has an influence on speed ratio. A gearbox is usually composed by 2 shafts. The primary or main shaft, trough the clutch, can be coupled with the crankshaft, or decoupled, according to driver action of clutch pedal. The torque is transmitted then to a secondary shaft trough a gear coupling. The ratio between the number of teeth of the coupled wheels represent the transmission ratio, which allows the secondary shaft to rotate with a different speed with respect to primary. In addition, secondary shaft is machined with a pinion, which is connected to the Crown gear of the differential. This final coupling represents another transmission ratio trough the different number of teeths of pinion with respect to differential crown wheel. To better understand the purpose of the transmission, it is useful to schematize the chain of rotating shafts and coupled toothed gears with five phases.

First, rotation speeds in different positions of the transmission chain:

- ω_e: Represents the rotation speed of the crankshaft. It is alimented by the combustion inside engine cylinders. Shape of the crankshaft exploits the alternating motion of engine pistons to rotate. Rotation speed of the engine at the crankshaft is directly controlled by the driver trough acceleration pedal, so it represents the input of the transmission chain.
- ω_p: Represents the rotation speed of the primary shaft of the transmission. It varies from zero to ω_e according to driver action on the clutch pedal, as the main shaft is directly connected to crankshaft when the clutch is engaged. It represents the input speed of the transmission.
- ω_s: Represents the rotation speed of the secondary shaft, which is related to ω_p trough the coupling of engaged gears.
- ω_d: Represents the rotation speed of the differential crown wheel, related to ω_s trough coupling with pinion machined on secondary shaft.
- ω_w: Represents the rotation speed of the wheels, directly related to ω_d trough a transmission ratio between the differential crown wheel rotation speed and the rotation speed of the semishafts.

The relations between angular speeds, called transmission ratios are the following:

$$\tau_p = \frac{\boldsymbol{\omega_p}}{\boldsymbol{\omega_e}} = 1 \; ; \qquad \tau_g = \frac{\boldsymbol{\omega_s}}{\boldsymbol{\omega_p}} = \frac{\boldsymbol{\omega_s}}{\boldsymbol{\omega_e}} \; ; \qquad \tau_d = \frac{\boldsymbol{\omega_d}}{\boldsymbol{\omega_s}} \; ; \qquad \tau_f = \frac{\boldsymbol{\omega_w}}{\boldsymbol{\omega_d}}$$

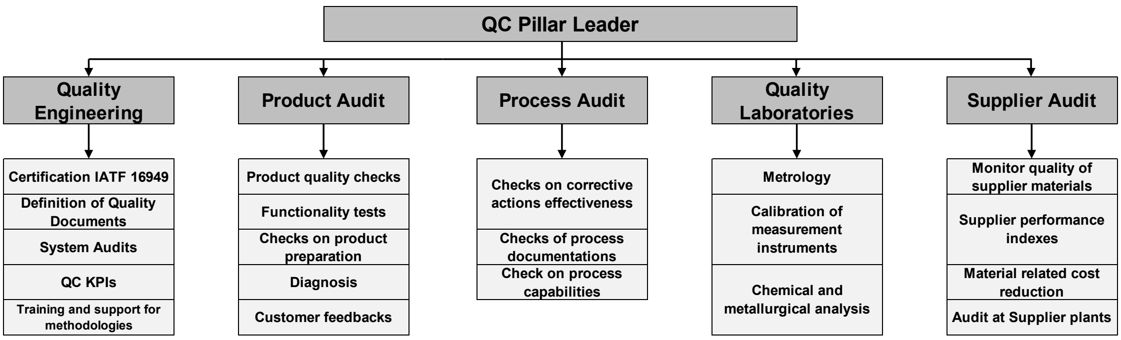
Considering the Effective Rolling radius of the wheels R_e, vehicle speed V is:

$$V = R_e \cdot \tau_f \cdot \tau_d \cdot \boldsymbol{\tau_g} \cdot \tau_p \cdot \boldsymbol{\omega_e}$$

This formula gives the correlation between the Vehicle Speed and the rotation speed of the engine. Considering The Clutch engaged and transmission ratios between secondary shaft and wheels fixed, the only variable parameter remains the Transmission ratio of the gearbox τ_g which is given by the coupling trough gears between primary and secondary shaft. An increase of the Ratio allows an increase of vehicle speed at the same engine speed. This allows to exploit engine Torque by shifting the gear and progressively increase the gearbox ratio by engaging different couples of gears, called speeds. The coupling is possible with the help of dedicated components called sleeves, that slipping along the input shaft, engage the gear selected trough the action of a selector fork, moved by Gear selector trough mechanical links. All gear wheels are always coupled, but only the couple for the selected gear is engaged to transmit torque, while the others rotate idle. The introduction of rings, called Synchronizes, having the role of intermediaire between sleeves and gears, can simplify the engagement even at high rotation speeds.

4.3 Quality Control

As stated during WCM introduction, the mission of Quality Control is to guarantee product quality and Customer Satisfaction. The entire production system is monitored for this purpose. First it is fundamental to prevent defective products from leaving the plant, so quality controls on the final product are required. Once the plant is able to detect all defects, corrective actions must be applied, in order to prevent defects. This brings to move the controls from the end of the line, directly to the station that potentially can cause a certain defect. The most robust solutions for assembly operations are "poka yoke" or "error proofing", while for what concerns machining processes, it is easier to improve machine capabilities and monitor directly the processes instead of waste a lot of money on controlling the production. The Pillar of QC is the organization that coordinates all quality-related operations, considering also quality of supplier materials and measurement laboratories and instruments. The hierarchical structure of Quality Control in FCA Mirafiori Powertrain Plant is the following:



4.3.0.1 QC hierarchic *scheme*

Controls: In Mirafiori FCA Powertrain, product quality is guarantee for all products coming out from the plant. Operational Excellence is still not reached, as internal processes are not sufficiently accurate and capable to avoid controls on production. These controls are located in different stages of the production process and can be grouped as follows:

- **Interoperational checks:** Performed in stations equipped with calibers or proper measurement instruments. Checks can be periodical, finalized to evaluate the correctness of an automatic process, or on the entire production, depending on the frequency and gravity of potential defects. All interoperational checks are regulated and defined in operational control plan, starting from the Process Failur Modes and Effect Analysis.
- **Final geometrical tests:** Performed at the end of machining process to verify the quality of gears and shafts. For transmissions, the main concern is guaranteeing a perfect coupling of gears once assembled on the input and output shafts. So the most important parameters for what concernes the shafts are the straightness, diameter and concentricity. While for gear wheels, the inner diameter, the dimensions and shape of teeth, concentricity, pitch and presence on hits on teeth surfaces.
- **Leak test:** Represents the first quality test on the final product, so the number of defective transmissions failing leak test are considered in the count of First Time Quality FTQ. This test evaluate the sealing resistence of the transmission from oil leakages. As applied to the entire production, if a transmission does not pass the test, it is required a repair, and finally a new evaluation. If the repaired transmission pass the leak test, it is considered a good product, but the repair still remains monitored for FTQ index.
- **Functionality Tests:** The entire production, after passing the Leak Test, must be tested with an advanced test bench equipped with accelerometers, capable of a deep NVH analysis. This quality test has the role of evaluating the functionality of the product which can be divided in Shiftability, noisiness, and correctness of gears ratios as required by regulations. In deeper details, test benches measure:
  - The engagement of gears
  - Time required for gear engagement
  - Effort required for gear engagement
  - Vibrations, divided between orders and spectrum in the frequency domain
  - Vibration in the time domain
  - Correctness of gear ratios

  If a transmission does not pass the Functionality test, the product is repaired and tested again considering also Leak test if some sealings were opened and substituted during repairing operations. When it succeed both quality tests, a product is considered compliant with quality standards. Number of failures at Functionality tests are monitored inside FTQ index.
- **Product preparation controls:** As the product is manufactured in many versions, control plan requires a final visive check on the final product to verify if all components are the correct ones for the order. This test is used to verify the presence of certain components and their correct assembly, but also the presence of marks required

by regulations. This represents the final step of the production process, before the shipping.

Defects: Before entering in matter of this project it is necessary to present the main defect modes for a transmission, together with the measurement system used to inspect the quality of gear wheel teeth. A part from oil leakages, which are simply caused by non-compliances of sealings, it is more interesting to focus on functionality defect modes:

- **Shiftability:** Group all problem related to gear engagement. These defect modes are mainly caused by assembly errors or macroscopic machining defects:
  - Component wrongly placed
  - Component missing
  - Wrong component assembled
  - Damages on components
  - Wrong machining operations
  - Missing machining operation

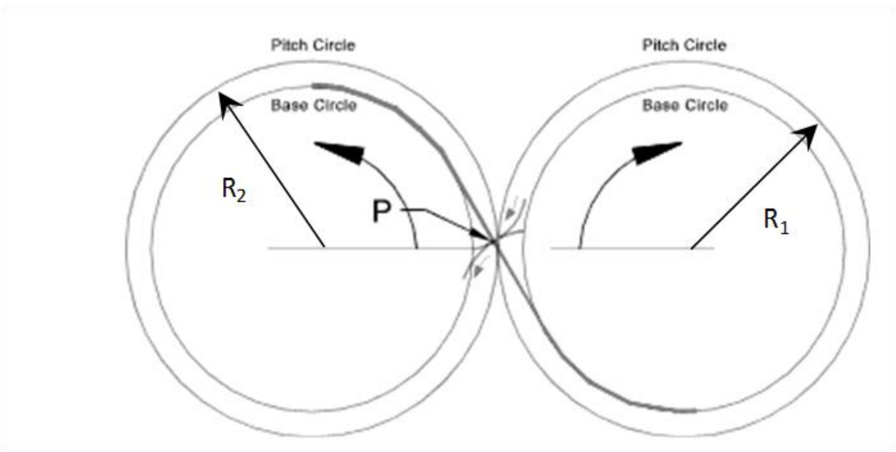
  These defects can be simply avoided by introducing in the assembly process sensors or cameras for visual checks on assemblies, to verify that all components are correctly chosen and placed, and without any damages. Some of these defect modes are evidenced during the final Functionality Test. The target is to equip the assembly lines with enough verification devices for error proofing, to stop these defects before reaching the final test bench.
- **Noisiness:** Defect modes which generate strong vibrations that can become noise once the transmission is installed on vehicle. The root cause is the profile shapes of gear teeth. Imperfections that are enhanced by high shafts rotation speed. In details, the main noise defects are the following:
  - **Teeth shape:** At high rotation speed, high precision is required to guarantee an effective contact between teeth of the engaged gear. If the roughness of the tooth surface is coarse, or the shape does not follow the ideal involute profile, the result is an increased stress on the smaller contact surface. Due to High production volumes and the high level of details, actually the only way to detect the problem is the functionality Test. The noise cause by tooth shape variations from compliance is identified trough an advanced NVH test performed starting from the input data of advanced accelerometers of the test bench. Vibration controls are in time domain, to identify periodical peaks due to singularities, while frequency domain is used to analyse the natural frequencies of the Transmission in the entire working range. This analysis can identify the couple of gear wheels defective, simplifying repairing operations.
  - **Hit on gear wheel tooth:** Damages on the surface of a tooth during machining operations or handling, usually enhanced by heat treatment. These deformations cause the reduction of the contact area between teeth of coupled wheels, up to cause a peak in time domain vibration analysis. This defect mode is intercepted at the source trough a dedicated control with a gear tester at the end of machining process. If the process results not robust enough, the advanced test benches are able to detect

the problem with a vibrational analisis in time domain, which permit also to identify the gear wheel damaged for its substitution during repairing operations.

- **Concentricity:** When shaft rotation axis and the rotation axis of a certain gear is not coincident, at high rotation speeds the transmission emit periodical high vibrations. This can be caused by non-compliances in machining operations of the internal diameter of the gear or on shaft surface destined to coupling with bearings or with gears. This defect is avoided guaranteeing an adequate capability of machining processes. The defect can also be detected during Functionality Test. Test banches are able trough measurement in time domain to identify the problem and the defective components that cause the vibration, for a fast repair of the product.
- **Distance between axes:** If primary and secundary shafts are not at correct distances or are inclined with respect to each other, the contact between teeth profiles of engaged gear is not completely correct and the result is a noise at high rotation speed. This defect is caused by wrong machining of shaft or non-compliance of transmission support, at the bearing contact area. The defect is mostly detected by test benches during the NVH frequency domain analysis.

4.4 Gear wheels

Gears are used to transmit Torque maintaining a constant speed ratio τ. This ratio is usually the design input for identifying the size, depth, number of teeth and the profile of their flanks. Considering 2 wheels in contact with a given radius R_1 and R_2 whose axis are fixed to a relative distance of $R_1 + R_2$.



4.4.0.1 Primitive diameters of coupled Gear wheels

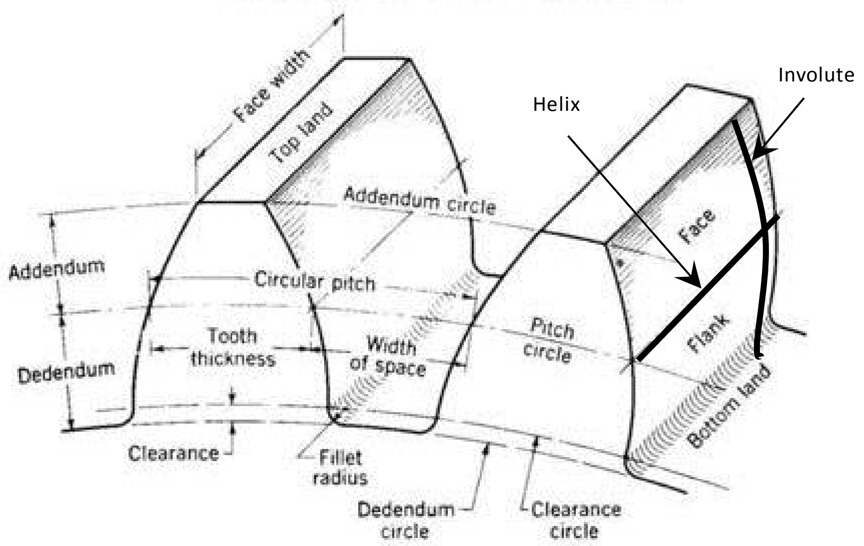
Admitting that there is no slip between the wheels, the Velocity at the point of contact P of a wheel, called driver, with radius R_1 is the same on the driven wheel with radius R_2:

$$V_P = \omega_1 R_1 = \omega_2 R_2$$

It is then possible to define the transmission ratio as:

$$\tau = \frac{\boldsymbol{\omega_2}}{\boldsymbol{\omega_1}} = \frac{\boldsymbol{R_1}}{\boldsymbol{R_2}}$$

This principle is maintained in toothed wheels if the tooth profiles are shaped as an involute. The action is the same as a cam, for each pair of mating teeth. The involute profile guarantees a proportional transmission of rotational speed from driver wheel to driven ones.



4.4.0.2 Gear Tooth profile characteristics

Before entering in matter of measurements it is useful to understand the gear wheel nomenclature and its main dimensions:

- **Pitch circle:** Ideal circumference representing the size of an equivalent ideal wheel without teeth
- **Addendum:** Radial distance between Pitch circle and Addendum circle, which represents the maximum measurable circumference of the gear wheel, corresponding to the top of 2 opposite teeth.
- **Dedendum:** Radial distance between Pitch circle and dedendum or base circle, which represents the minimum measurable circumference of the gear wheel, corresponding to the bottom of 2 opposite teeth.
- **Z:** Number of teeth
- **Circular pitch p:** Circular distance between the same point of 2 consecutive teeth, it is constant for each pair of mating gears:

$$p = \frac{2\pi R_1}{Z_1} = \frac{2\pi R_2}{Z_2}$$

Circular pitch p is also the sum of tooth thickness and with of space between consecutive teeth

- **Modulus m:** Size measured in mm, which represents the circular pitch p divided by π. It is a constant parameter for each pair of mating gears.

$$m = \frac{2R_1}{Z_1} = \frac{2R_2}{Z_2}$$

- **Gear ratio τ:** It can be defined also knowing the value of modulus m or circular pitch p:

$$\tau = \frac{\boldsymbol{\omega_2}}{\boldsymbol{\omega_1}} = \frac{\boldsymbol{R_1}}{\boldsymbol{R_2}} = \frac{\frac{mZ_1}{2}}{\frac{mZ_2}{2}} = \frac{\frac{pZ_1}{2\pi}}{\frac{pZ_2}{2\pi}} = \frac{\boldsymbol{Z_1}}{\boldsymbol{Z_2}}$$

- **Clearence:** Added through a fillet radius on the base to avoid dangerous contacts between the top of a tooth with a sharp edge in the base of the mating tooth. It defines the clearance circle.
- **Involute:** Shape of tooth flank profile. It is one of the most important parameters to be measured during gear production process, as a non-compliance on involute profile can affect the intensity of vibrations of the entire transmission.
- **Helix:** Another important parameter of gear wheels affecting noise perception on the transmission. It is defined as the shape of tooth flank in gear width direction.

Gear Measurements: When a transmission does not pass a functionality test for high vibrations evidenced by NVH analysis, the gear couple identified as defective is measured in order to better understand the problem and start an analysis to identify a countermeasure for the problem. These measurements are also used for normal production to monitor the capability of machining processes of finishing, which in the case of Mirafiori FCA Powertrain plant it is represented by a shaving operation. For these purposes, the most important parameters measured are the following:

- **Cα:** Convexity of Involute profile. If the value measured is negative, the profile is not convex but concave.
- **fHα:** Angle of involute profile, it is defined as the distance on horizontal direction between the bottom and the top of the involute, with respect to the vertical axis of the tooth. For this definition, a correct involute has always a negative value.
- **Fα:** Error on shape of the involute from the ideal one. It is an unidirectional measure, as a perfect profile corresponds to a value 0.
- **Cβ:** Convexity of Helix profile. If the value measured is negative, the profile is not convex but concave
- **fHβ:** Angle of Helix profile, it is defined as the distance on vertical direction between the two extremities of the helix.
- **Fβ:** Error on the shape of the Helix from the ideal one. It is an unidirectional measure, as a perfect profile corresponds to a value 0.
- **Fp:** Maximum error of the circular pitch p from the ideal one. From evaluating p for each couple of consecutive teeth, after a comparison with the ideal value it is chosen the Maximum error.
- **Fp:** Sum of all errors of circular pitch p evaluated for all consecutive teeth
- **Fu:** maximum circular pitch between two consecutive teeth
- **Fr:** Error of concentricity, it represents the deviation of the position of the axis from the ideal one in correspondence of each tooth, then the maximum value is chosen as a parameter.

Chapter 5 PLAN: Application of WCM methodologies for FTQ Improvement

The purpose of this project is to improve Quality inside Mirafiori FCA Powertrain plant trough a reduction of scraps and repairs, a necessary step for reaching operational excellence. In current situation,the capability of detecting defects is very high. Indicators from final customers and manufacturing clients of vehicle plants are very satisfying, the further improvement is then an increase of effectiveness with a preventive approach. Most of existing defect modes are detected at the end of the line: oil leakages are found during leak test, while shiftability and noise problems are detected by NVH analysis of test benches. To better understand the procedure and methods applied to reach the target, a theoretical introduction of WCM with a specific focus on QC pillar was necessary, together with a presentation of the production processes inside the plant, the transmission manufactured and its functioning, and the main features of gear wheels. The scheme to be followed is the Deming cycle PDCA suggested by Kaizen method. First step, Plan, which is the main part of the project, starts from the definition of the problem to its solution, passing trough all necessary analysis that will be explained in details. DO is the second step, which consist on the implementation of the solution, it follows the CHECK Step, which is essentially a monitoring period, and finally ACT step identifies the full implementation of the improvement also to similar cases. Once the problem is identified, the target is to reduce related defects of 60%.

5.1 Definition of FTQ

First Time Quality represents one of main KPIs of QC Pillar. It is an indicator that indirectly evaluates the capability of production process from the quality point of view. As already stated, FTQ represents the number of products respecting Quality Standards without requiring repairing operations in relation to the total number of products. Adapted to Mirafiori FCA Powertrain Plant, FTQ measures the quantity of transmissions that succeed Leak Test and Functionality Test. FTQ is measured only for the transmission and not for monitoring scraps of previous machining and assembly operations. It follows that knowing:

- $\boldsymbol{N_{TOT}}$**:** number of manufactured transmissions
- $\boldsymbol{n_L}$**:** number of transmissions failing leak test at the first time
- $\boldsymbol{n_F}$: number of transmissions failing Functionality test at first times

The KPI can be defined as:

$$FTQ\ [\%] = \frac{N_{TOT} - n_L - n_F}{N_{TOT}}$$

Where $N_G = N_{TOT} - n_L - n_F$ represents the number of transmissions with good quality at the first time.

For operational excellence the final target is reaching Zero defects, which means FTQ = 100%. This project instead aims to analyze and attack the main defect modes affecting FTQ index in order to start a progressive improvement of the KPI that will bring a reduction of scraps and repair costs together with an overall increase of productivity.

5.2 Identification of the problem

Before starting the analysis, it is necessary to understand the different contributions affecting FTQ index in Mirafiori FCA Powertrain Plant. The main tool is plant QA Matrix, which, as presented in chapter related to QC, is used to rate problems trough a priority index:

- ***A:* Frequency,** it is chosen an integer value from 1 to 5 to evaluate the frequency of the defect, which is more relevant more often is detected
- ***B:* Material costs,** it is chosen an integer value from 1 to 5 to evaluate the increase of material costs caused by defect
- ***C:* Labour costs,** it is chosen an integer value from 1 to 5 to evaluate the increase of material costs caused by defect
- ***D:* Detection,** concerning FTQ it is always considered a value equal to 1
- ***E:* Gravity,** it is chosen an integer value from 1 to 5 to evaluate the gravity of the problem, based on FMEA

$$PI = A \times (B + C) \times D \times E$$

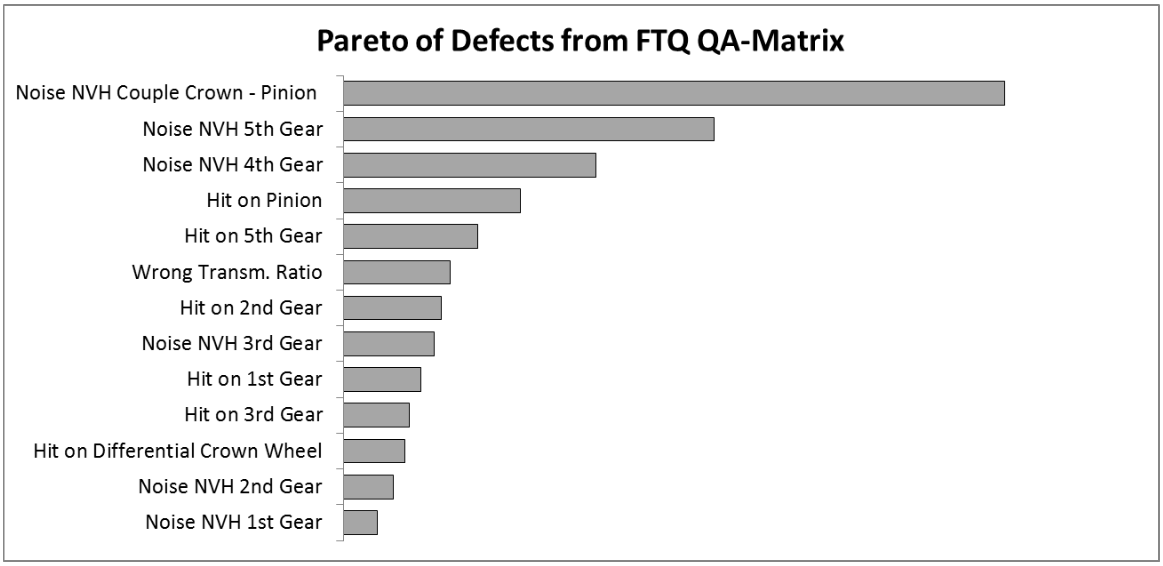
By Design, QA Matrix gives more importance to Warranty, pulls and Assys. For this reason, rows related to FTQ have a low priority index causing the risk of being mislead from chosing correctly the first problem to be analyzed.

It is useful then to elaborate already defined Priority Index by modifiyng the Detection variable, which for FTQ otherwise would remain constant and equal to 1:

- $\boldsymbol{D_{FTQ}}$ **= 5:** Problems detected trough advanced NVH analysis in frequency domain, capable of intercept all problems, but sometimes it represents a filter too restrictive. In matter of vibrations it is difficult to correlate directly amplitude and frequency with the noise that could be generated once the transmission is installed on a running vehicle. The compromise to be able of detecting all defects is to accept that in certain limit cases, test benches consider as defective good transmissions.
- $\boldsymbol{D_{FTQ}}$ **= 4:** Problem detected during leak tests. High difficulty of detection is due to severity of the test. As for functional test, it is possible that a good transmission is considered defective because of leaks in correspondence of temporary sealings applied during the test.
- $\boldsymbol{D_{FTQ}}$ **= 3:** Problem detected trough NVH analysis in time domain, characterized by the presence of some unwanted periodical peaks.
- $\boldsymbol{D_{FTQ}}$ **= 2:** Problem concerning shiftability detected during Functionality tests.
- $\boldsymbol{D_{FTQ}}$ **= 1:** Grave problem of easy detection, as the absence of a component, or a wrong assembly.

It is finally possible to define Priority Index for FTQ:

$$PI_{FTQ} = A \times (B + C) \times D_{FTQ} \times E$$



5.2.0.1 Pareto of FTQ Defects

Considering FTQ rows of Plant QA Matrix, with the new defined priority index, the top 3 defect modes are the following:

- Noise of secondary shaft pinion-differential crown wheel couple detected trough NVH
- Noise of 5th gear couple detected trough NVH
- Noise of 4th gear couple detected trough NVH

QA Matrix refined for the purpose of this project has identified the main problems related to FTQ in Mirafiori FCA Powertrain Plant. The output is reasonable, as these defects are all related to NVH analysis in frequency domain that could cause the so called "False scrap": in order to filter all noise problems, sometimes it considers certain vibrations as noise when following repairing operations does not confirm non-compliances of components. A part from this aspect, these noise related defect modes have also a relevant frequency, as they are caused by imperfections undetectable to human eyes on teeth profiles and measurements are not possible for the entire productive volume. To conclude the verification of the correctness of this rank, the top defect has also an high value for Labour costs, as its repairing require the time to substitute the secondary shaft and of the differential crown wheel, requiring also the complete reassembly of these two modules.

5.3 5W1H

WCM states that every problem must be considered, so the standard Kaizen procedure should be followed for each line of the QA Matrix starting from the first one. In addition, considering that the top problems are of the same nature, it is useful to develop parallel analysis at the same time, to exploit eventual correlations to reduce time required for identifying effective countermeasures.

For each of analyzed defects, the first step is to find an answer to the following question:

- **What?**
  - What is the problem?
  - On what component was it detected?

- **When?**
  - When was the problem detected?
  - When was it generated? day, shift and hour
- **Where?**
  - Where was the problem detected?
  - Where was the problem generated? In which station?
- **Who?**
  - Who detected the problem?
  - Who generated the problem?
- **Which?**
  - Which is the number of defects caused by the problem?
  - Is the number of defects increasing?
- **How?**
  - How is the component with the defect?
  - Equipment, machines, tools and measurement instruments were working correctly?

As these problems were already be analyzed with a Standard Kaizen, the resolution requires a stronger procedure. To answer to 5W1H questions correctly it was introduced a new method of tracking defects, the fast-response Showcase.

5.3.1 Fast-response Showcase

Measurements of gear teeth profiles and NVH analysis post Test Bench evaluations require a lot of time. With high production volumes, the low percentage of defective transmissions represents still a number too high for considering 100% of scraps for the analysis. It is necessary to select most significant cases among the scraps, according to the Top results of FTQ QA Matrix. A Showcase, together with a summary board, was introduced for the purpose of collecting for further analysis the defective components chosen from selected transmissions, among the ones that failed functionality tests for the three main defect modes. To better explain the importance of this tool, here follows the procedure to be iterated each day in order to gather information about number of defects and their potential root cause:

1. Test benches discard daily a certain number of transmissions
2. NVH Specialist selects from test bennches output databases, a defined number of significant transmissions, following both the priority given by FTQ QA Matrix and the effective defects detected by test benches during the day
3. These selected transmissions are immediately repaired, and identified defective components are brought to the showcase, instead of being scrapped as done following the standard procedure.
4. Once defective components are placed on the showcase, the operator fill in the summary board with the following informations:
   a. What is the problem
   b. What is the component on which the problem was detected
   c. When the problem was detected
   d. Where the problem was detected
   e. Who detected the problem

f. Number of defects caused by the problem
g. Tell If the number of defects increasing

5. Once a day, all components present on the showcase are taken by the corresponding team leaders of machining operations. The hierarchical structure of machining shop include for each component at least one expert technician, whose role will be to understand the component history in order to obtain the following informations and add them to the summary board:
   a. When the problem was generated, day, shift and hour
   b. In which station the problem was generated
   c. Who generated the problem
   d. Tell if Equipment, machines, tools and measurement instruments were working correctly
6. Defective components taken from the Showcase are analyzed with dedicated instruments capable of measuring teeth profiles of gear wheels with a precision of a tenth of micron. The output of the analysis is, for each wheel, a standard set of values for following parameters:
   a. $C\alpha$: Convexity of Involute
   b. $fH\alpha$: Angle of involute
   c. $F\alpha$: Shape of involute
   d. $C\beta$: Convexity of helix
   e. $fH\beta$: Angle of helix
   f. $F\beta$: Shape of helix
   g. fp: Maximum error on p, circular pitch
   h. fu: Maximum value of p, circular pitch
   i. Fp: Sum of errors on p, circular pitch
   j. Fr: Maximum error on Concentricity

   This analysis leads to answers to the last questions:
   a. How is the component with the problem
7. Final step of the standard daily procedure of Fast-response Showcase is to gather all data available for every single problem listed on the summary table, in order to identify the final correct answers for the 5W1H questions. In addition, the main contribution to the project is given by the values measured for the defective components, which are added to a database for a further statistical analysis.

The idea of introducing a fast-response Showcase helped the data gathering for defective components related to the three main FTQ problems. Previously, these analysis were performed for single cases independently, using a method not capable of leading to robust and long lasting solutions. This tool also helps to find the real answers to 5W1H questions, allowing to define correctly the problem, which is necessary in order to proceed in the correct direction toward the solution.

Shape of components and data avaliable for problem related to Noise of 4th gear couple detected trough NVH, 3rd main defect mode are similar to the ones for 5th gear couple. The project will be focused only on the first two elements of FTQ QA Matrix:

- Noise of secondary shaft pinion - differential crown wheel couple detected trough NVH
- Noise of 5th gear couple detected trough NVH

Starting from Fast-response Showcase output, it follows a preliminary answer to 5W1H for both problems.

5.3.2 5W1H Crown wheel – Pinion couple

The first one related to coupling of secundary shaft pinion and crown wheel can be divided, as it is generated by two independent and separate conditions:

- Noise is detected because of teeth profile shapes of pinion
- Noise is detected because of teeth profile shapes of crown wheel

After gathering data, it is useful to inspect the results obtained from the 5W1H questions, which are presented in a standard table format for both mentioned cases:

Noise of secondary shaft pinion and differential crown wheel couple detected trough NVH		
5W1H		
What	**What is the problem?**	Transmission n: ($t_1,t_2,t_3,\dots,t_N$) failed functionality test. Excessive Noise detected trough NVH analyis on Differential crown wheel and pinion coupling
	On what component was it detected?	Differential Crown Wheel
When	**When was the problem detected?**	dd/mm/yyyy during shaft X at hh:mm during Functionality Test (for each t_i)
	When was it generated? day, shift and hour	(dd/mm/yyyy during shaft X at hh:mm) of grinding operation (for each defective transmission t_i) ; Defects are generated when the machining tool is worn
Where	**Where was the problem detected?**	Functionality Test Bench n. X, on NVH curves relative to Analysis of the Orders of Final reduction ratios
	Where was the problem generated? In which station?	In station X during Grinding operations
Who	**Who detected the problem?**	Worker responsible of Functionality Test Bench, test is 100% automatic, operators have no influence on detection of the defect
	Who generated the problem?	Workers responsible of grinding machines, adequately trained to follow standard procedures
Which	**Which is the number of defects caused by the problem?**	N, depending on the number of crown wheels machined before restoring the grinding tool
	Is the number of defects increasing?	No, production process is precise and not changing over time, only variable is the wear of grinding tools
How	**How is the component with the defect?**	Crown teeth profiles have a wrong shape, repeated for all teeth of the wheel
	Equipment, machines, tools and measurement instruments were working correctly?	Grinding tool is worn

5.3.2.1 5W1H Defective Crown wheel

When the defective component is the crown wheel, the resolution of the problem is simple because of the high reliability and capability of grinding process. The answers to 5W1H are complete and correct. At this stage, the issue is defined and it is possible to follow the procedure of a Quick Kaizen to identify a countermeasure for this defect mode characterized by tooth profiles of consecutive crown wheels having a non-compliant shape which repeat itself for all machined teeth.

Noise of secondary shaft pinion and differential crown wheel couple detected trough NVH		
5W1H		
What	**What is the problem?**	Transmission n: (t_1,t_2,t_3,…,t_N) failed functionality test. Excessive Noise detected trough NVH analyis on Differential crown wheel and pinion coupling
	On what component was it detected?	Pinion of secondary shaft
When	**When was the problem detected?**	dd/mm/yyyy during shaft X at hh:mm during Functionality Test (for each t_i)
	When was it generated? day, shift and hour	(dd/mm/yyyy during shaft X at hh:mm) identified for: begin of shaving operations, begin of heat treatment, end of eat treatment (for each defective transmission t_i) ; Defects can be generated during normal production process, not requiring a special condition
Where	**Where was the problem detected?**	Functionality Test Bench n. X, on NVH curves relative to Analysis of the Orders of Final reduction ratios
	Where was the problem generated? In which station?	In station X during Shaving operations / In Station Y during Heat Treatment
Who	**Who detected the problem?**	Worker responsible of Functionality Test Bench, test is 100% automatic, operators have no influence on detection of the defect
	Who generated the problem?	Workers responsible of shaving machine / responsible of Heat Treatment operations, well trained to follow standard procedures
Which	**Which is the number of defects caused by the problem?**	N, each case is a singularity as same NVH noise problem can be caused by different parameters out of compliance range
	Is the number of defects increasing?	No, production process is stable but not 100% effective, defects have a random cadency not changing over time
How	**How is the component with the defect?**	Pinion teeth are not regular, measurements on involute, helix, Some of measured pinion teeth evidence values out of compliance range for involute, helix, circular pitch, concentricity.
	Equipment, machines, tools and measurement instruments were working correctly?	Heat treatment is OK, but thermal process introduces high randomic variations on teeth profiles. Up to hobbing op. machines are OK. Cutting tool of shaving machines is OK. But shaving machines have non compliances on backlash of bearings keeping position and direction of rotating

5.3.2.2 5W1H Defective Pinion

Considering the case of a defective pinion, the task is harder as the root cause is unknown at this stage, and also first answers found for 5W1H are not unique. It is possible to draw following considerations:

- The problem is always detected during Functional test, when automatic NVH analysis evaluate noise related to final reduction for all gear ratios.

- Noise is caused by imperfection on teeth profiles of pinions. These imperfections are not regular as the ones after grinding operation for the following reasons:
  - Grinding finishing operation is performed after heat treatment, not available for pinions.
  - Shaving finishing operation, required for pinions, is performed before heat treatment
  - Shaving has a lower level of precision than grinding.
  - Heat treatments after shaving operations cause uncontrollable randomic deformations on teeth profiles. If a tooth profile is already non-compliant after shaving finishing, heat treatments have always a worsening effect.
- Defects are not caused by special situations as machine setups, breakdowns, change of shift, distraction of operators, wear of shaving tools. The problem can be generated randomly during regular production.
- Defects can be caused both by a shaved out of compliance tooth profile, or by a worsening effect of tooth profile due to heat treatments.
- Measurements on defective pinions reveal that Noise cannot be correlated to a parameter out of tollerances. Noise root cause requires a deeper analysis.

Before starting 4M analysis it is required a detailed analysis of the production to better understand the correlation of noise, with pinion tooth profile shapes and relative measured values.

5.3.2 5W1H 5th gear wheels

Noise of 5th gear couple detected trough NVH		
5W1H		
What	What is the problem?	Transmission n: $(t_1,t_2,t_3,\dots,t_N)$ failed functionality test. Excessive Noise detected trough NVH analyis on 5th Gears coupling
	On what component was it detected?	5th Gear Driver wheel / 5th Gear Driven wheel
When	When was the problem detected?	dd/mm/yyyy during shaft X at hh:mm during Functionality Test (for each t_i)
	When was it generated? day, shift and hour	(dd/mm/yyyy during shaft X at hh:mm) identified for: begin of shaving operations, begin of heat treatment, end of eat treatment (for each defective transmission t_i) ; Defects can be generated during normal production process, not requiring a special condition
Where	Where was the problem detected?	Functionality Test Bench n. X, on NVH curves relative to Analysisof 5th Gear transmission ratio Order
	Where was the problem generated? In which station?	In station X during Shaving operations / In Station Y during Heat Treatment
Who	Who detected the problem?	Worker responsible of Functionality Test Bench, test is 100% automatic, operators have no influence on detection of the defect
	Who generated the problem?	Workers responsible of shaving machine / responsible of Heat Treatment operations, well trained to follow standard procedures

Noise of 5th gear couple detected trough NVH		
5W1H		
Which	Which is the number of defects caused by the problem?	N, each case is a singularity as same NVH noise problem can be caused by different parameters out of compliance range
	Is the number of defects increasing?	No, production process is stable but not 100% effective, defects have a random cadency not changing over time
How	How is the component with the defect?	Teeth of 5th Gear wheels are not regular, measurements on involute and helix evidence values out of compliance range.
	Equipment, machines, tools and measurement instruments were working correctly?	Heat treatment is OK, but thermal process introduces high randomic variations on teeth profiles. Up to hobbing op. machines are OK. Shaving machines are OK.

5.3.3.1 5W1H Defective 5th Gear wheels

It is possible to proceed in parallel with the second main problem related to FTQ, as Noise detected by Test Benches with an NVH analysis can be considered similar even with different components and transmission ratios. In particular, production process of 5th gear wheels is identical to pinions on secondary shaft. First step of the analysis is to find an answer to 5W1H, drawing following considerations:

- The problem is always detected during Functional test, when automatic NVH analysis evaluate noise related to final reduction for all gear ratios. As for pinions.
- Noise is caused by imperfection on teeth profiles of 5th gear wheels, both driven and driver wheels. These imperfections are not regular as the ones after grinding operation for the following reasons:
  - Grinding finishing operation is performed after heat treatment, not available for 5th gear wheels. As for pinions.
  - Shaving finishing operation, required for 5th gear wheels, is performed before heat treatment
  - Shaving has a lower level of precision than grinding. As for pinions.
  - Heat treatments after shaving operations cause uncontrollable randomic deformations on teeth profiles. If a tooth profile is already non-compliant after shaving finishing, heat treatments have always a worsening effect. As for pinions.
- Defects are not caused by special situations as machine setups, breakdowns, change of shift, distraction of operators, wear of shaving tools. The problem can be generated randomly during regular production. As for pinions.
- Defects can be caused both by a shaved out of compliance tooth profile, or by a worsening effect of tooth profile due to heat treatments. As for pinions.
- Measurements on defective 5th gear wheels reveal that Noise cannot be correlated to a parameter out of tollerances. Noise root cause requires a deeper analysis. As for pinions.

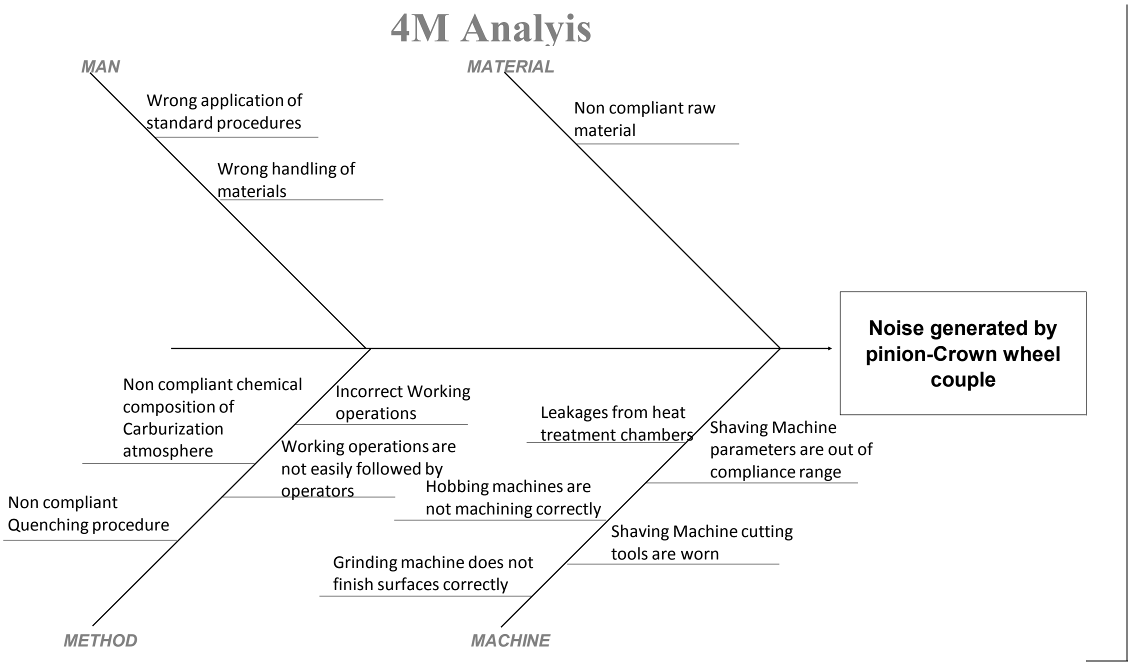
Main part of the Analysis will focus on Pinions, than, the same method will be applied for 5th gear wheels.

5.4 4M Analysis

Next step is represented by an accurate 4M Analysis, it will follow a specific Design of Experiments to understand the phenomenon and potential correlations between noise, measured microgeometrical parameters on teeth profiles, and effective capacity of production process.

5.4.1 4M Analyis Crown Wheel – Pinion couple

After defining the problem it is useful to understand the potential causes to reach the root. If a countermeasure is applied to an intermediate cause, the problem can reappear, as the real source was not identified. The most useful WCM tool for this purpose is the 4M analysis, which helps identifying the nature of a problem distinguishing it in four classes: Man, Material, Method, Machine. First it is necessary to consider all possibilities, even the most unlikely, and list them in the Ishikawa diagram ,which represents simply a visual relation between causes and effect, in this case, the Noise detected on pinion-crown wheel couple. As anticipated before, this problem must be split as the causes are different according to the non-compliant component of the gear couple. For a better explaination, it is anyway useful to follow the mental procedure and consider for now the problem as a whole, with an Ishikawa diagram containing all potential root causes.

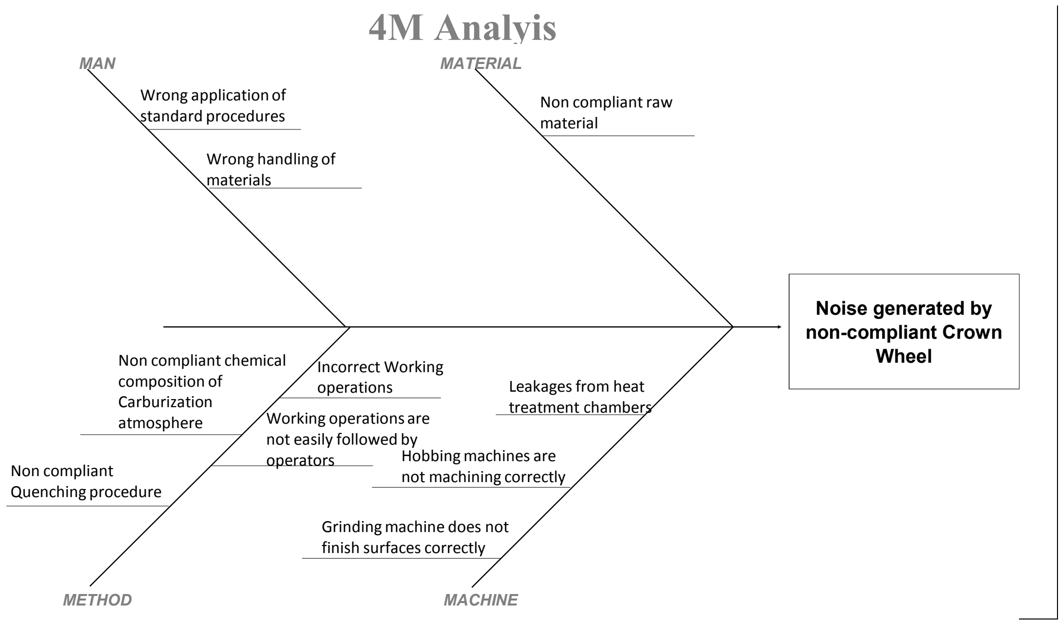


5.4.1.1 Ishikawa diagram for Crown wheel – Pinion couple 4M Analysis

Present Ishikawa diagram is complex, and this could mislead to a wrong solution, it is useful then to split in two, considering the wrong shape of crown wheel, and wrong shape of pinion as two different problems both related to Noise generated by their coupling.

5.4.2 Standard Kaizen for defective Crown wheels

Plan - 4M Analysis: The Ishikawa diagram for Non-compliant Crown wheel is much simpler than the previous one.



5.4.2.1 Ishikawa diagram for defective Crown wheel 4M Analysis

Before proceeding it is necessary to check all possibilities to understand if some of them have the expected influence on the problem or if they are wrong intuitions. If the procedure does not lead to results, it is required to reiterate this preliminary analysis in deeper details. In this case:

- **Man:**
  - **Wrong Application of standard procedures:** The entire production process of differential crown wheel has been analyzed proceeding backwards, but all operations are performed correctly by operators, which are well trained and capable of conducing machines. For this component, all operations are automatic and operators does not influence directly product quality. This cannot be a cause of the problem.
  - **Wrong handling of materials:** The process is automatic and defects are not linked to potential damages due to a wrong handling. This cannot be a cause of the problem.
- **Material:**
  - **Non-compliant raw material:** Defective crown wheels were measured to evaluate the chemical composition, the material was compliant. These checks are also performed periodically for each new stock of raw material entering the company, to inspects its quality and compliance. This cannot be a cause of the problem.
- **Method:**
  - **Non-compliant chemical composition of carburization atmosphere:** Standards are followed for the entire heat treatment process. However, technology applied for the process cannot guarantee to gears a tooth surface finishing with the same precision of a grinding operation. The heat process causes deformations and in general a

worsening of surface roughness. This problem cannot influence surface finishing as crown wheels have a finishing grinding operation after heat treatment. This cannot be a cause of the problem.

- **Non-compliant quenching procedure:** Procedure has been analyzed and proven correct. In addition, as said for carburization atmosphere, heat treatment does not influence crown wheel teeth surface finishing, as the final step of production process is a grinding operation. This cannot be a cause of the problem.
- **Incorrect working operations:** All steps of production process have been analyzed, but without finding anything wrong. This cannot be a cause of the problem.
- **Working operations are not easily followed by operators:** Process is automated and operators have only a marginal influence on product quality. Operators conducing the machines have been interviewed to verify their knowledge about procedures and they didn't lament some difficulties or incomprehensions. This cannot be a cause of the problem.

- **Machine:**
  - **Leakages from heat treatment chambers:** Entire heat treatment process has been verified. All ovens result compliant with standards. Although, a low performance is accepted as the process cannot guarantee an high precision on surface finishing. However, as already stated, grinding operations are performed after heat treatment, so it does not influence the product finishing. This cannot be a cause of the problem.
  - **Hobbing machines are not machining correctly:** Machines parameters were checked resulting compliant. In addition, periodical measurement are taken from daily normal production, and process results capable. In addition, finishing of teeth surface is entirely related to performances of grinding operations. This cannot be a cause of the problem.
  - **Grinding machine does not finish surfaces correctly:** The defect consists on a wrong shape of finished tooth profiles of grinded crown wheels. This wrong shape is repeated with high precision for all teeth of the wheel. This means that the capability of grinding operation remain adequate, but there is something wrong with the surface finishing. **This can be a cause of the problem.**

5 WHYS: The potential Machine cause of the problem has been easily identified with the Ishikawa diagram. Before applying the 7 steps for quality maintenance it is useful to question this preliminary answer in order to find the true root cause:

Differential crown wheel teeth shape is non-compliant

WHY?

Grinding machine does not finish surfaces correctly

WHY?

Grindstone is excessively stressed during machining cycle

WHY?

Excessive Transversal *Displacement/round for given rounds/working cycle*

Do: Solution

Revision of working cycle with the following modifications:

- First step, grindstone rotation speed increased + reduction of transversal displacement. Purpose of the first step is to uniform the profiles of all teeth from macro errors result of previous operations. Modifications soften the sollecitations on grindstone by increasing the number of rounds per working cycle and reducing de transversal displacement per round. By doing so, the total displacement is kept constant, as the cycle time. Stress passes from the grindstone to the rotation axis, as the rotation speed increases.
- Second step, grindstone rotation speed increased + reduction of transversal displacement. Purpose of this step is material removal from teeth profiles, it represents the most stressful phase of the working cycle, so the modification, identical to the previous one, aims to move sollecitations from grindstone to machine attachments. Increase rotation speed can cause small oscillation problems on profiles, but at this stage this is not determinant, as the machine is working for removing material and not for the final finishing of the profile
- Third step, Rotation speed mantained + Reduction of transversal displacement. This final step is the one that determines the final finishing on profile surface. For this reason, an increse of rotation speed would worsen profile quality, while a reduction of displacement guarantees a reduction of sollecitations to grindstone, and so better performances of the tool.
- In addition, it was reduced the number of components machined with a grindstone before its sharpening cycle, in order to avoid the possibility of low quality for last components machined with a grindstone.

Application of 7 steps of Quality Maintenance: In this case, machines were purchased with their X-Matrix and QM-Matrix. Machine parameters affecting defect modes were checked resulting compliant with standards, confirming effectiveness of Preventive Maintenance cycles. In this case the root cause was a setting of the machine. The solution was found easily with the intervention of an expert technician. This new setting was added to machine parameters to be verified on the X-Matrix and to Preventive Maintenance cycles suggested by QM Matrix.

Check: 5QFZD: At the end, to verify the effectiveness of the solution, five questions for zero defects must be evaluated, answering to standard form related to machine problems:

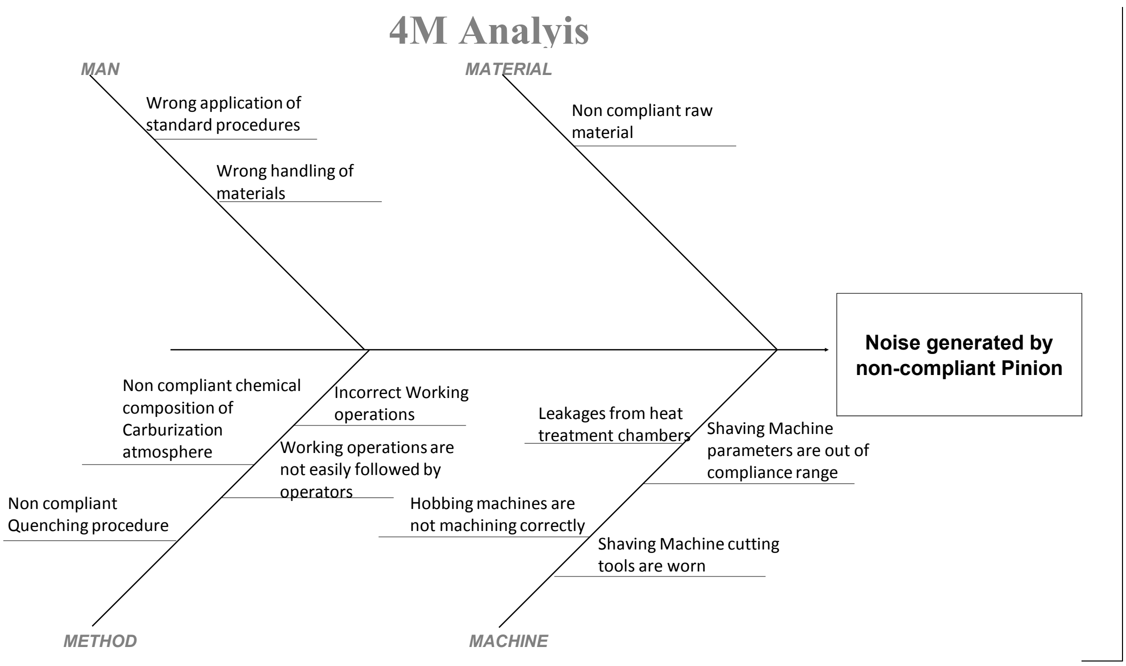
#	Machine	ANSWER		
		1	3	5
1	Are the settings defined?	The settings are defined and shared.	A method to check the settings is defined.	The settings are easy to see without special access or tools.
2	Is the machine easy to adjust to return to specified settings?	Difficult to adjust/set.	Easy to adjust/set.	Adjustment is automatic.
3	Are the equipment outputs varying outside the specification range?	During operation.	Only at set-up.	Varies only by exception.
4	Is the equipment variation of output detectable?	Low probability of seeing it.	The periodic inspection system is able to detect the variation.	Continuous monitoring ensuring immediate alert.
5	Is it easy to bring the equipment output back into specification?	Difficult, requiring specialized technical skills and high downtime.	Easy, once a person is qualified	Automatic adjustment (closed loop)

5.4.2.2 5QFZD for defective Crown wheel

The implemented solution gives satisfying results, the countermeasure is robust and if working conditions are monitored as planned the defect cannot be generated. The problem can be considered solved and ready to enter the final Act step of PDCA.

5.4.3 Major Kaizen for defective secondary shaft Pinions

4M Analysis: The Ishikawa diagram for Non-compliant pinions is extracted from the first one showed. It is similar to the one for non-compliant crown wheels, but involved processes cannot be considered the same, as involved machines are different, especially the finishing operations. In fact, shape of secondary shaft does not allow a grinding operation after heat treatment, the only solution for teeth surface finishing is a shaving operation before heat treatment. Here follows the Ishikawa diagram:



5.4.3.1 Ishikawa diagram for defective Pinion 4M Analysis

Before proceeding it is again necessary to check all possibilities, even if most of them look identical to previous case. If the result is not unique, the solution will not be easy to find or to implement.
In this case:

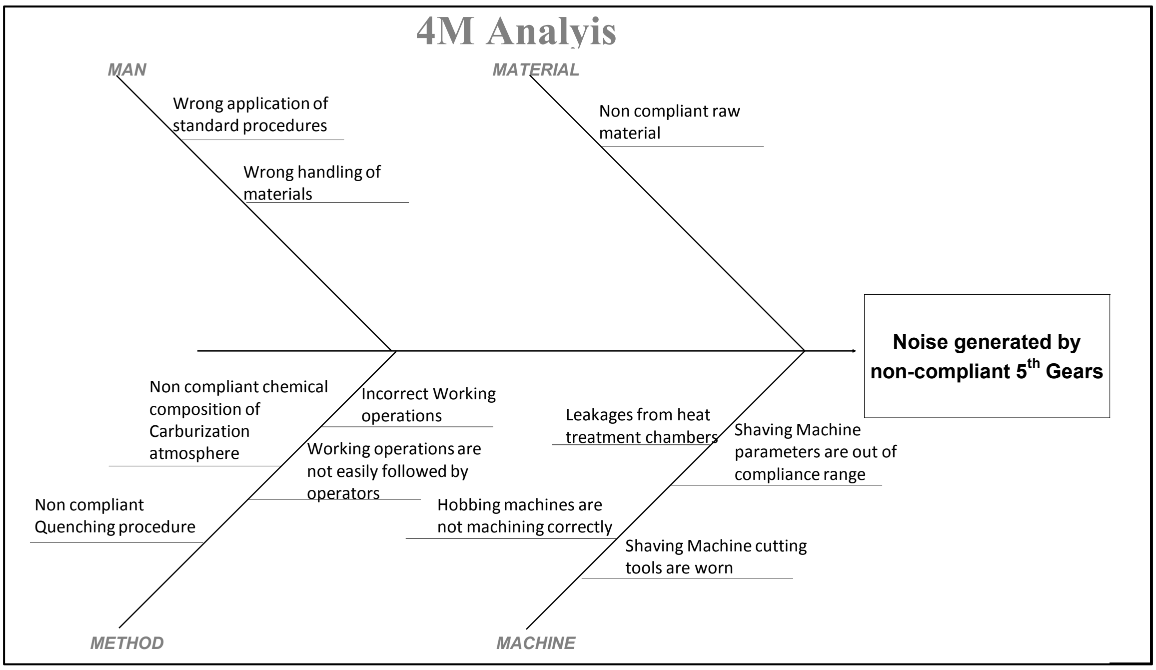
- **Man:**
  - **Wrong Application of standard procedures:** The entire production process of secondary shaft with a particular focus to its pinion, has been analyzed proceeding backwards, but all operations are performed correctly by operators, which are well trained and capable of conducing machines. Also for this component, all operations are automatic and operators does not influence directly product quality. This cannot be a cause of the problem.
  - **Wrong handling of materials:** The process is automatic and defects are not linked to potential damages due to a wrong handling. The defect mode related to handling, in general to damages to tooth surfaces is called "hit" and it is characterized by a periodical resonance. Nothing related to Noise detected with analysis in frequency domain. This cannot be a cause of the problem.
- **Material:**
  - **Non-compliant raw material:** Defective pinions were measured to evaluate the chemical composition, the material was compliant. These checks are also performed periodically for each new stock of raw material entering the company, to inspects its quality and compliance. This cannot be a cause of the problem.
- **Method:**
  - **Non-compliant chemical composition of carburization atmosphere:** Standards are followed for the entire heat treatment process. However, technology applied for the process cannot guarantee to gears a tooth surface finishing with the same precision of a grinding operation. The heat process causes deformations and in general a worsening of surface roughness. **Even if standards are satisfied, for certain worst case conditions this could be a cause of the problem.**
  - **Non-compliant quenching procedure:** Procedure has been analyzed and proven correct. However, as the process technology is old, as said for carburization atmosphere, **method of heat treatment could be , for certain worst case conditions, a couse of the problem.**
  - **Incorrect working operations:** All steps of production process have been analyzed, but without finding anything wrong. This cannot be a cause of the problem.
  - **Working operations are not easily followed by operators:** Process is automated and operators have only a marginal influence on product quality. Operators conducing the machines have been interviewed to verify their knowledge about procedures and they didn't lament some difficulties or incomprehensions. This cannot be a cause of the problem.
- **Machine:**
  - **Leakages from heat treatment chambers:** Entire heat treatment process has been verified. All ovens result compliant with standards. Although, a low performance is accepted as the process cannot guarantee an high precision on surface finishing. **This could be a cause of the problem.**

- **Hobbing machines are not machining correctly:** Machines parameters were checked resulting compliant. In addition, periodical measurement are taken from daily normal production, and process results capable.This cannot be a cause of the problem.
- **Shaving machine parameters are out of compliance range:** Machines were checked, and some rotation axis have an higher backlash. This is not a problem common to all machines who presented the defect. **This could be a cause of the problem.**
- **Shaving machine cutting tools are worn:** Cutting tools are periodically reworked and after their standard working life subsitituted. Defects are generated during normal production, wear cannot be a root cause but an influencing factor. **This could be a cause of the problem.**

The output of the 4M analysis for non-compliant pinions is not satisfactory, as it leads to several potential causes, without guiding to a single and efficient direction. It is then required a further analysis of the defect mode and its potential causes. This project will focus on Machine related causes, as improvements on Heat Treatment are expensives, as the method is already refined at maximum of its possibilities, and important investments are necessary for further improvements. Before proceeding with the Kaizen schedule, for this problem it is required a deep defect mode analysis, and the design of a set of experiments to better understand the phenomenon.

5.4.4 Major Kaizen for defective 5th gear wheels

4M Analysis: The problem of Noise identified for 5th gear by Test Benches is similar to the one related to Pinion non Compliances. It is then possible to solve in parallel both problems. Before entering in matter of Experiments, it is necessary to perform 4M Analysis also for these defects.



5.4.4.1 Ishikawa diagram for defective 5th gear wheels 4M Analysis

It is necessary again to check all possibilities, even if production process of 5th gear wheels, both driven and driver, is identical to production process of pinions. If the result is not unique, the solution will not be easy to find or to implement, as already stated for pinions. In this case:

- **Man:**
  - **Wrong Application of standard procedures:** The entire production process of both 5th gear wheels, has been analyzed proceeding backwards, but all operations are performed correctly by operators, which are well trained and capable of conducing machines. Also for this component, all operations are automatic and operators does not influence directly product quality. This cannot be a cause of the problem. Same results obtained for pinions.
  - **Wrong handling of materials:** The process is automatic and defects are not linked to potential damages due to a wrong handling. The defect mode related to handling, in general to damages to tooth surfaces is called "hit" and it is characterized by a periodical resonance. Nothing related to Noise detected with analysis in frequency domain. This cannot be a cause of the problem. Same results obtained for pinions.
- **Material:**
  - **Non-compliant raw material:** Defective 5th gear wheels were measured to evaluate the chemical composition, the material was compliant. These checks are also performed periodically for each new stock of raw material entering the company, to inspects its quality and compliance. This cannot be a cause of the problem. Same results obtained for pinions.
- **Method:**
  - **Non-compliant chemical composition of carburization atmosphere:** Standards are followed for the entire heat treatment process. However, technology applied for the process cannot guarantee to gears a tooth surface finishing with the same precision of a grinding operation. As for pinions, production process does not include grinding after heat treatment. The heat process causes deformations and in general a worsening of surface roughness. Same results obtained for pinions. **Even if standards are satisfied, for certain worst case conditions this could be a cause of the problem.**
  - **Non-compliant quenching procedure:** Procedure has been analyzed and proven correct. However, as the process technology is old, as said for carburization atmosphere, **method of heat treatment could be , for certain worst case conditions, a couse of the problem.**
  - **Incorrect working operations:** All steps of production process have been analyzed, but without finding anything wrong. This cannot be a cause of the problem. Same results obtained for pinions.
  - **Working operations are not easily followed by operators:** Process is automated and operators have only a marginal influence on product quality. Operators conducing the machines have been interviewed to verify their knowledge about procedures and they didn't lament some difficulties or incomprehensions. This cannot be a cause of the problem. Same results obtained for pinions.

- **Machine:**
  - **Leakages from heat treatment chambers:** Entire heat treatment process has been verified. All ovens result compliant with standards. Although, a low performance is accepted as the process cannot guarantee an high precision on surface finishing. Same results obtained for pinions. **This could be a cause of the problem.**
  - **Hobbing machines are not machining correctly:** Machines parameters were checked resulting compliant. In addition, periodical measurement are taken from daily normal production, and process results capable.This cannot be a cause of the problem. Same results obtained for pinions.
  - **Shaving machine parameters are out of compliance range:** Machines were checked, resulting compliant for all machine parameters. This cannot be a cause of the problem.
  - **Shaving machine cutting tools are worn:** Cutting tools are periodically reworked and after their standard working life subsitituted. Defects are generated during normal production, wear cannot be a root cause but an influencing factor. **This could be a cause of the problem.**

The output of the 4M analysis for non-compliant 5th gear wheels, as for pinions, is not satisfactory. This project will focus on Pinions, as it is the most important defect influencing FTQ, afterwards, methodologies applied to Pinions will be adopted also for 5th gear wheels, to evaluate equivalences and differences among components and root causes.

5.5 Design of Experiments for Defective Pinions

The problem is defined and the causes are associated to pinion teeth finishing and on the following heat treatment. In order to find a solution it is first necessary to understand better the defects, entering in matter of geometrical measures of teeth profiles. It is necessary first to introduce the relation between the compliance of components and the ability of test benches to detect the defects. To guarantee Product Quality, test benches discard all defects plus a part of good products, “false scraps”. Components can be divided in:

- **Compliant:** Respect the standards, all measured geometrical parameter of teeth profiles are within compliance ranges and test benches.
- **Non-Compliant:** Component non respecting standards. These product are defective and does not guarantee product quality. Test benches must detect them by discarding transmissions on which they are mounted.
- **New Standard:** Target of this project is to propose a new tollerance Range from experimental and statistical analysis on product quality starting from teeth profiles microgeometry measures taken from both good products and defective ones.

FTQ is directly related to defective non-compliant components, but also to the small portion of “false scraps” among all components which are compliant but discarded by mistake during functionality tests. The best way to improve FTQ is to question existing tollerancies, starting from effective measures on products manifactured, and consider only the more restrictive standards.

The analysis starts from the evaluation of all measures gathered with the fast-response showcase, considering only the strict standard tollerance ranges, with the target of identifying the most influencing parameters. This new standard has been identified considering values taken from two populations:

- False scrap emerged from Fast-response showcase measures
- Good products correctly evaluated by Functionality Test benches

The scope of this New Standard is limited only on Production and FTQ improvement, for this reason, it is not requested an intervention of Product Engineering. The target is to set a more restrictive selection during manufacturing process in order to reduce the percentage of defects and false scraps, by improving overall production process capability. The reason why it is easier to introduce new restrictions on products instead of simply adjusting Test Benches evaluations in matter of false scrap is that, by doing this, the risk of reducing the detection efficiency of Functionality Tests increases. The best way is then improve product quality, to avoid problems at the end of the line during Test Benches. The analysis advances with a comparison between machines and products to understand if the defect is equally distributed or if it is specific for one machine or to certain versions of pinion. Third step is the definition of experiments on normal production for the double purpose of identifiying the distribution of products inside compliancy ranges and inside New defined standard. The scope is than understanding the relation between measures after shaving and after heat treatment. This will lead finally to the definition of the most important tooth profile parameters influencing noise and the solution to apply in order to avoid the defect. Once the experimental phase is concluded, after gathering the informations obtained, the Kaizen procedure can proceed with the 7 steps for Quality Maintenance, if identified cause is confirmed to be be machine related.

5.5.1 Database of defects

The starting point for the analysis is the output of Fast-response showcase. All measurement collected from defective components have been listed in a complete database having the following structure:

Progressive	Problem	Transmission	Component	Transm. ratio	Side	Status	Date	Parameter	Compliance	Value	Compliance coupled wheel	n. of measure

5.5.1.1 Database of defects for Design of Experiments

- **Progressive:** Integer number used to keep a logical and chronological order
- **Problem:** Identifies which defect mode was detected:
  - Noise of secondary shaft pinion and differential crown wheel couple detected trough NVH

- Noise of 5th gear couple detected trough NVH
- Noise of 4th gear couple detected trough NVH
- Others

- **Transmission:** Identifies the code number of the product presenting the defect
- **Component:** Specifies the component to which the measurement are referred. For each case, all data related to the couple of wheel causing the problem were added to the database. For each Transmission, there are always two components listed on the database
- **Transmission Ratio:** Indicates the τ of the defective couple, useful to distinguish different versions with different ratios having the same problem
- **Side:** Specifies to which flank of a tooth is referred the value measured. Each wheel has a tooth side under stress during *Traction*, and a side under stress during *Release*. Considering that a wheel is always driving, and the other is always driven, traction side is under stress when the driving wheel is transferring torqua to driven one. Release side is under stress when driver wheel does not transmit torque and it is braked by resistent torque acting on driven wheel.
- **Status:** Represents the general evaluation for the component to which is referred the measured value. There are three possibilities:
  - **Compliant:** Component respects Quality standards and tollerances
  - **Non-Compliant:** Component does not respect Quality standards and tollerances
  - **New Standard:** More restrictive than current tollerancy range. It has been set by comparing values of good products and good products discarded during functionality tests commonly called "False scraps". Tollerance range of this proposed standard is a compromise between real process capabilities and required tollerance range to obtain zero false scrap.
- **Date:** Date in which the defect was detected. This column was introduced to evaluate an eventual time influence on parameter values and number of defects.
- **Parameter:** Identifies the parameter to which is referred the value. For each component, the measured parameters are the following:
  - **Involute:** Cα; fHα; Fα; mean Cα; Variation range fHα
  - **Helix:** Cβ; fHβ; Fβ; mean Cβ; Variation range fHβ
  - **Circular pitch p:** fp, fu, Fp
  - **Concentricity:** Fr

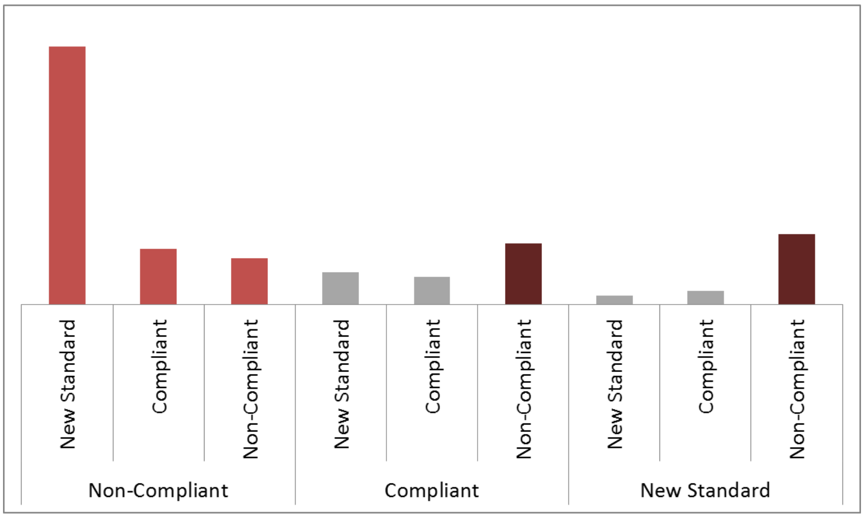
  Where the mean simply measures an arithmetic average between available values available for a single side of a single component. Variation range measures the difference between the maximum and the minimum values available for a single side of a single component
- **Compliance:** This column states if the single value is compliant or not, considering for each component the tollerance range contained in a lookup table:
  - **Value > max tol:** Value is not compliant as it is higher than the maximum limit of tollerance range
  - **Value < min tol:** Value is not compliant as it is lower than the minimum limit of tollerance range
  - **Min tol ≤ Value ≤ Max tol:** Value is compliant

- **Value:** This column contain measured values. Each row represent a single value. For each transmission there are two components, for each component there are several parameters, for each parameter there are two sides, one for traction and one for release, and for each side there are several measured values.
- **Compliance of coupled wheel:** As compliance column, it states if the coupled wheel is compliant, non-compliant or Compliant to new Standard . Even if this information is contained also in Compliance column referred to coupled component, it is useful to distinguish cases as:
  - **Pinion Non-Compliant + Crown wheel non-compliant:** Represents the combination of both possible causes of this defect mode, worst case in matter of noise.
  - **Pinion Non-Compliant + Crown wheel compliant:** Most frequent case, considering the high capability of grinding process of crown wheel with respect to shaving finishing of pinions. However, for this analysis, this combination accepts only values which are compliant but not compliant for New Standards
  - **Pinion Non-Compliant + Crown wheel under New Standard :** Couple composed by a non-compliant pinion and a Crown wheel which respects the more restrictive standards.
  - **Pinion Compliant + Crown wheel non-compliant:** Cases related to crown wheel non-compliance analyzed with a quick Kaizen, non taken in account in this section of the project.
  - **Pinion Compliant + Crown wheel compliant:** This is called "False scrap", because these components were discarded by test benches despite being compliant. These scraps are generated when an NVH curve passes close to its upper accepted limit, overpassing it in a single point. This represents a drawback caused by higher importance of product quality with respect to productivity.
  - **Pinion Compliant + Crown wheel under New Standard:** Similar to previous case.
  - **Pinion under New Standard + Crown wheel non-compliant:** Another case related to non-compliance of crown wheels.
  - **Pinion under New Standard + Crown wheel compliant:** Another possibility for false scraps for crown wheel, but not for pinions.
  - **Pinion under Under New Standard + Crown wheel under New Standard:** Limit cases in matter of False scraps, both components respect tollerancies more restrictive than assigned, but still test bench has discarded the transmission.
- **Number of measure:** This last column was added in order to identify uniquely values related to the same measure for different components. It represents a progressive integer number, so for each component measured, same value of this column represents the same measure. It is just an helpful tool to stanardize the reading and tabulation of new data.

5.5.2 Output from Database of defects

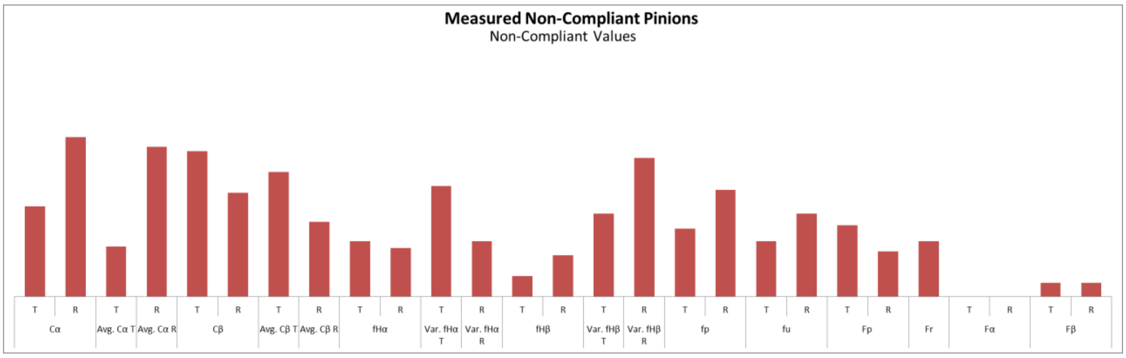
Compliance of couples: Evaluates how efficient is the filter represented by test benches on discarding defective components and releasing compliant ones. This chart presents the distribution of all possible combinations, the cases of defective pinions related to

DOE analysis are evidenced in red, non-compliant crown wheels are coloured in dark red. In gray, the false scrap, which is not negligible. As it represents a waste for the company, it should be reduced, but acting directly on NVH tollerance limits could compromise Product Quality, for this reason the only solution is a strong improvement on tooth profile shapes, in order to lower the amplitude of NVH curves and avoid all red and dark red cases. Amount of discarded couples with components both compliant is very low, the target is then to remain within New standard tollerances for entire production, even if compliant components guarantee product quality, for a reduction of False scraps, and consequently an improvement of FTQ.



5.5.2.1 Crown wheel – pinion couples of defective transmissions

Compliance of values to New Standards: After the evaluation of Compliance for each involved component, it is necessary to enter in the details of single measurements. The next chart lists the values out of compliance for each analyzed parameter, also distinguishing Traction side from release side. This means that the same chart plotted for a population of compliant pinions with respect to new defined standard would have all columns equal to zero. As the target is to reach the new standard without considering current standard tollerances.



5.5.2.2 Measured parameters for defective Pinions

This leads to several considerations about the problem. From this chart:

- It is not possible to correlate a single parameter to noise

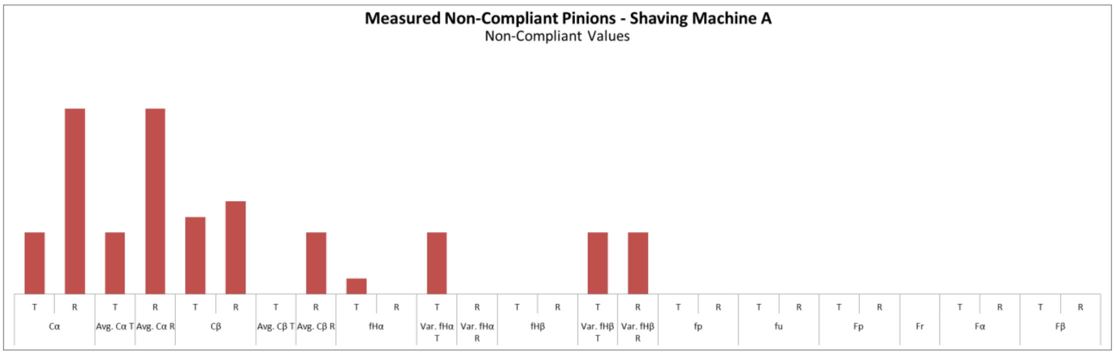
- It is not possible to know if those parameters are correlated to each other
- Traction and release have different behaviour, as they have different number of values out compliance. This is not due to differences in production process, the cause must be identified.
- Low numbe of non-compliant fHβ together with high values of Variance fHβ means that helix angles are mostly inside tollerance range, but have not a regular direction if correlated to each other.

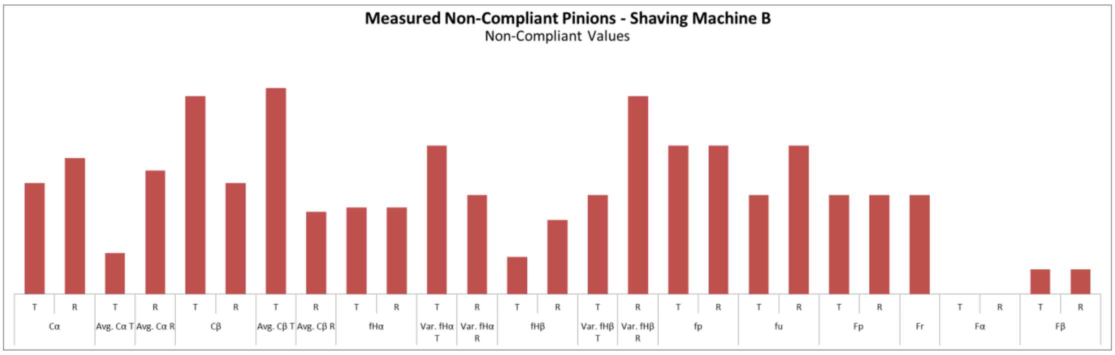
The chart represents the entire population of defective pinions. This is a limit as it avoids considering differences between products or between machines. Considering that all pinions have the same heat treatment process after machining operations, so it does not requires a classification. The only variables are the transmission ratios of different versions, and the shavng machines performing finishing operations, as previous machining steps are verified and compliant for the entire production. Tt is then useful before further analysis to extract specific data for each shaving machine and for each pinion model, considering the following table representing the link between machines and types of pinion:

	Machine A	Machine B	Production volumes
Pinion 1	X		High
Pinion 2		X	Low
Pinion 3		X	Low
Pinion 4		X	Low
Pinion 5		X	Low

5.5.2.3 Pinions and Machines for experiments

The main pinion is Pinion 1, machined only with Shaving Machine A. Shaving Machine B produces instead the other four types of pinions, alternating them according to production plan. The following chart compares the two machines, showing the number of parameters out of New Standard ranges, without considering existence of current standards.



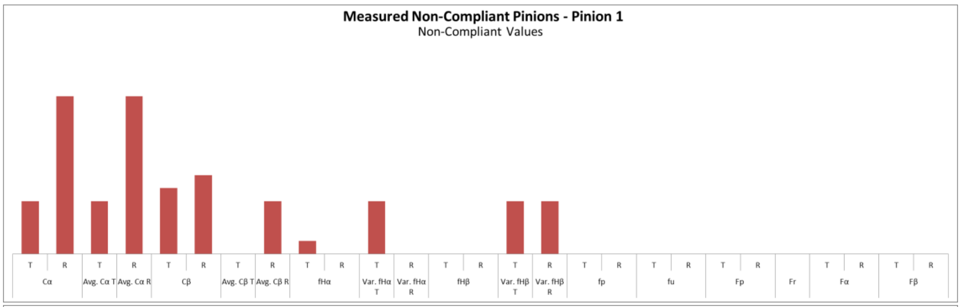


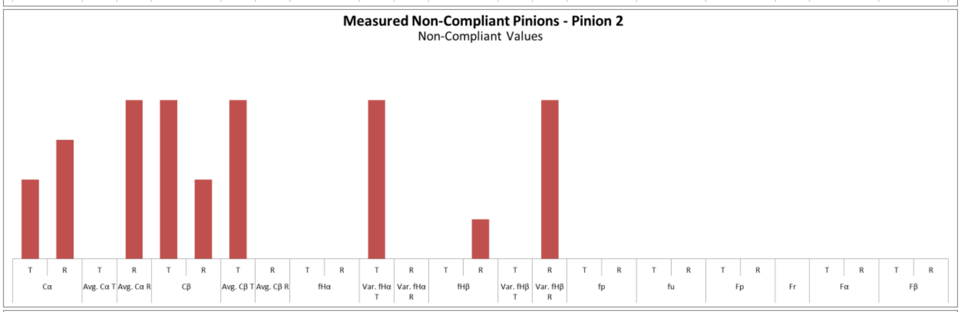
5.5.2.4 Measured parameters for defective Pinions divided for machines

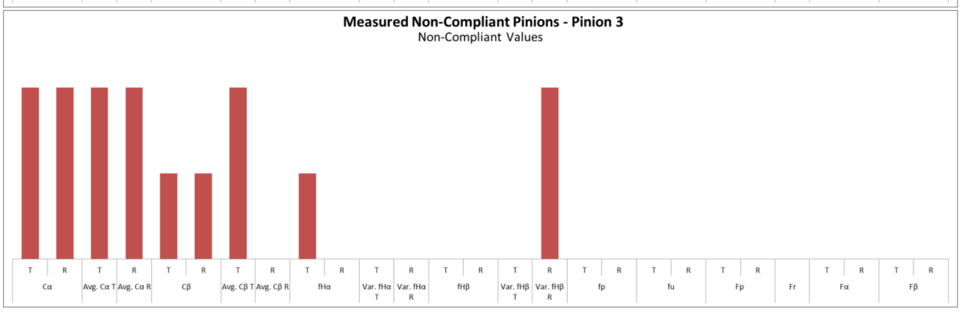
These charts show that:

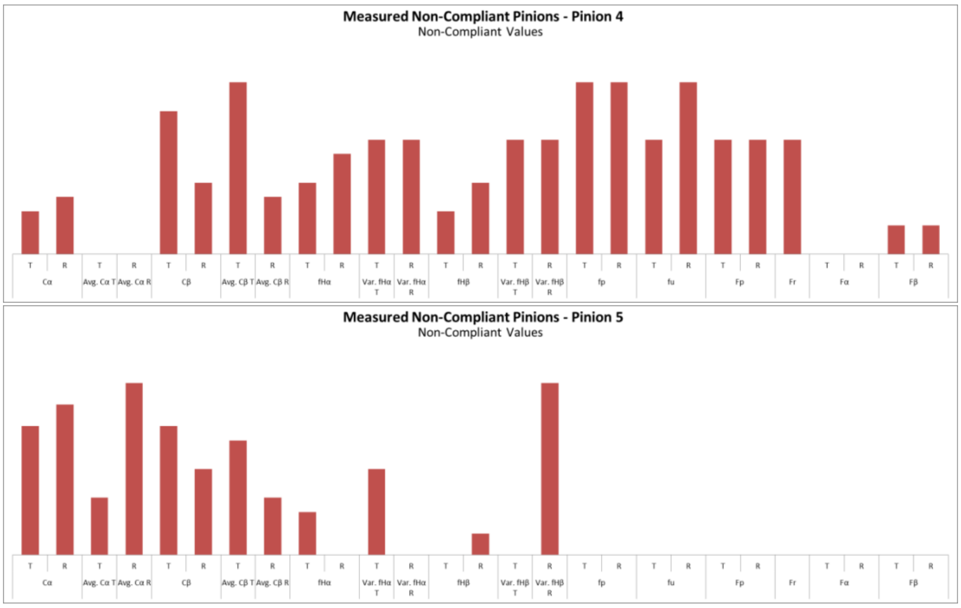
- Non-compliant values are not equally distributed along the two machines.
- Considering that all measures are taken from noisy couples, this leads to following possibilities, which must be verified with further analysis:
  - Parameters out of compliance in second plot that are compliant in first plot does not influence noise perception. This leads to associate noise to Cα, Cβ and Variance of fHβ
  - It is possible to obtain the same defect mode trough different combinations of non-compliant parameters

Before proceeding with the experiments, the following charts will show if different pinions have the same non-compliant parameters:









5.5.2.5 Measured parameters for defective Pinions divided for models

Charts evidence that:

- Plot of Pinion 1 is the same as the one for Machine A, as it is the only one produced
- The sum of Pinions 2, 3, 4 and 5 gives chart of Machine B
- One pinion is worse then the others, except for Cα parameters.
- Parameters always out of compliance are Cα, Cβ and Variance of fHβ, while errors of circular path fp, fu, Fp and concentricity Fr are present only for Pinion 4, which is a low production model.

5.5.3 Definition of Experiments

After measuring the defects, it is necessary to measure the compliant population, considering as already said, restrictive tollerances of new standards, and not the currently used ones. The expected result is a chart of the same type of the ones already presented for defects, with some geometrical tooth parameters out of new tollerance ranges, but still within compliance range. The output of the experiments mus identify the entire production, so for each test it is required a statistically significant number of measures. The targets are the following:

- Understand the fraction of parameters which measures are compliant and not under restrictive New standards
- Define a Capability for each significant parameter, also distinguishing traction from release
- Evaluate possible correlations between measures taken before and after heat treatment
- Verify the eventual time dependency of measured values

Finally, here is the set of populations defined for the tests:

Test	Machine	Pinion	Quantity	Frequency	Machine Parameters
1	**A**	**1**	50	Consecutives	Compliant
2	**A**	**1**	50	Periodic measurement	Compliant
3	**B**	**2**	50	Periodic measurement	Before Restoration
4	**B**	**3**	50	Periodic measurement	Before Restoration
5	**B**	**4**	50	Periodic measurement	Before Restoration
6	**B**	**5**	50	Periodic measurement	Before Restoration
7	**B**	**2**	50	Periodic measurement	After Restoration
8	**B**	**3**	50	Periodic measurement	After Restoration
9	**B**	**4**	50	Periodic measurement	After Restoration
10	**B**	**5**	50	Periodic measurement	After Restoration
11	**A**	**1**	50	Periodic measurement	Compliant

5.5.3.1 List of experiments for Pinions

For each component measured, a standardized sequence of operation is defined as follow:

1. Secondary shaft proceeds along production process up to shaving operation
2. After shaving operations, measured Pinion is taken from production line for the measurements
3. Measures are taken for a significant number of teeth, considering parameters already mentioned for analysis of scraps:
    a. **Involute:** Cα; fHα; Fα; mean Cα; Variation range of fHα
    b. **Helix:** Cβ; fHβ; Fβ; mean Cβ; Variation range of fHβ
    c. **Circular pitch p:** fp, fu, Fp
    d. **Concentricity:** Fr
4. Secondary shaft are marked, to define a progressive number and identify the measured teeth. This helps handling operations and avoid mistakes in the following steps of the procedure.
5. Marked secondary shafts are transferred for heat treatments. All components of a test population are heat treated together, to remove the eventual time influence on heat treatment.
6. Treated secondary shafts are again measured in correspondence of previously signed teeth.

5.5.4 Database of experiments

A database similar to the one already presented for defect pinions has been used to gather all data related to experimental tests. Here its structure:

Progressive	Component	Transm. ratio	N. Test	N.	Side	Status	Shaving Machine	Oven	Date	Shift	Parameter	Compliance Before HT	Value Before HT	Compliance After HT	Value After HT	n. of measure

5.5.4.1 Database for experiments

- **Progressive:** Integer number used to keep a logical and chronological order.
- **Component:** Specifies the component to which the measurement are referred.
- **Transmission Ratio:** Indicates the design τ for measured component, useful to distinguish different versions with different ratios.
- **N. Test:** Identifies the set of data to which is referred the considered measure, It corresponds on the first colum of table in which experimental tests tests are defined.
- **N.:** Represents the progressive number of measured components. Considering populations of 50 components, values in this colum go from 1 to 50.
- **Side:** Specifies to which flank of a tooth is referred the value measured. Each wheel has a tooth side under stress during *Traction*, and a side under stress during *Release*. Considering that a wheel is always driving, and the other is always driven, traction side is under stress when the driving wheel is transferring torqua to driven one. Release side is under stress when driver wheel does not transmit torque and it is braked by resistent torque acting on driven wheel.
- **Status:** Represents the general evaluation for the component to which is referred the measured value. There are three possibilities:
  - **Compliant:** Component respects Quality standards and tollerances, but not New Standards
  - **Non-Compliant:** Component does not respect Quality standards and tollerances. For measurement taken from normal production, non compliant measures are not expected, or expected with a very low frequency.
  - **New Standards:** Component is Compliant considering Standard Quality Tollerances, and also respects the more restrictive rules introduced in this project
- **Shaving Machine:** This column identifies the shaving machine that finished measured component. In case of Pinions, there are Machine A and Machine B.
- **Oven:** This column indicate the Oven used for heat treatment for a given test population. However, considering that all secondary shaft during normal production process are heat treated always in the same Oven, this is not a variable in this Analysis. The column was added in case of further evolution of the tests, considering different chambers even if standard operations does not require them.
- **Date:** Date in which the component was first measured after shaving operations. This column was introduced to evaluate an eventual time influence of measured values.

- **Parameter:** Identifies the parameter to which is referred the value. For each component, the measured parameters are the following:
  - **Involute:** $C\alpha$; $fH\alpha$; $F\alpha$; mean $C\alpha$; Variance $fH\alpha$
  - **Helix:** $C\beta$; $fH\beta$; $F\beta$; mean $C\beta$; Variance $fH\beta$
  - **Circular pitch p:** fp, fu, Fp
  - **Concentricity:** Fr

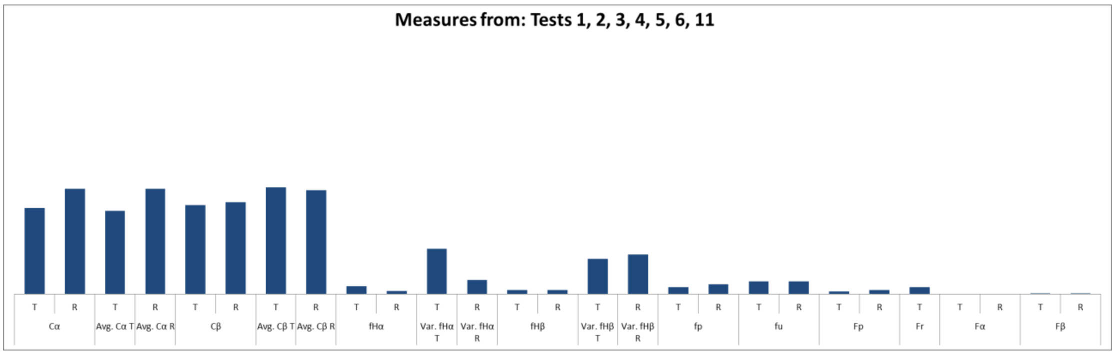
Where the mean simply measures an arithmetic average between available values available for a single side of a single component. Variation range measures the difference between the maximum and the minimum value available for a single side of a single component.

- **Compliance Before HT:** This column states if the single value measured before heat treatment is compliant or not, considering for each component the restrictive New tollerance range and not current standard:
  - **Value > max tol:** Value is not wanted as it is higher than the maximum limit of new tollerance range.
  - **Value < min tol:** Value is not wanted as it is lower than the minimum limit of new tollerance range.
  - **Min tol ≤ Value ≤ Max tol:** Value is compliant to New Tollerance.
- **Value Before HT:** This column contains values measured before Heat Treatment. Each row represent a single value. For each transmission there are two components, for each component there are several parameters, for each parameter there are two sides, one for traction and one for release, and for each side there are several measured values.
- **Compliance After HT:** It has the same meaning of previous column but referred to the same measures after Heat Treatment
- **Value After HT:** Indicates values measured after Treatment, corresponding to values measured before heat treatment in the same row of the table.
- **Number of measure:** This last column was added in order to identify uniquely values related to the same measure for different components. It represents a progressive integer number, so for each component measured, same value of this column represents the same measure. It is just an helpful tool to stanardize the reading and tabulation of new data.

5.5.5 Output from Database of experiments

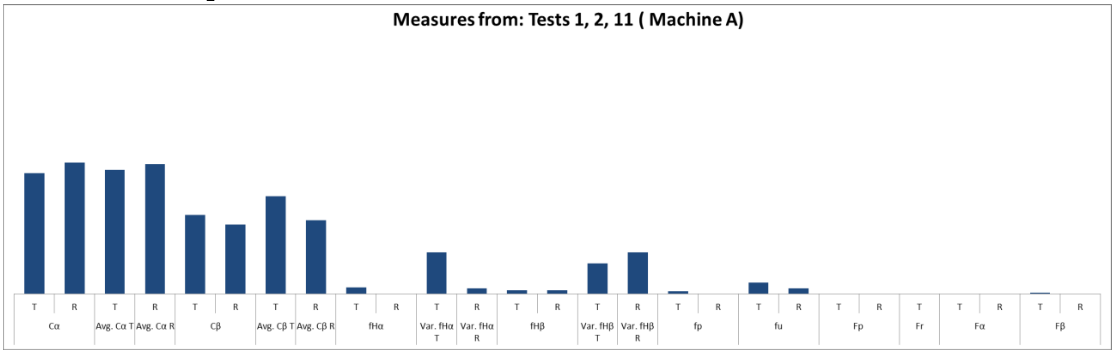
Following analysis will proceed backwards, from the interpretation of measures taken after heat treatment, to the correlation between shaving operations.

Compliance of values: First, it is necessary to evaluate the output of production, to understand the fraction of measures which does not respect the new defined compliance standards. At this point of the analysis it is not required to distinguish between fraction of less restrictive compliant components which are not respecting new standards. As the target is to reduce also the fraction of parameters out New Standards, in order to reduce also the number of false scraps, other than the number of defects, for a better FTQ improvement.

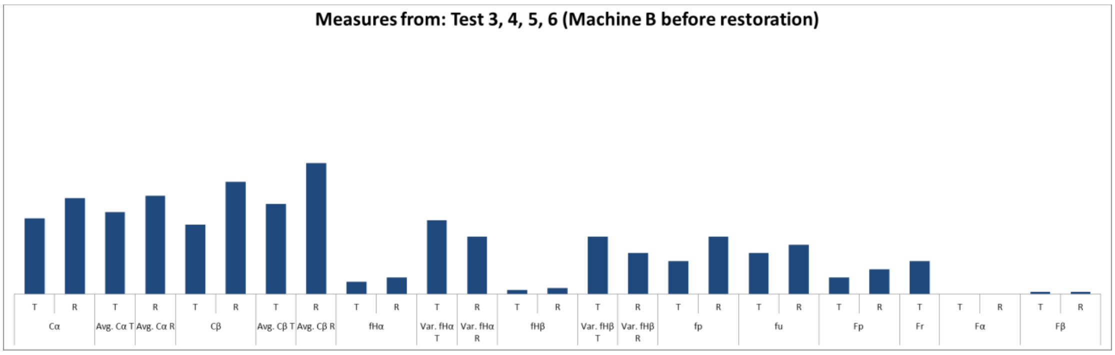


5.5.5.1 Measured parameters for Tested Pinions

This plot includes all measures taken for tests performed before restoration of Machine B. Represents the entire pinion production in current situation, which as expected is not totally within new tollerance ranges, resulting than non compliant for new standards. Before drawing first conclusions, it is necessary to split tests for identifying possible differences among machines and models.



5.5.5.2 Measured parameters for Tested Pinions Machine A



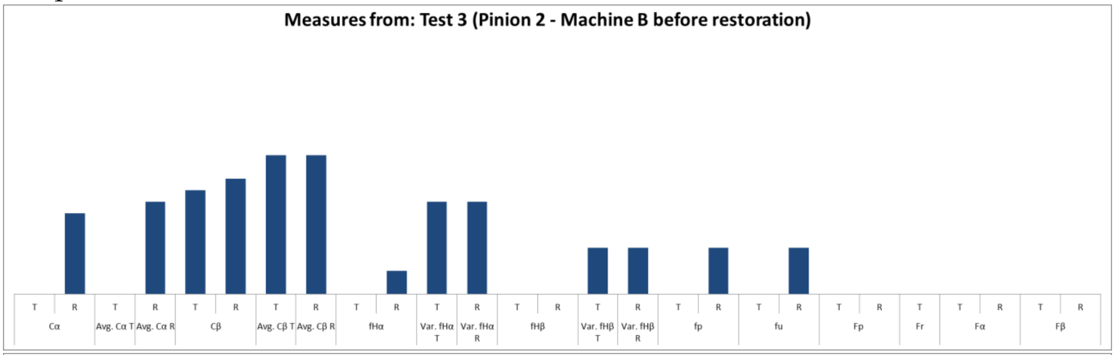
5.5.5.3 Measured parameters for Tested Pinions Machine B

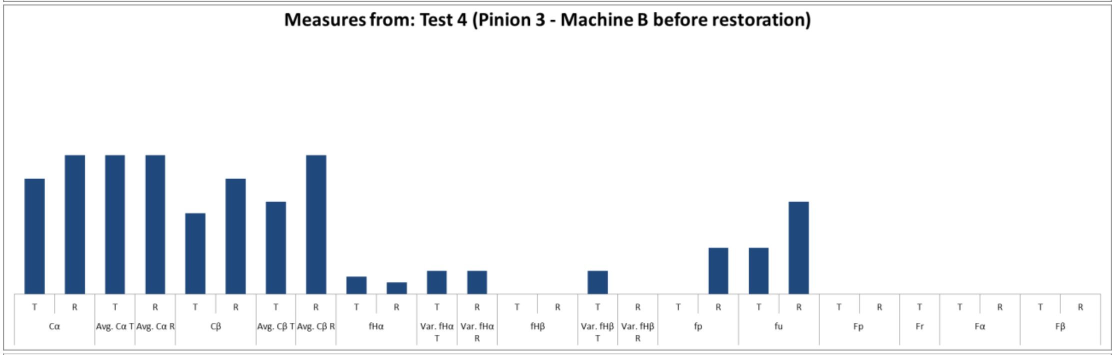
First comparison between machines A and B gives some important results:

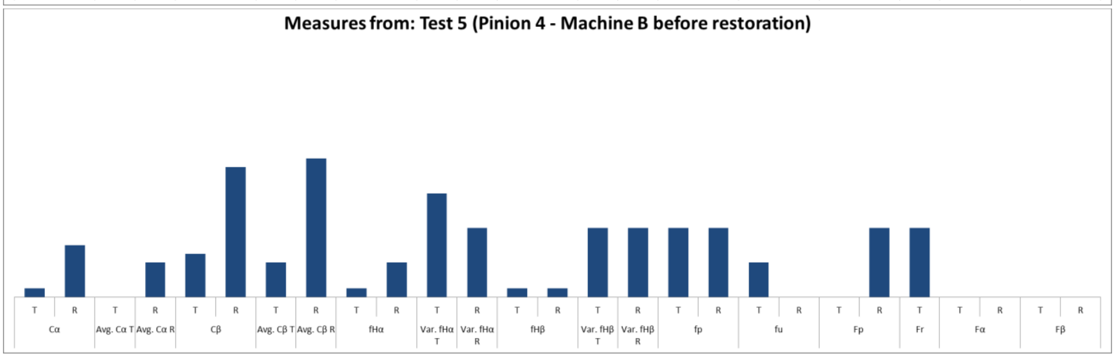
- Machine A normal production follows the same trend of its defective pinions, parameters mostly non respecting new standards are:
  - Cα and Average Cα
  - Cβ and Average Cβ
  - Variation Range of fHα
  - Variation Range of fHβ
  - In general, Release side is worse than Traction side

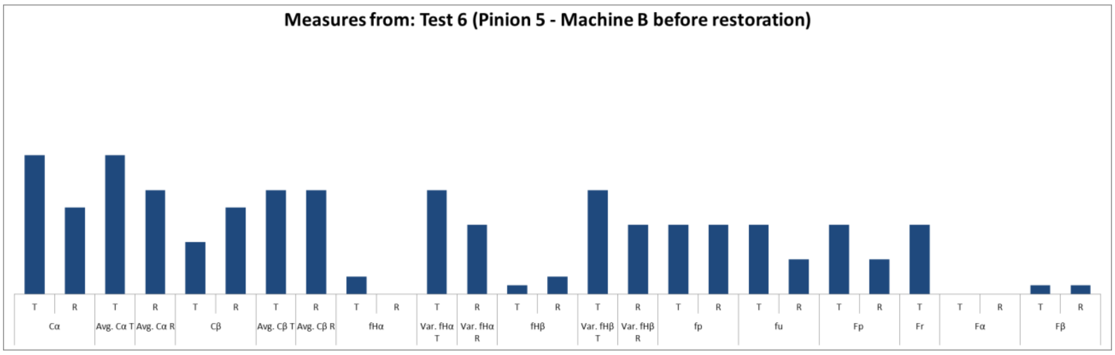
- Also Machine B normal production confirms the trend of its defective pinions, parameters mostly out of new tollerances are:
  - Cα and Average Cα
  - Cβ and Average Cβ
  - Variation Range of fHα
  - Variation Range of fHβ
  - Circular pitch p: fp, fu, Fp
  - Concentricity: Fr
  - In general, Release side is worse than Traction side

From the mechanical point of view, a part from the different number of teeth of cutting tools used, and the major variety of production of Machine B, the major difference between the two machines is the non-compliance of two rotating axes of Machine B. From this first comparison, the parameters affected by the non-compliance of rotating machine axes are the ones related to Circolar Pitch (fp, fu, Fp) and Fr related to Concentricity. It is than expected a reduction of the number of non-compliant values for these parameters after the restoration of the machine.









5.5.5.4 Measured parameters for Tested Pinions divided for models

These plots represent for each Pinion shaved with Machine B, Pinion 1 is neglected as it is unique for Machine A, so already analyzed during machine comparison. Results are interesting as:

- For each model, parameters related to circular pitch (fp, fu, Fp) and concentricity (Fr) are not 100% compliant as measures taken from defective pinions
- Trend for Cα, Cβ, Average Cα, Average Cβ, Variance of fHα and Variance of fHβ is confirmed for all Pinions and machines

In general, after splitting Tests and analyzing them one by one, it is possible to assume that:

- Parameters certainly affecting Noise performance of pinions are:
  - Cα and average Cα
  - Cβ and average Cβ
  - Variance of fHα
  - Variance of fHβ
- Parameters probably not affecting Noise performance of pinions are:
  - fp, fu, Fp
  - Fr
  - Release Side is worse than Traction side

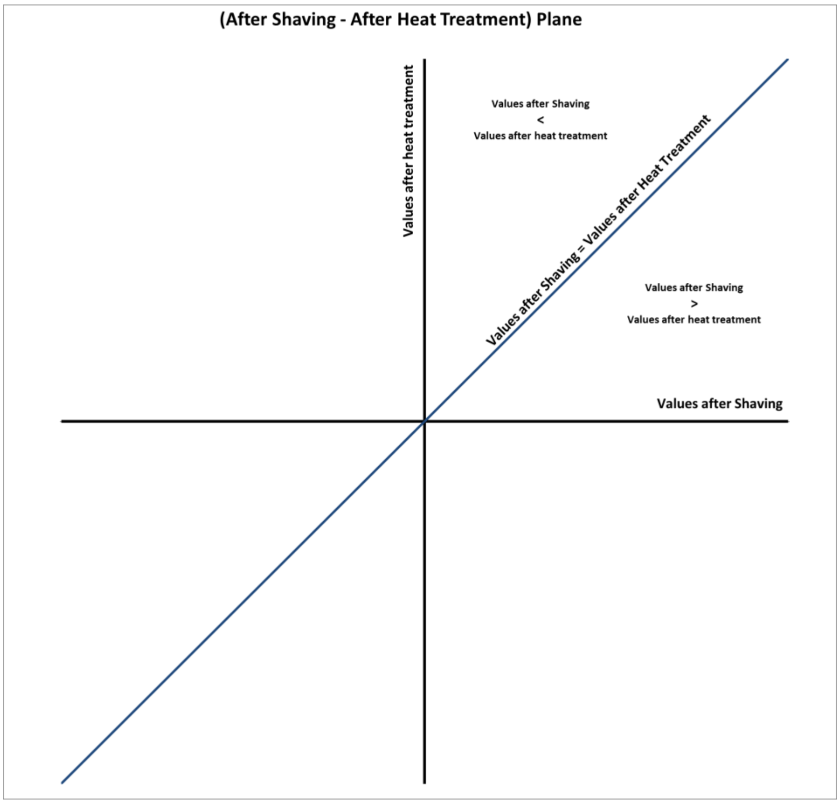
Starting from these assumptions, following analysis will concentrate of four defined parameters, neglecting all the others. It is worth to mention that shape parameters Fα and Fβ are always compliant, with a capability and precision very high.

Influence of heat treatment on shaved profiles: Now it is evaluated an eventual correlation between a value measured after shaving operation and the same value after heat treatment. Because of old technology used for heat treatments, it is expected that all parameters will worsen, for each value measured after shaving operations.

It is usefult for this purpose to consider each single measure as a point on a XY plane, where:

- X_i represents the i^{th} measured value after shaving operations
- Y_i represents the i^{th} measured value after heat treatment

This plane (After Shaving – After Heat Treatment) will be full of points, representing all measures gathered. For increasing measured value after Shaving, the point will move to the Right on this plane, while for decreasing values it will move to the left. Vertical direction is instead influenced by measures after heat treatment, for increasing values, the point moves upward in the plane, while it moves downwards for lower measured values.

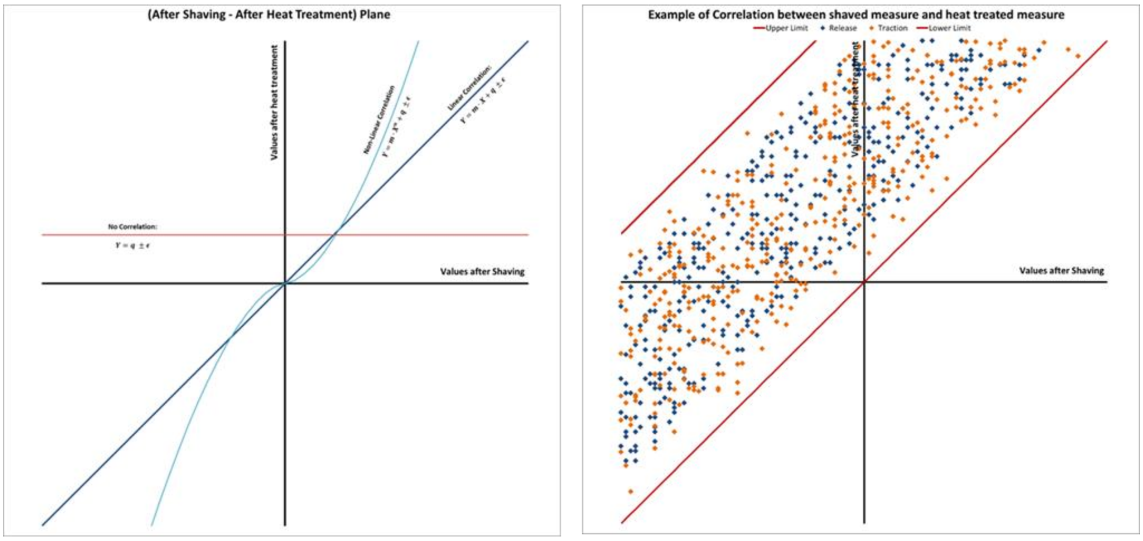


5.5.5.5 Plane of correlation between shaving and heat treatment measures

Considering this definition, the plane can be divided in Significant areas:

- Points close to bisector of first and third quadrant conserve their value from shaving to heat treatment. An Ideal heat treatment process would have all points lying on this line and precision of the process would depend only on precision of shaving operations
- Points below bisector of first and third quadrant have a decrease after heat treatment from measure taken after shaving.
- Points above bisector of first and third quadrant have an increase after heat treatment from measure taken after shaving.
- Precision of shaving operations is increasing when all points are restricted to a closer range in x direction
- Precision of final component, after heat treatment, is increasing when all points are restricted to a closer range in y direction
- A good component has an high precision after heat treatment, independently from values after shaving operations on x direction

Before starting evaluations about real measured values it is necessary to define a structure for the plot, in order to better understand the conclusions to be drawn from data available.



5.5.5.6 Example of correlation between shaving and heat treatment measures

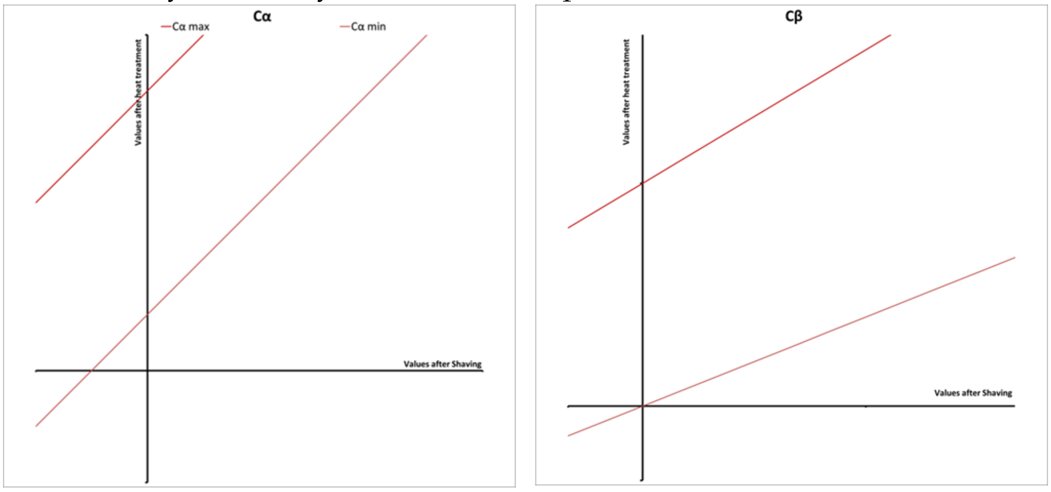
This example containing just random values can completely explain the procedure that has been followed for all following analysis. All points are plotted on the plane, as already anticipated, but with a further diversification obtained distinguishing measures related to Release sides (In Blue) from the ones related to Traction sides (In Orange). All points will follow a trend, strictly dependent from the real influence of heat treatment process on measured values. From the distribution of all plotted points, it is possible to extrapolate a “range” separating the area in which we can expect points, from the outer part of the plane that should remain empty. Depending on the shape of point distribution on the plane it is possible to define an analytical correlation that, given a certain value after shaving (X), allows to determine an Y range of possible values after heat treatment. If such correlation exists, it is possible to tune the Shaving process in order to obtain a higher capability after heat treatment.
In general, as explained in the previous chart, there are three possibilities of correlation, according to the trend line of all plotted points:

- **Linear correlation:** Influence of heat treatment is linear, according to following analyitical relation: $Y(X) = m \cdot X + q \ \pm \epsilon$ where:
  - X: Variable, represents an hypothetical measure after shaving operation
  - Y: Represent a prevision of an expected measure performed after heat treatment, knowing measure X after shaving operations
  - m: is the tangent of the angle of the trend line with respect to horizontal direction
  - q: is an offset which affect all values after shaving (X). If q>0 the effect is an increase of value after heat treatment, while q<0 causes a reduction.
  - ϵ: Represents an Error on value Y generated by the high variability introduced by heat treatment. For each X value it is not possible to identify a unique Y, but it is necessary to consider a range of equiprobable Y: [Y- ϵ;Y+ ϵ]
- **Non-Linear correlation:** Influence of heat treatment is linear, according to following analyitical relation: $Y(X) = m \cdot X^n + q \ \pm \epsilon$, where in addition to already introduced symbols:
  - n: Exponent of X representing the non-linearity. If n>1 the increase of Y is higher for increasing X. If n<1 Y tends toward saturation for increasing X

- **No correlation:** Influence of heat treatment is not dependent from measure taken aftershaving operation, according to following analyitical relation: $Y(X) = q \pm \epsilon$ In this case it is not possible to tune shaving operations to improve Product quality. It is necessary to tune heat treatment to modify existing values of q and to reduce ϵ. In practice, this is not economically praticable.

Considering that the secondary shaft is made of the same material for all versions, and 5 pinions are similar, it is possible to obtain a relation for each parameter valid for all pinions, also valid for both Traction and Release sides.

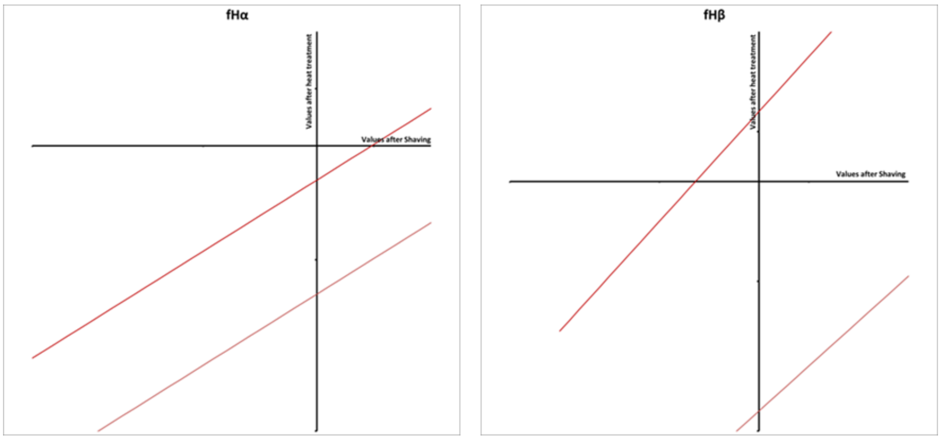
For what concerns Cα, the parameter is controllable thanks to a linear correlation. Plots show that the tangent of the trend line is almost unitary, while the offset is positive, that means that in general, it is not possible, after heat treatment, to obtain values lower than the ones measured previously after shaving operation. Heat treatment tends in fact to increase the entity of covexity of teeth Involute profiles.



5.5.5.7 Analytical model for Convexity of Involute Ca and Helix Cβ

Also Cβ shows a linear correlation between measures taken after shaving and after heat treatment. However, for Convexity of Helix this correlation is not strong and the tendency is to worsen the precision for higher measures after shaving. The possibility of tuning shaving operations for improving Product quality is limited due to the high variability, which is represented by the distance in vertical direction between the two identified limit lines. For each value in X direction, the relative Y value could be in a random vertical position among the two lines.

Also fHα has a precise linear behaviour as Cα. Confirming the strong correlation between shaving and heat treatment for what concerns Involute profile. This means that it is possible to tune Shaving operations to improve the final result after heat treatment, knowing the analytical formula that allows to predict with a certain precision limited by error ϵ.



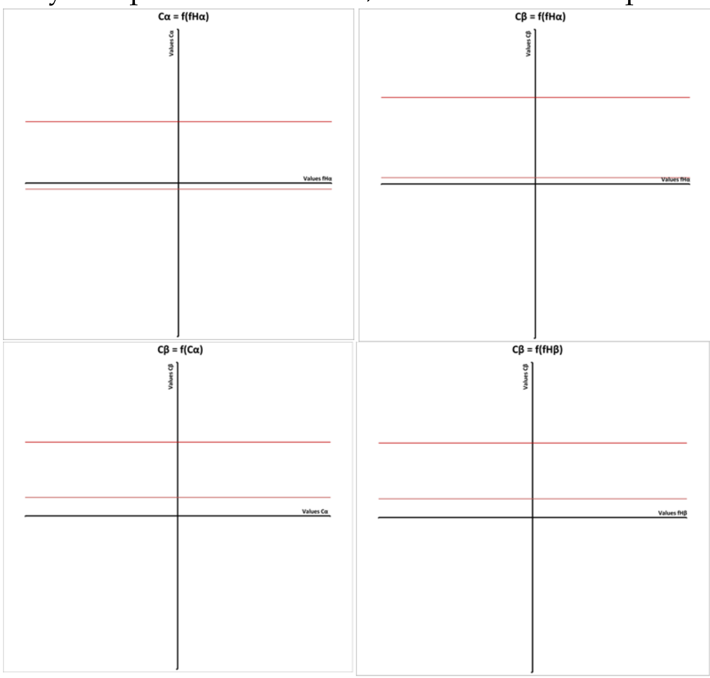
5.5.5.8 Analytical model for Angle error of Involute fHa and Helix fHβ

Finally, fHβ is similar to Cβ, confirming a linear tendency affected by a worsening of precision for increasing values measured after shaving.

Correlation between parameters: Before entering in matter of shaving operations, it is interesting to evaluate a possible existing correlation between different parameters. If such correlation exists, the tuning of shaving operations which affect a certain parameter will affect also the ones correlated to it. Procedure to follow for these evaluations is the same already described, with the single difference of changing the meaning of X and Y:

- X: Parameter considered as a variable
- Y: Parameter considered a function of the variable parameter X

In this case, fHα and Cα, despite their similar behaviour and conceptual link as both referred to involute profile, it is not possible to identify a correlation. The horizontal trend proves a complete independency of Cα from fHα.
Also Cβ is completely independent from fHα, as the trend line is perfectly horizontal.



5.5.5.9 Correlation between independent parameters

Cβ results independent even changing variable, plot are identical, as the only variable is the X axis, while Y values are not affected by varying X, which in these two cases is represented respectively by Cα and fHβ

This plot evidences an existing correlation between The angular error of involute profile fHα and angular error on Helix profile fHβ. In this case, for increasing values of fHα fHβ decreases, this means that the tangent of the curve is negative. Considering the formula previously introduced: $Y(X) = m \cdot X + q \ \pm \epsilon$, m is negative.

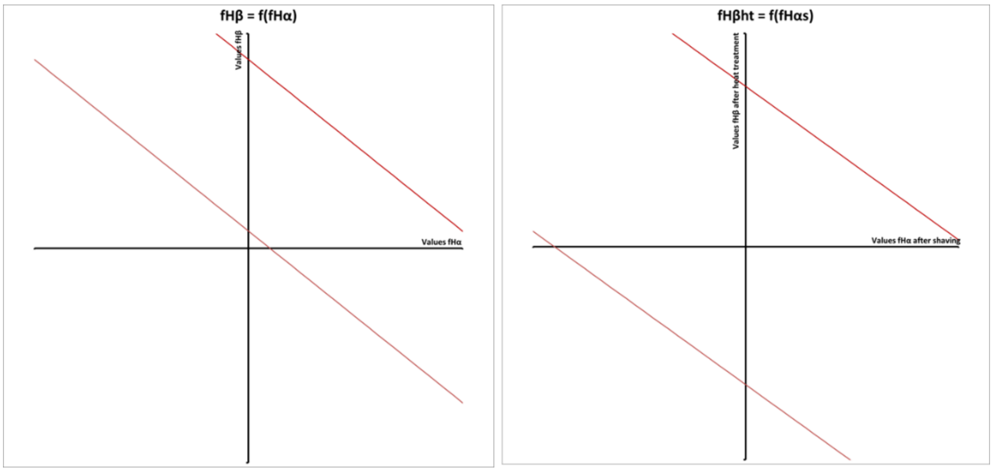
Due to this correlation. Theoretically, tuning fHα during shaving operations, will tune also fHβ, influencing for both parameters the final result after heat treatment.

It is possible to directly correlate fHα after shaving with fHβ after heat treatment by considering this system of equations:

$$\begin{cases} fH\beta_s = m_s \cdot fH\alpha_s + q_s \ \pm \epsilon_s \\ fH\beta_{ht} = m_{ht} \cdot fH\beta_s + q_{ht} \ \pm \epsilon_{ht} \end{cases}$$

In which:

- Subscript s for shaving, refers to measure taken after shaving operation
- Subscript ht for heat treatment, refers to measure taken after heat treatment
- m_{ht} as said is negative



5.5.5.10 Existing correlation between fHa and fHβ

It is finally possible to obtain:

$$fH\beta_{ht}(fH\alpha_s) = \ m_{ht} \cdot m_s \cdot fH\alpha_s + m_{ht} \cdot q_s \ + q_{ht} \ \pm m_{ht} \cdot \epsilon_s \ \pm \epsilon_{ht}$$

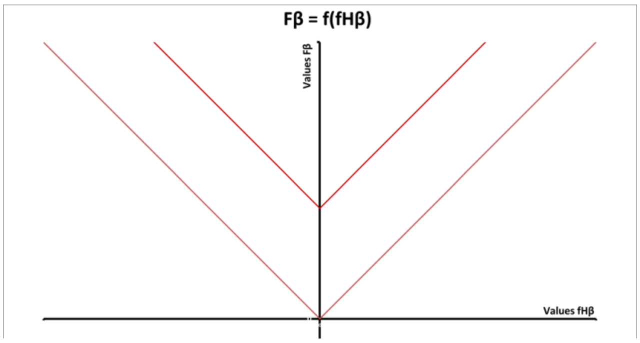
Which represents the direct correlation between shaving parameter fHα and final fHβ after heat treatment.

To conclude, it is useful to mention an existing correlation between fHβ and Fβ after heat treatment, which is a parameter evaluating the shape of the Helix profile. This correlation results useful as for excessively high values of fHβ, also Fβ goes above tollerance ranges. The Shape symmetrical to Y axis is due to the fact that Fβ represents a deviation error, so its minimum value is zero.

As already done before, considering fHβ after heat treatment as a function of fHα after shaving, it is possible to define Fβ after heat treatment as function of fHα after shaving, solving the following system:

$$\begin{cases} fH\beta_{ht}(fH\alpha_s) = \ m_{ht} \cdot m_s \cdot fH\alpha_s + m_{ht} \cdot q_s \ + q_{ht} \ \pm m_{ht} \cdot \epsilon_s \ \pm \epsilon_{ht} \\ F\beta_{ht}(fH\beta_{ht}) \ = \ m_{F\beta} \cdot |fH\beta_{ht}| + q_{F\beta} \pm \epsilon_{F\beta} \end{cases}$$

$$F\beta_{ht}(fH\alpha_s) = \ m_{F\beta} \cdot |m_{ht} \cdot m_s \cdot fH\alpha_s + m_{ht} \cdot q_s \ + q_{ht} \ \pm m_{ht} \cdot \epsilon_s \ \pm \epsilon_{ht}| + q_{F\beta} \pm \epsilon_{F\beta}$$



5.5.5.11 Existing correlation between shape error Fβ and fHβ

To conclude, parameters tuned for shaving operations that can strongly influence final measures after heat treatment are:

- **Cα:** Independent parameter representing a measure of convexity of Involute profile. If it is possible to tune this parameter for shaving operations, the result will be an influent correction on final heat treated tooth, which can represent an influent improvement from the noise performance point of view, as Cα is assumed to be one of the major causes of Noise.
- **fHα:** Parameter correlated to fHβ, represents the angle error of tooth involute profile. A tuning of this parameter during shaving operations can influence results for both fHα, fHβ, plus Fβ after heat treatment. An optimal tuning can reduce drastically the number of values out of compliance range in current production, erasing the fraction of defective components and improving FTQ.
- **Cβ:** Independent parameter with a weak correlation between measures taken after shaving and after heat treatment. Defective components lack in precision for what concernes this parameter, but the margin of action is lower than the previous ones.

Before entering in matter of machine parameters and cutting tools tuning, it is necessary to analyze the current capability of production for what concerned the most significant parameters, already analyzed from the point of view of heat treatment.

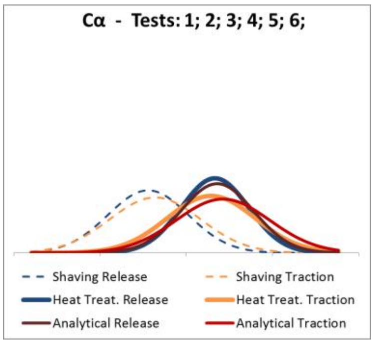
Distribution of measurements: For what concerns tollerance ranges for shaving process, current situation does not have a defined standard to follow. Accepted measures are tuned with a feedback system from heat treatment output. In order to obtain a satisfying result, current practices and procedures to tune shaving machines must not be considered, as the number of defects need to be reduced.

Before focusing only on shaving process, it is necessary to compare, for each test, the distribution related to after shaving measures, to the ones after heat treatment. To prove the veridicity of previously identified formulas, it is usefule to compare the real results with the analytical distribution of measures after heat treatment expected starting from given measures after shaving. If these two distributions are similar, the analytical model can be applied to entire production.

Cα: First parameter to consider is Convexity of Involute profile. The plot shows Gaussian distributions of 6 populations:

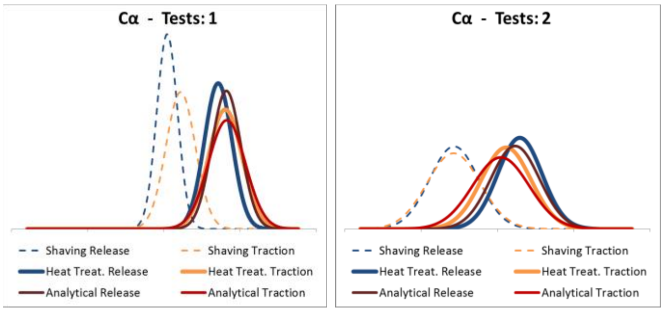
- **Dotted Blue line:** Measures of Release profiles after Shaving
- **Continuous Blue line:** Measures of Release profiles after Heat Treatment
- **Continuous Dark Red line:** Distribution of Release profiles after Shaving obtained applying Analytical model to measures of Release profiles after Shaving

- **Dotted Orange line:** Measures of Traction profiles after Shaving
- **Continuous Orange line:** Measures of Traction profiles after Heat Treatment
- **Continuous Light Red line:** Distribution of Traction profiles after Shaving obtained applying Analytical model to measures of Traction profiles after Shaving



5.5.5.12 Gaussian distribution of measured values VS analytical model - Ca

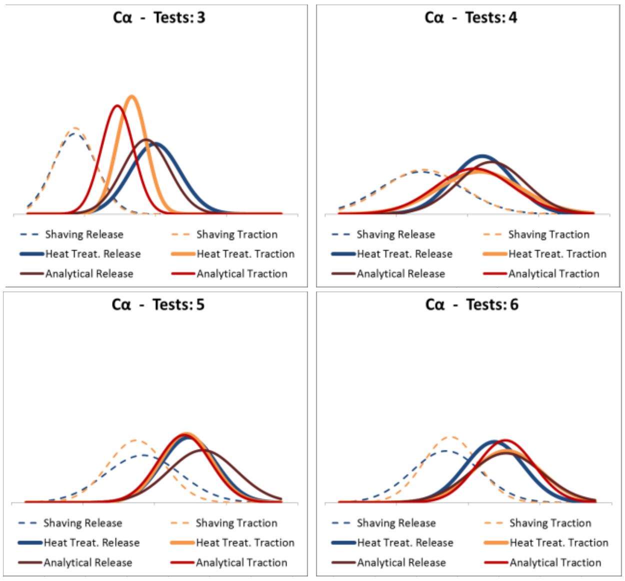
First plot shows result of entire production for Both Shaving Machine A and Shaving Machine B.



5.5.5.13 Gaussian distributions Tested Pinions for Machine A - Ca

Second plot gives a focus to Machine A, with a comparison between 2 tests:

- **Test 1: Machine A – Pinion 1,** performed taking a population of 50 consecutive pinions
- **Test 2: Machine A – Pinion,** pinions has been taken after a certain time delay.



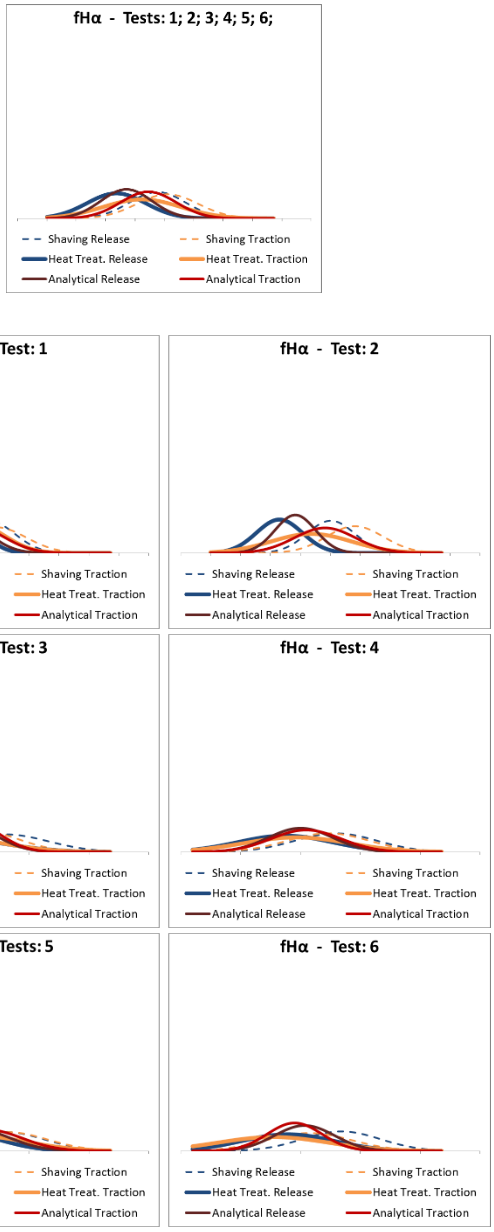
5.5.5.14 Gaussian distributions Tested Pinions for Machine B - Ca

Third plot shows performances of production relative to Shaving Machine B:

- **Test 3: Machine B – Pinion 2,** pinions has been taken after a certain time delay.
- **Test 4: Machine B – Pinion 3,** pinions has been taken after a certain time delay.
- **Test 5: Machine B – Pinion 4,** pinions has been taken after a certain time delay.
- **Test 6: Machine B – Pinion 5,** pinions has been taken after a certain time delay.

Comparison between Continuous and Red lines show that the Analytical model is Effective and allows a correct prevision of Final product starting from a measure before Heat Treatment. On Traction Side (Red compared to Orange) The model is more precise, while for Release (Dark Red compared to Blue) variability introduced during Heat Treatments is greater than the one forecasted by model. However, model can still be used also for release, as in all cases the prevision represents a Worst Case.

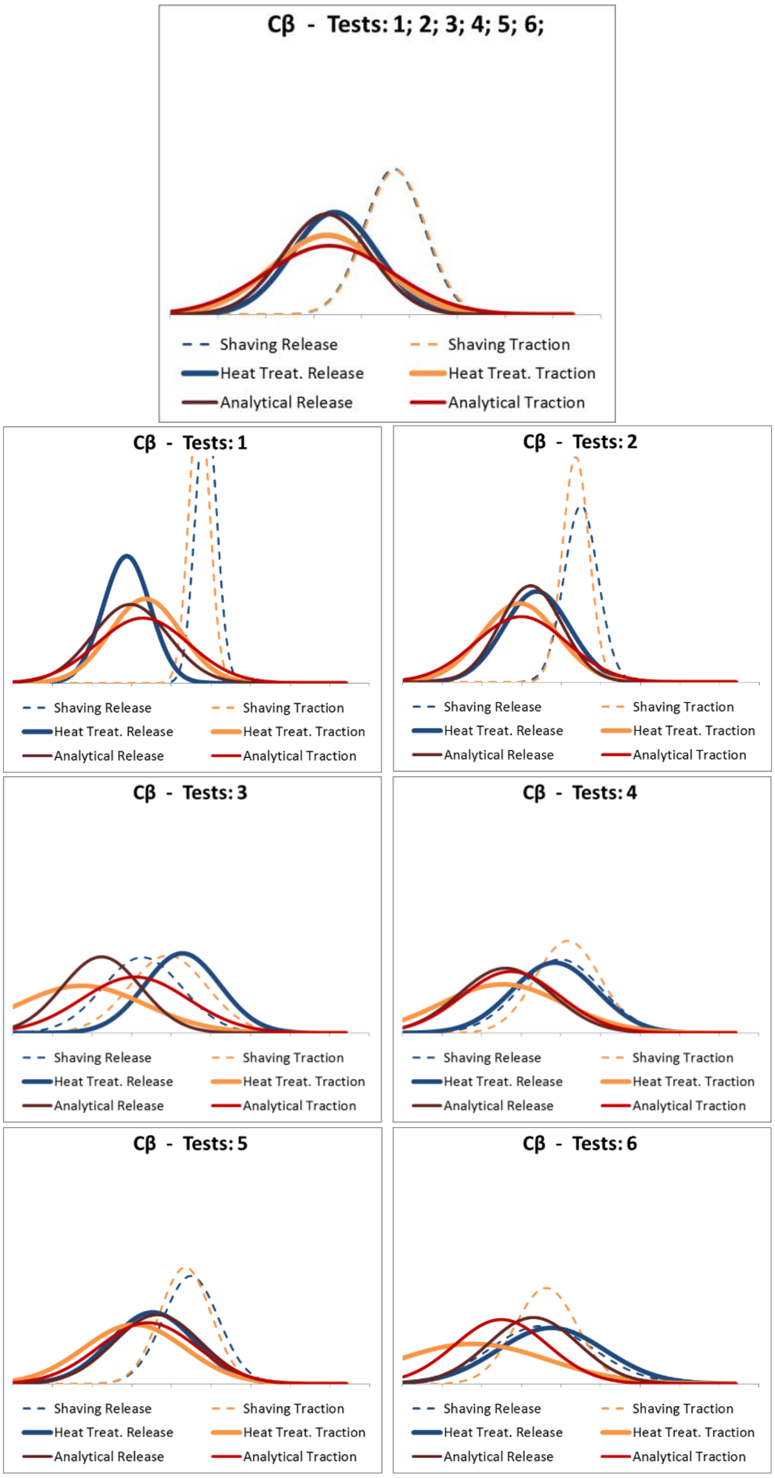
fHα: Second parameter to consider is Angular error of Involute profile. The plot has the same scheme of the one already presented for Cα:



5.5.5.15 Gaussian distributions Tested Pinions - fHa

Even for angle error of involute profule the model is effectively representing real distributions after heat treatment, so it can be used to determine tollerances. The model for Cα is more precise, especially for low production pinions, but the model represents a worst case, as the defects are reconduced to values higher than tollerance and not lower.

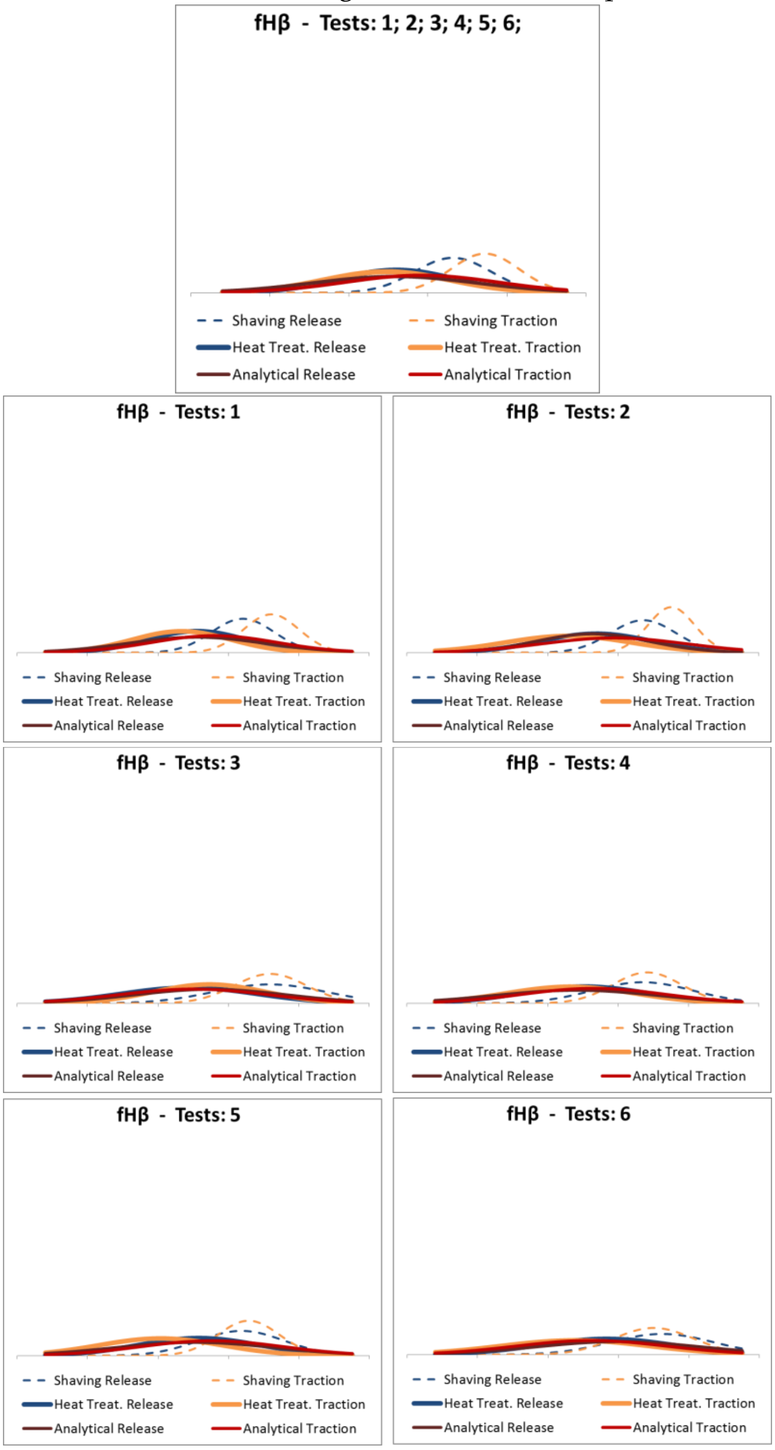
Cβ: Third parameter to consider is Convexity of Helix, always with the same scheme:



5.5.5.16 Gaussian distributions Tested Pinions - Cβ

Precision of Cβ model is good, except for Pinion 2 and Pinion 5, which are low production and for this reason it is useless to differentiate the model to take in account the small differences. The analytical model can thou be used to identify shaving process tollerances for Cβ.

fHβ: Second parameter to consider is Angular error of Helix, presented as already seen:



5.5.5.17 Gaussian distributions Tested Pinions - fHβ

To conclude, fHβ model is precise for all Pinions. Unfortunately, heat treatment process worsens the parameter after shaving, so angular errors have a weak influence on shaving process while heat treatment is more determinant.

Tollerances for Shaving Process: Starting from analytical model it is now possible to define new tollerances for Shaving process, in order to obtain the entire population of Heat Treated pinions within Compliance range. To improve the overall process capability, it is then sufficient to focus only to shaving operations. If shaving process is improved and all measures fall within these tollerances, it is certain that the final pinion will be compliant, even considering the high variability of heat treatment. Before improving Shaving process, it is necessary to analyze it, for both Machine A and Machine B, for all Pinions, starting to Pinion 1 which represents the majority of production, and the time dependency of shaving process, to evaluate the influence of wear and cutting tool setups. For each analyzed parameter i: Cα, fHα, Cβ, fHβ, It can be used the corresponding analytical model to define shaving process tollerances starting from the requirements on final product:

$$HT_i(S_i) = m_i \cdot S_i + q_i \pm \epsilon_i$$

Given a measure of parameter i after shaving process S_i, this model gives a forecast of the same measure after heat treatment HT_i. To obtain instead the Shaving compliance limits, it is necessary to invert the formulas, so, given the required HT_i, it is possible to know the necessary S_i.

$$S_i(HT_i) = \frac{1}{m_i} \cdot HT_i - q_i \mp \epsilon_i$$

After defining the inverted model, upper and lower tollerance limits are identified as follow:

$$S_{i_{min}}(HT_i) = \frac{1}{m_i} \cdot HT_{i_{min}} - q_i + \epsilon_i$$
$$S_{i_{MAX}}(HT_i) = \frac{1}{m_i} \cdot HT_{i_{MAX}} - q_i - \epsilon_i$$

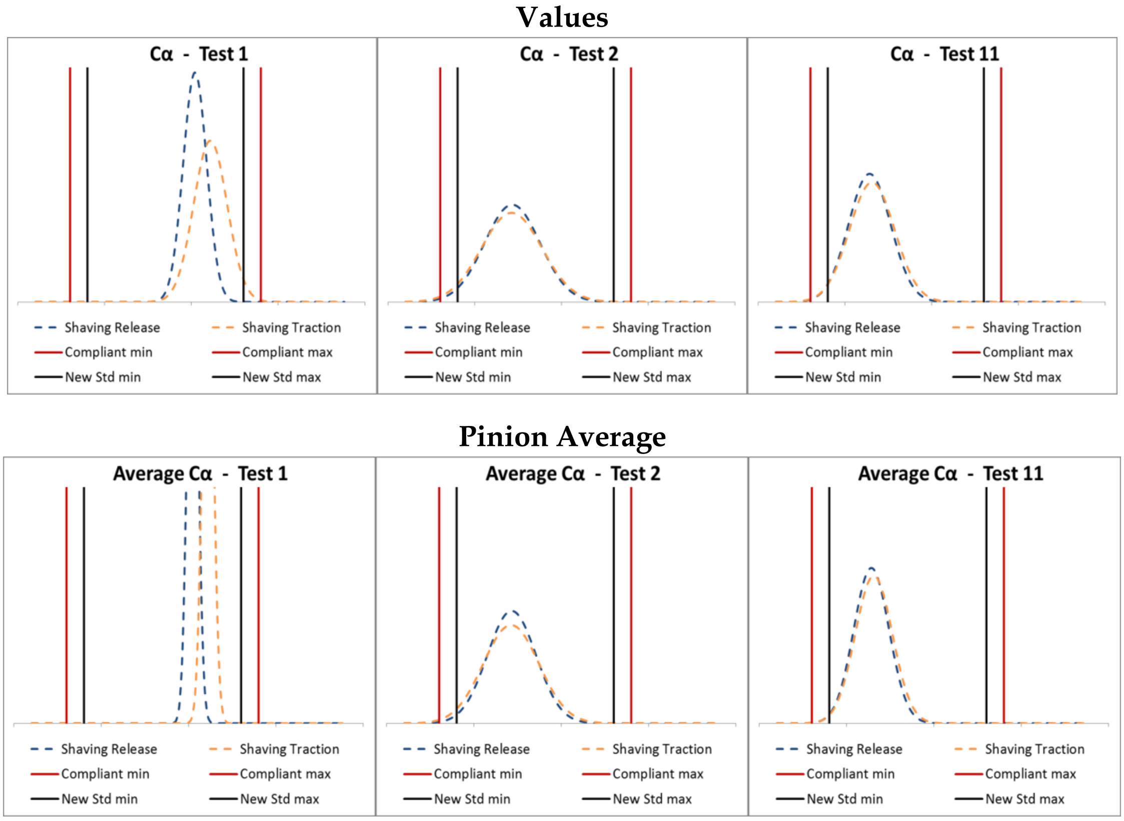
If defined in this way, tollerances on shaving process are sufficiently restricted to avoid non compliances caused by the variability of heat treatments, and guarantee a reduction of defects. To make another important set, it is necessary to consider the New Standards already introduced during previous analysis, instead of required compliance tollerance, in order to avoid false scraps at test benches. This will lead to an increase of $HT_{i_{min}}$ and so of $S_{i_{min}}$ and a reduction of $HT_{i_{MAX}}$ and correlated $S_{i_{MAX}}$. The final analysis will focus on Shaving process considering both these two limits: The one required to obtain pinions within standards after heat treatments, and the New standard, necessary to reduce false scrap at test benches.

Time dependency of process quality: First question to answer about shaving process is related to the supposition made about the influence of cutting tool wear on the generation of defects. To this purpose, three different tests are available for evaluating performances of a shaving machine over time:

- **Test 1: Machine A – Pinion 1,** These pinions were measured consecutively
- **Test 2: Machine A – Pinion 1,** These pinions were measured periodically, in order to expand the time elapsed from the first element and the last of the population
- **Test 11: Machine A – Pinion 1,** These pinions were measured periodically as for Test 2, but the test has been repeated after a certain period of time, to inspect eventual alterations

Now, a detailed Capability analysis divided by analyzed parameter, in order to detect which ones are not enough capable, and so, must be improved to avoid risk of generating defects.

Cα: Convexity of Involute profile



5.5.5.18 Ca Shaving process Capability Machine A

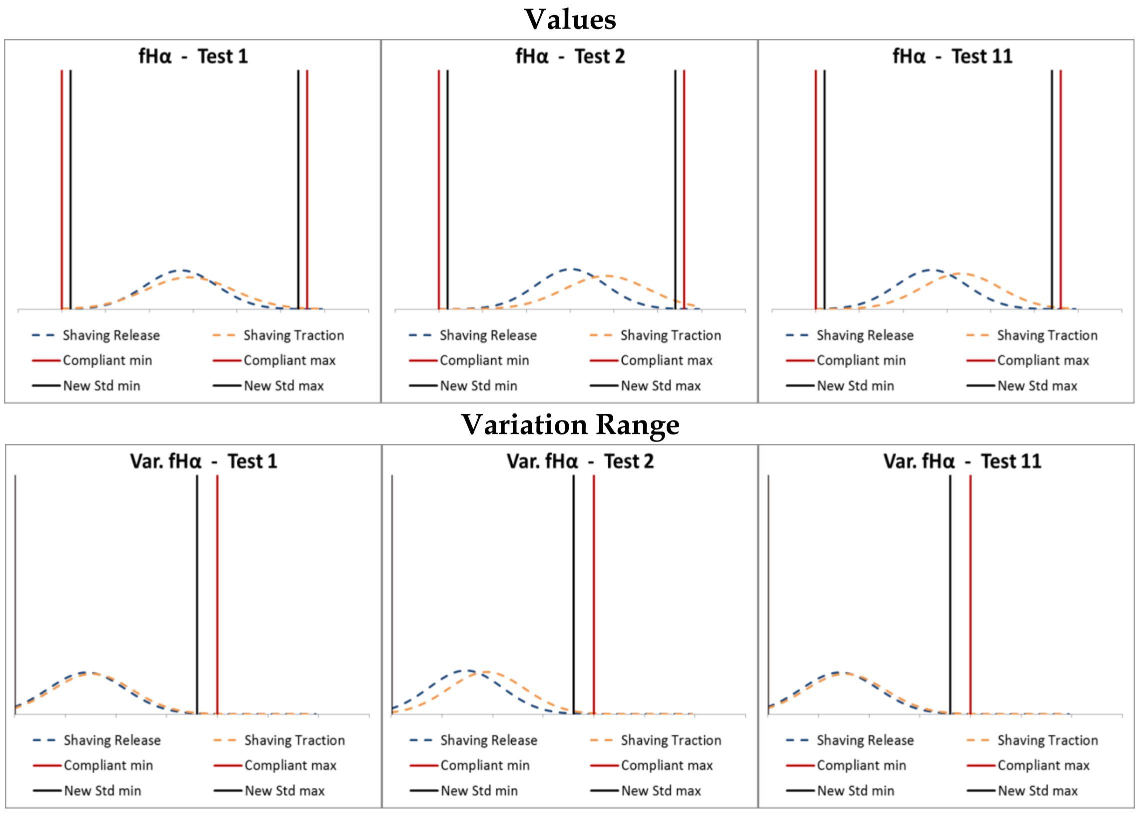
These plots represent the Gaussian normal distribution of measured Cα values before heat treatment, immediately after shaving operations. First plot presents the distribution of each single value available, considering a tooth profile as a unit and not a pinion. Second plot instead shows the distribution of the average value Cα among all measured teeth of selected pinions, which in this case is the unit. For each measured tooth, it has been distinguished the side stressed during Traction, Orange dotted line, from the other stressed during Release, Blue dotted line, which by design are always the opposite geometrical side of the tooth, the left and the right, of course the one corresponding for example to Traction is related to the definition of the geometrical left/right side of the tooth, according to component techical design. From these plots it is evidenced that:

- In general, Cα capability is not high enough as:
  - Cpk ≈ 1 when considering Current tollerance range
  - Cpk < 1 when considering New more restrictive compliance range
- Consecutive parts (Test 1) have an higher capability than parts measured after defined time periods (Test 2 and Test 11).
- The same test performed after a certain period of time leads to different capabilities (Test 2 and Test 11) this means that the process is highly variable with time, as different factors can affect the process. Something that cannot happen if it is

considered a population of consecutive pinions, with the same tool and the same tool wear.
- The Side destined to Release has, in general, an higher capability for Cα.
- Comparison between the distribution of values and their average in a pinion shows that:
  - In Test 1 the average Cα is kept identical for all consecutive pinions, with a capability very high Cpk > 2, more then necessary.
  - In Test 2 and Test 11 average Cα distribution is almost equal to the distribution of the single values. This means that i

First results confirm that some factors changing over time can influence the process capability. Especially concerning the position of the average Cα among the values of a single pinion. For Consecutive wheels, the average is constant while the values oscillate around the center with an acceptable capability. However, considering instead a population of non consecutive pinions, introducing factors as tool wear or tool substitution this is no more valid. This could be caused by cutting tool wear, or even by an incorrect design of the regeneration cycle of the cutting tool.

fHα: Angle error of Involute profile

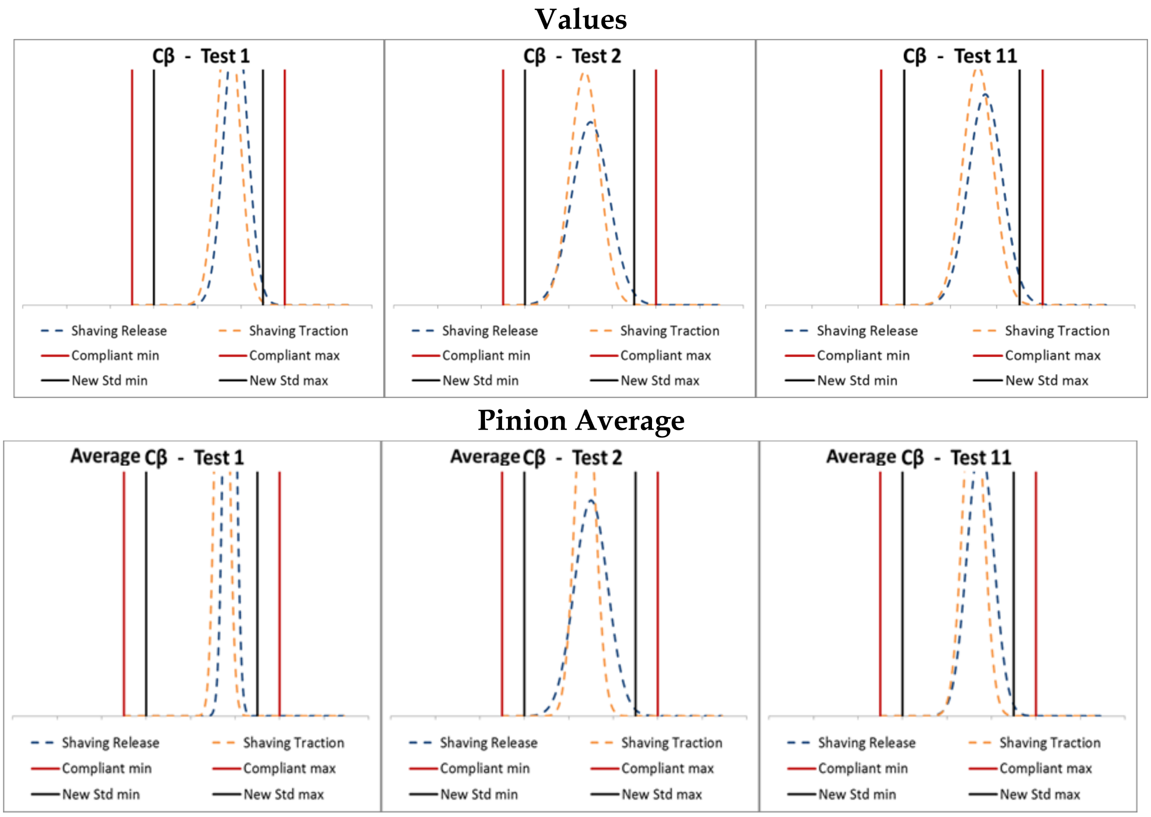


5.5.5.19 fHa Shaving process Capability Machine A

Same scheeme has been applied for fHα. First plot shows all values available for three tests performed on Machine A for Pionion 1. Second plot instead show the Distribution of Ranges among all pinion measured. Where the measure considered is the Var. = fHα max - fHα min, which sufficiently represents the distribution of the range amplitude of values for all pinions. Again, Traction is plotted in Orange and Release in Blue. What emerges from these plots is:

- In general, Cα capability is not high enough as:
    - Cpk > 1 when considering Current tollerance range
    - Cpk ≈ 1 when considering New more restrictive compliance range
- There are no significant differences between consecutive components and components manufactured after certain time delay. This means that fHα is not strongly affected by condition of cutting tool
- The difference between Traction and Release is lower for consecutive pinions
- Range of values for a pinion does not change with time and wear of cutting tools. This is proven by the similarities among Test 1, 2 and 11 in second plot Var. fHα.

Cβ: Convexity of Helix



5.5.5.20 Cβ Shaving process Capability Machine A

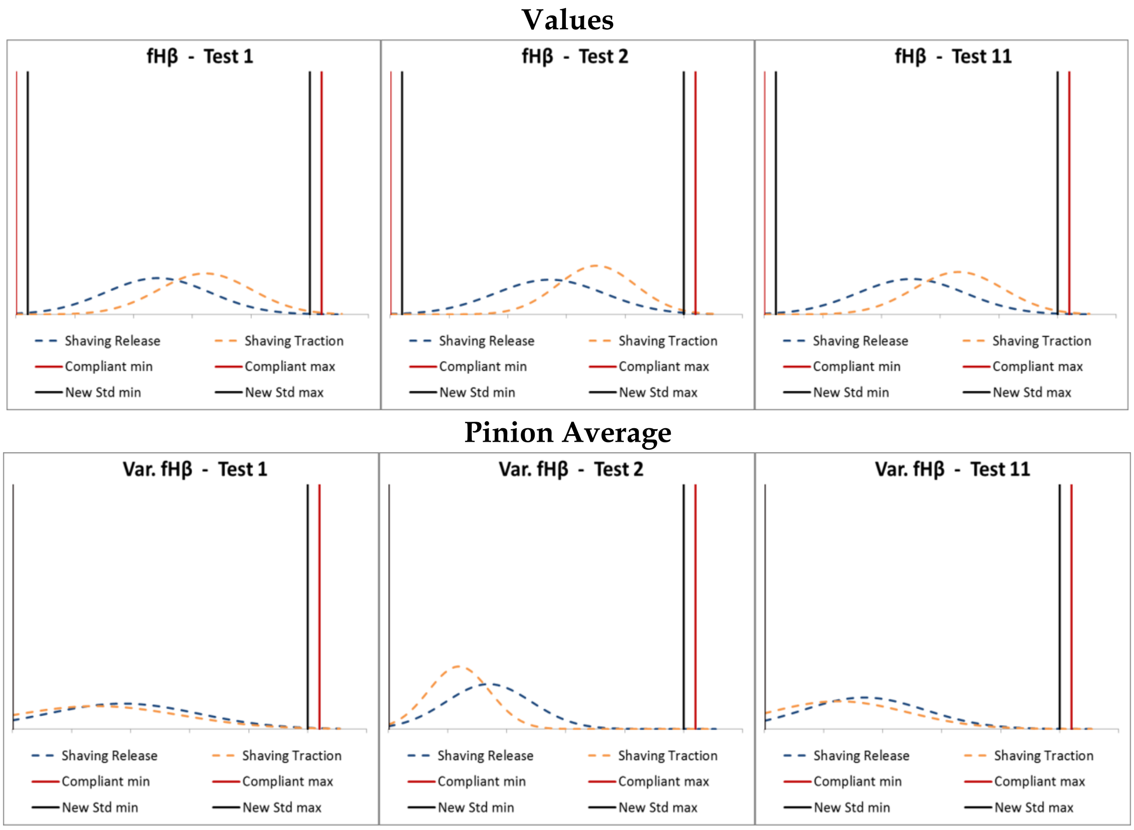
These plots represent the same gaussian distribution seen before but referred parameter Cβ. First one presents the distributions of all measured values during Tests 1, 2 and 11. Second one focuses on pinions, showing the distribution of their average value of parameter Cβ among all measured Helix measured for each pinion. The comparison between the three tests allows to draw other conclusions:

- In general, Cβ capability is optimal from the precision point of view, but an improvement is possible as the process is not perfectly centered in tollerance range:
    - Cp > 1.67 when considering current tollerance range
    - Cpk ≈ 1.33 when considering current tollerance range
    - Cp > 1.33 when considering new more restrictive compliance range
    - Cpk ≈ 1 when considering new more restrictive compliance range
- Consecutive parts (Test 1) have an higher capability than parts measured after defined time periods (Test 2 and Test 11).

- In this case Test 2 and Test 11 gives similar results.
- The Side destined to Traction has, in general, an higher capability for Cβ.
- Comparison between the distribution of values and their average in a pinion shows that average distribution is similar to value distributions for non consecutive pinions (Test 2 and Test 11), while for consecutive pinions (Test 1) the average is very precise, with a capability $Cp > 2$, but this is not maintained over time.

Results obtained from Cβ analysis are completely different from the ones obtained for the conceptually similar parameter Cα. Capability for this parameter after shaving operations is higher than for Cα, but still it is necessary to center the process in the middle of tollerance range to obtain the best performances. The influence over time on Cβ is less important than on Cα. This means that assumptions made for the involute may not apply to helix. Only the comparison between values and their average for each pinion gives the same results. Capability is very high for Cβ, so this parameter is particularly good after shaving.

fHβ: Angle error of Helix



5.5.5.21 fHβ Shaving process Capability Machine A

Final parameter to be considered is fHβ. First plot shows distribution of values, while the second presents the distribution of variation ranges within a single pinion. Comparison between three tests allows to draws other conclusions:

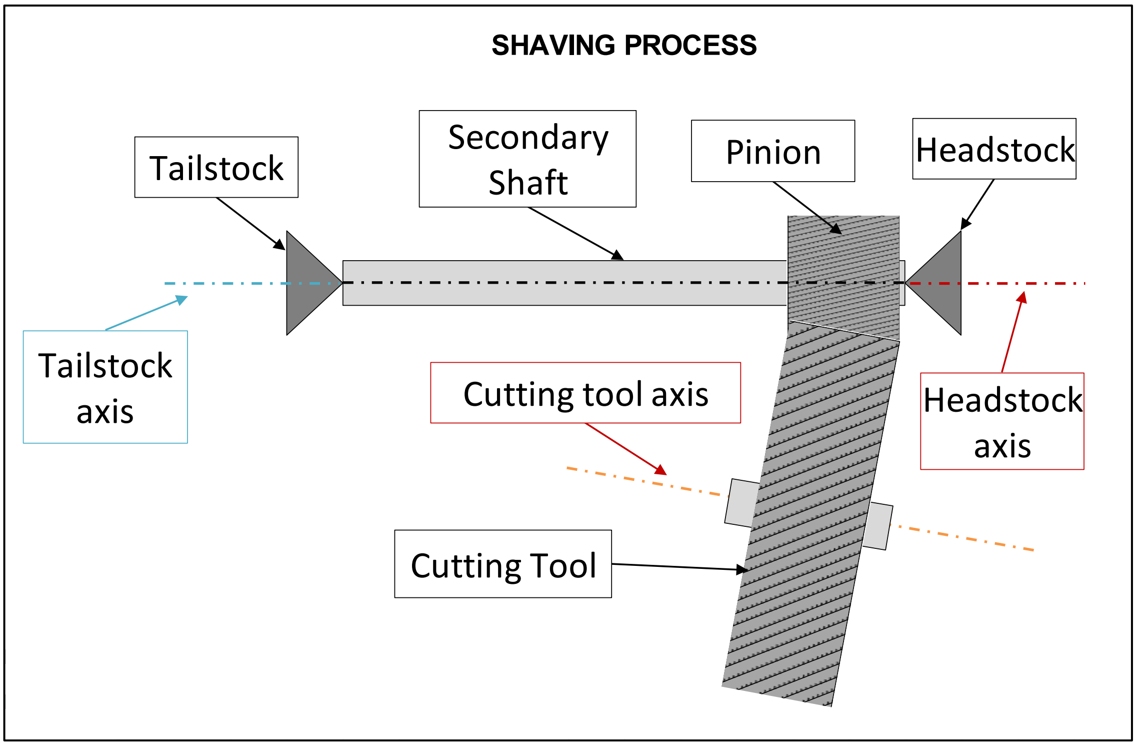
- Capability of fHβ is high and enough centered, both for Traction and Release, even if also for this parameter there is a significant difference between the two sides.
- Process capability is not variant with time, as distributions of values for different tests are similar

- For what concerns Variation Range within single pinions Test 2 shows a better capability. This means that the parameter can be improved by machine and cutting tool setup
- For higher values it is easier to obtain smaller Variation Ranges. In all three tests, Distribution of traction values have an higher average and a smaller variation Range.

Machine standards require that each tool should shave a stated number of pinions, if follows a regeneration cycle, than the tool can reiterate this procedure given number of times before finally discarding the tool. Restoration cycle and number of parts machined with a cutting tool can be tuned in order to improve performances. From the analysis is evident that shaving tool is determinant for shaving process, especially for what concerns $C\alpha$ parameter. While $C\beta$ should be analyzed from machine point of view to move the average value and better center the distribution inside the new standard tolleration range.

Machine Parameters: First it is useful to explain how shaving process works. The product, in this case a shaft, is fixed between a fixed Tailstock and an adjusting headstock. The machine starts shaft rotation, trough its anchorages that must be aligned. An important role is played by bearings of Headstock and Tailstock, that must guarantee rotation and concentricity of rotating axis of both machine components, together with machined shaft. The pinion is shaved trough a specific gear wheel commonly called Shaving tool, which is set to have an offset angle from machined component, according to the angle of the helix, and to guarantee material removal from a side of the helix to the other. Rotating around its axis, cutting tool proceeds with the finishing of the pinion. Machines parameters that mostly affect product quality are the following:

- **Tailstock axis:** Rotating axis of tailstock, determined by its supporting bearing.It must ensure the correct positioning of machined shaft, and guide its rotation without offsets from the correct rotation axis.
- **Headstock axis:** Rotating axis of headstock, determined by its supporting bearing.It must ensure the correct positioning and fixing of machined shaft, and guide its rotation without offsets from the correct rotation axis.
- **Cutting tool axis:** Rotating axis of cutting tool, determined by its supporting bearing.It must ensure the correct orientation of shaving tool, and guide its rotation without offsets from the correct rotation axis, which as said is not perpendicular but skewed with respect to shaft rotating axis.
- **Cutting tool:** This is the most important component in the shaving process. The shape of cutting tool teeth determines the quality of production, when all rotating axis are compliant with standards defined by machine constructors. An important requirement for shaving tool is to use a number of teeth not multiple of machined component number of teeth, in order to ensure that for each round, pinion teeth will couple with different teeth of shaving tool, and avoid that the coupled profiles are always the same. This is necessary to avoid periodicities on tooth profiles determined by small imperfections on shaving tool. The shape of teeth profiles of cutting tool can be tuned in order to adjust pinion teeth profiles. Tuning can affect directly $C\alpha$ and $fH\alpha$, while for what concerns $C\beta$ and $fH\beta$, the role of cutting tool is marginal.



5.5.5.22 Scheme of Shaving process

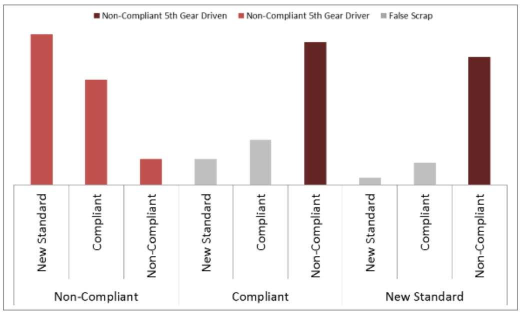
Status of Machines: Machine parameters have been analyzed in details. For what concerns rotating axis:

- **Machine A:**
  - **Headstock axis:** Compliant
  - **Tailstock axis:** Compliant
  - **Cutting tool axis:** Compliant
- **Machine B:**
  - **Headstock axis:** Compliant but Higher than Machine A
  - **Tailstock axis:** Compliant but Higher than Machine A
  - **Cutting tool axis:** Compliant but Higher than Machine A

While cutting tools are compatible with both machines and specific for each pinion. For production reasons, Cutting tool of Machine A, used for Pinion 1, is not used on Machine B, while Pinions 2, 3, 4 and 5 have different cutting tools equipped to Machine B. All typologies of Cutting tools have a specific and standard restoration cycle performed using a dedicated machine. Each restoration is verified with teeth profile measurements, to ensure compliant of cutting tool before deployment to production for its use.

5.6 Design of Experiments for Defective 5th Gear Wheels

Experiments performed for Pinions are repeated identical for both driver and driven 5th gear wheels. The starting point is the Fast-Response Showcase. Part of transmissions discarded for Noise on 5th gear after NVH analysis are disassembled and defective gears are analyzed measuring their microgeometry parameters for several teeth. The Output of the analysis is a proposal of a New Standard , more restrictive than the requirements. The target of this New Standard is to reduce false scraps, which for this problem are more evident than for pinions. Measurements on defective components confirm that if a component respects the more restrictive New Standards, the false scrap is reduced. The final goal of this analysis is to improve Production process capability, to reduce number of defects and also false scraps.



5.6.0.1 5th Gear wheel couples of defective transmissions

This Chart presents all the combinations of driver and driven 5th Gear wheels analyzed in Fast Response Showcase. In most cases, Noise is generated only by one non compliant wheel in the couple, this is expected considering the overall high capability of the process, and the low probability of couple two non compliant wheels. The columns related to New Standard comprehend all wheels Compliant both for Official Requirement and new Proposed tollerances, while Compliant colums include only gears respecting requirements but not the New Standards. In Red the total amount of cases of Noise generated by non-compliant driver wheel, in dark red cases caused by non-compliant driven wheel. In gray are reported all cases of false scrap. It is interesting to notice that the couple having both wheels respecting new standards is the one that appear with less frequency in Fast-Response-Showcase.

5th Gear Wheels are manufactured in several versions, but the production system is identical and only variable among them is the number of teeth and transmission ratios. For this reason, the analysis will consider only three versions:

- **5th Gear Wheels 1:** Due to high volumes, are machined using full time two shaving machines.
- **5th Gear Wheels 2:** Low volumes and maximum transmission ratio among all versions.
- **5th Gear Wheels 3:** Low volumes and minimum transmission ratio among all versions.

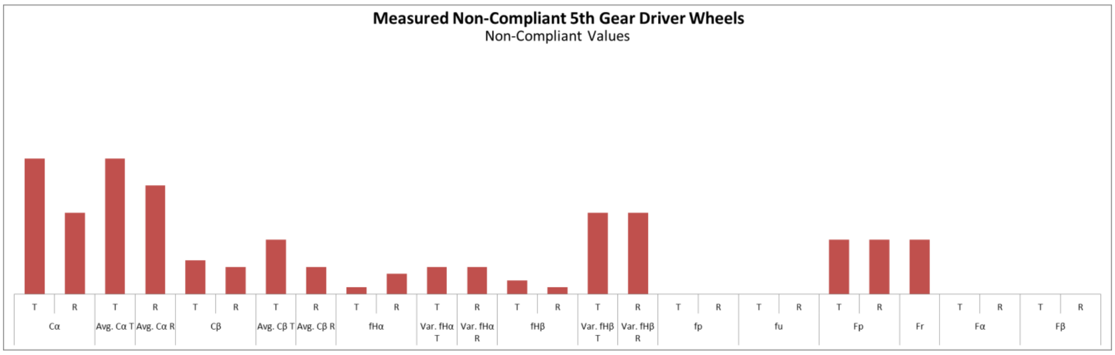
Shaving Machines involved are instead four:

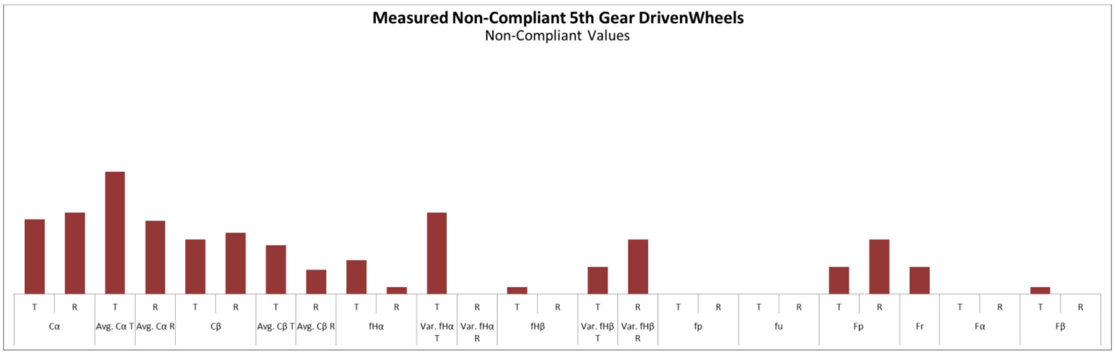
- **Machine C:** Dedicated to Driver wheel of 5th Gear 1.
- **Machine D:** Dedicated to Driven wheel of 5th Gear 1.
- **Machine E:** Destined to Driver wheels of all other low volume versions of 5th Gears.
- **Machine F:** Dedicated to Driven wheels of all other low volume versions of 5th Gears.

	Machine C	Machine D	Machine E	Machine F	Production volumes
5th Gear Driver 1	X				High
5th Gear Driven 1		X			High
5th Gear Driver 2			X		Low
5th Gear Driven 2				X	Low
5th Gear Driver 3			X		Low
5th Gear Driven 3				X	Low

5.6.0.2 5th Gear wheels and Machines for experiments

All values measured from Defective 5th Gear wheels obtained trough Fast-Response Showcase were plotted. For all parameters, it is evaluated the fraction of values out of New Standard requirements.





5.6.0.3 Measured parameters for defective 5th Gear wheels

For Both wheels it is evident that main parameters non-compliant for cases presenting noise are:

- Cα and Average Cα
- Cβ and Average Cβ
- Variation Range of fHα
- Variation Range of fHβ

To better understand the importance of each parameter on noise generation, it is necessary to compare previous plot with the equivalent related to normal production obtained trough Design of Experiments test. It is expected that the fraction of measures not respecting new Standard will be higher for defective components for parameters influencing noise, while should be equal for other parameters. This means that requirements introduced with New Standard can be neglected for all parameters non influencing noise. For sake of simplicity, as the procedure is identical to the one applied to Pinions, we will only focus on Main transmission Ratio for 5th gear, neglecting all low production models. The analysis was performed on three versions of 5th Gear wheels, and results were similar to each other, and especially similar to pinions. From now on, a part from analysis of Defects from Fast-Response Showcase and parameter non respecting New Defined Standards for 5th Gears, the output presented in this project will focus only on the differences from Design of Experiments performed for Pinions, neglecting the similarities as already well explained in previous pages.

Test	Machine	Component	Quantity	Frequency	Machine Parameters
1	**C**	**Driver Wheel 1**	50	Consecutives	Compliant
2	**C**	**Driver Wheel 1**	50	Periodic measurement	Compliant
3	**D**	**Driven Wheel 1**	50	Consecutives	Compliant
4	**D**	**Driven Wheel 1**	50	Periodic measurement	Compliant
5	**E**	**Driver Wheel 2**	50	Periodic measurement	Compliant
6	**F**	**Driven Wheel 2**	50	Periodic measurement	Compliant
7	**E**	**Driver Wheel 3**	50	Periodic measurement	Compliant
8	**F**	**Driven Wheel 3**	50	Periodic measurement	Compliant
9	**C**	**Driver Wheel 1**	50	Periodic measurement	Compliant
10	**D**	**Driven Wheel 1**	50	Periodic measurement	Compliant

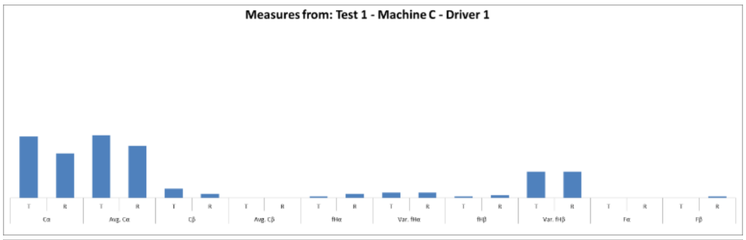
5.6.0.4 List of experiments for *5th Gear wheels*

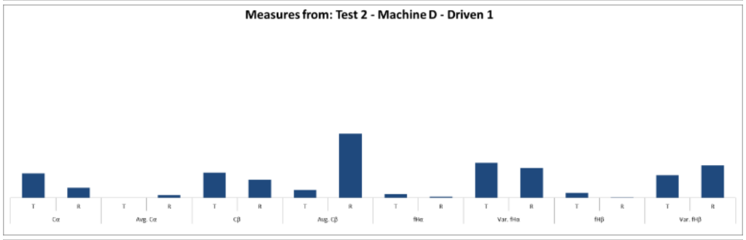
The table presents the schedule of Tests:

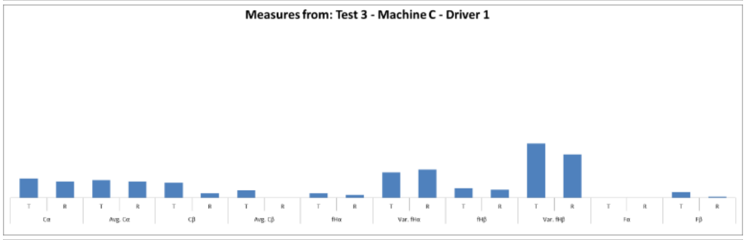
- **Test 1:** Aims to evaluate maximum process Capabilty for high volume driver wheel 1, by taking as sample a population of consecutive components.
- **Test 2:** Aims to evaluate maximum process Capabilty for high volume driven wheel 1, by taking as sample a population of consecutive components.
- **Test 3:** Aims to evaluate normal production Capabilty for high volume driver wheel 1, by taking as sample a population of non consecutive components. Useful also to evaluate an eventual influence of time on shaving process.
- **Test 4:** Aims to evaluate normal production Capabilty for high volume driven wheel 1, by taking as sample a population of non consecutive components. Useful also to evaluate an eventual influence of time on shaving process.
- **Test 5:** Aims to evaluate normal production Capabilty for second Machine and low volume driver wheel 2, by taking as sample a population of non consecutive components.
- **Test 6:** Aims to evaluate normal production Capabilty for second Machine and low volume driven wheel 2, by taking as sample a population of non consecutive components.

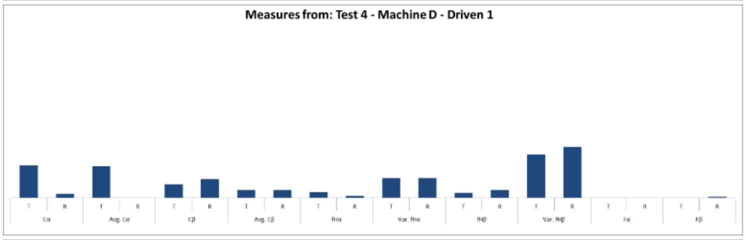
- **Test 7:** Aims to evaluate normal production Capabilty for second Machine and low volume driver wheel 3, by taking as sample a population of non consecutive components. Useful also to evidence similarities and difference among versions.
- **Test 8:** Aims to evaluate normal production Capabilty for second Machine and low volume driven wheel 3, by taking as sample a population of non consecutive components. Useful also to evidence similarities and difference among versions.
- **Test 9:** Aims to evaluate normal production Capabilty for high volume driver wheel 1, by taking as sample a population of non consecutive components after introduction of countermeasures.
- **Test 10:** Aims to evaluate normal production Capabilty for high volume driven wheel 1, by taking as sample a population of non consecutive components after introduction of countermeasures.

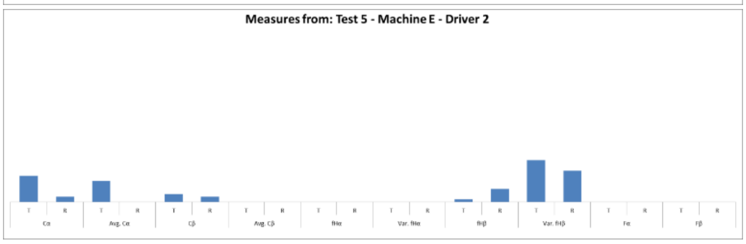
Following plots will show obtained results, which in part confirm the expectations:

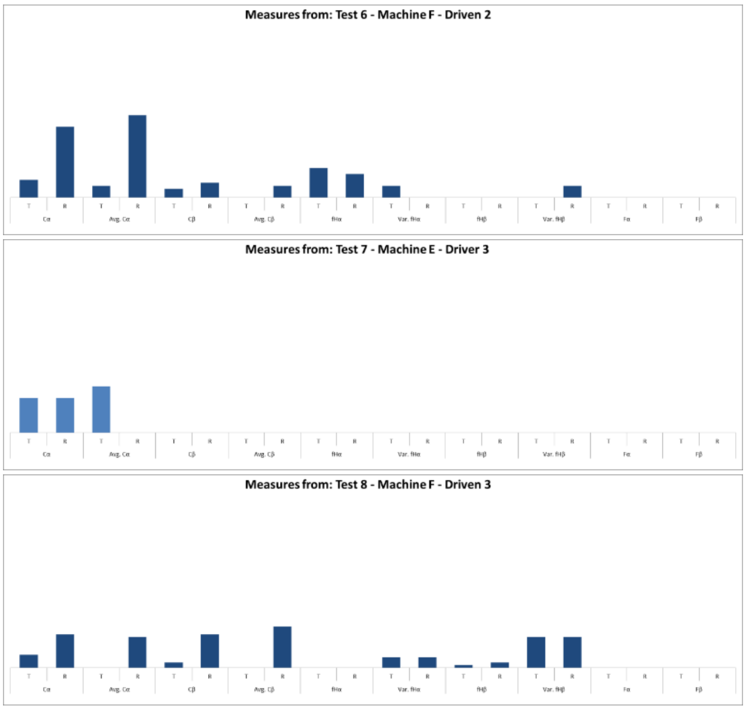








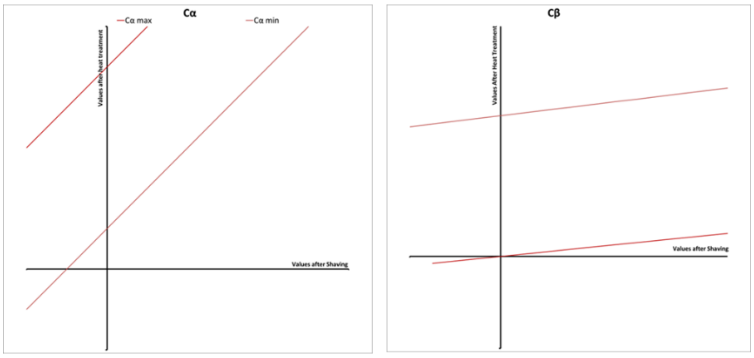




5.6.0.5 Measured parameters for Tested 5th Gear wheels

As Expected, all Tests evidence values of Cα, fHα, Cβ and fHβ non compliant with New Standards, but with a fraction which is lower than that measured for defective components. In particular, the major difference is on Cα. Convexity of Involute profile can be assumed to be the main factor influencing noise generated by 5th gear couple.

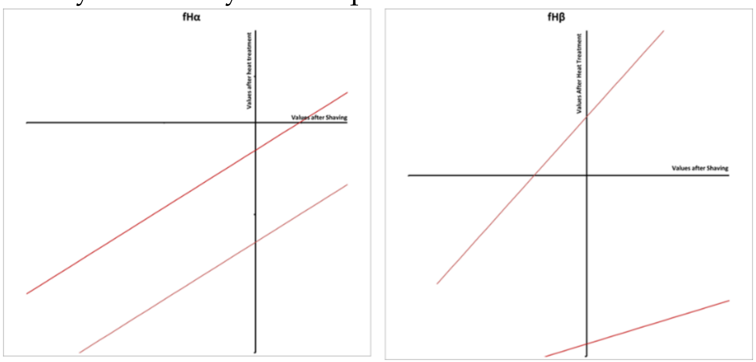
From now on, all considerations will focus only on 5th Gears 1, without distinguishing from Driver wheel and Driven wheel, as their behaviour is similar. Before finding countermeasures it is necessary to understand the influence of Heat treatment on production process. Plotting for each measured profile a point on a plane having as abscissa its value after Shaving and on ordinate its value after Heat Treatment it is possible to evidence correlations between these two operations, and from that utilize a mathematical model to forecast the possible range of a certain shaved profile after heat treatment.
For what concerns Cα, the parameter is controllable thanks to a linear correlation. Plots show that the tangent of the trend line is almost unitary, while the offset is positive, that means that in general, it is not possible, after heat treatment, to obtain values lower than the ones measured previously after shaving operation. Heat treatment tends in fact to increase the entity of covexity of teeth Involute profiles. These considerations are identical to the ones obtained for pinions. This means that Cα modifications due to heat treatment are always the same independently from evaluated components. This is a very important result, because it allows to apply the same analytical model also for other components, as for example 4th Gear wheels representing third main problem related to FTQ.



5.6.0.6 Analytical model for Convexity of Involute Ca and Helix Cβ on 5th Gear wheels

Also Cβ shows a linear correlation between measures taken after shaving and after heat treatment. This is worse than for Pinions, the correlation is almost horizontal, this means that for each value associated to an helix profile, it is impossible to forecast with precision what will be the same measure after heat treatment. For what concerns convexity of helix, considerations made for Cα are not valid in general for entire production if the target is to tune with precision this parameter. However, from a general point of view, Cβ of 5th gear wheel behave as Cβ of pinions, but with a smaller tangent of linear curve, so with a lower capacity of improvement by tuning shaving operations.

Also fHα has a precise linear behaviour as Cα. Confirming the strong correlation between shaving and heat treatment for what concerns Involute profile. Again, analytical model is identical to the one obtained for pinions. This means that it is possible to tune Shaving operations to improve the final result after heat treatment, knowing the analytical formula that allows to predict with a certain precision limited by error ϵ, independently from analyzed component.

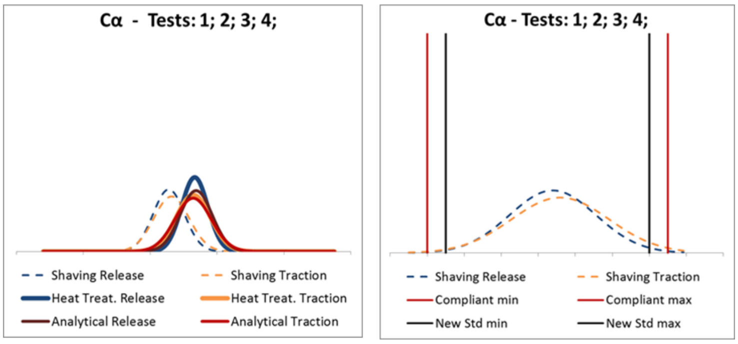


5.6.0.7 Analytical model for Angle error of Involute fHa and Helix fHβ on 5th Gear wheels

Finally, considerations about fHβ are identical to the ones for Cβ. Helix is in general incontrollable during shaving, as after heat treatment measures are not predictable with sufficient precision. This is valid also for pinions.

Cα has been assumed to be the main parameter influencing noise for 5th gear wheels. For sake of brevity, all other parameters will be neglected, as showing again results similar to the ones already presented for pinions and not leading to useful results it is not interest of this project.

After defining mathematical model, it is necessary to prove its effectiveness. This is made by a comparison between measured data after heat treatment, and application of the model to relative profiles measured after Shaving Operations. Again the model confirms its effectiveness, as shown in the chart, the distributions in Red and Dark Red are similar respectively to Orange and Blue, which indicate real values measured after heat treatment for Traction side and Release side. Mathematical model is introduced to define a Tollerance Range also for shaving operations, to give a guide for tuning of finishing operations in order to obtain desired values of Cα before heat treatment. All deformations and high variability introduced by Heat Treatment are considered for definition of shaving tollerancies. This allows to focus only to finishing operations, with the final target of improve Cα measures before 5th Gear wheels can enter Heat Treatment.



5.6.0.8 Shaving Process Capability for 5th Gear wheels

Finally, the distributions of Release Side and Traction Side of shaving process, related to its defined tolleration ranges. Results evidence that Capability is not sufficient as on the upper side a wide area under the Gaussian distribution is beyond red and black lines, representing respectively current requirements and New introduced Standards. The target is to improve Cpk by lower the mean value by tuning the Shaving machine cutting tool restoration cycle. Current situation have a Cpk ≈ 1. The expected improvement after applying countermeasures is a Cpk > 1.33.

Chapter 6 DO: Application of Countermeasures for FTQ Improvement

After analyzing check phase of Kaizen Problem solving procedure, it is now time to explain the applied countermeasures. Difference between processes of Pinions and 5th Gear Wheels are negligible, however, Pinions have more problems related to noise, and their solution is more complicated than the one for 5th Gear wheels.

6.1 Noise of secondary shaft pinion - differential crown wheel couple

First countermeasures to be explained are the ones related to Pinion Shaving Machines. Deep analysis performed guides to several actions to be applied in order to improve shaving process and better monitor its capability, to avoid degradation of process quality and generation of defects. The monitor period is twelve weeks long, and it is necessary to evaluate the correctness and effectiveness of introduced modifications, which are the following:

- **Restoration of Basic conditions on Machine B:** As mentioned before, backlash on rotating axes of Tailstock, Headstock and Cutting tool of Machine B were higher than other machines. First countermeasure to reduce defect generation was restoration of basic conditions of this Shaving machine.

- **Modification of Cutting tool Restoration programs:** To obtain, on pinion teeth profiles, values of Cα and fHα within new introduced requirements, which take in account also the variability introduced by heat treatment process.
- **Periodical controls on production:** Control Plan, actually require periodical checks to ensure the correct status of shaving tools. Considering the introduced more restrictive tollerances, the number of pinions machined before each restoration can be reduced if values during checks does not respect the new standards. This is still a preventive action, as ufficial standards can still be satisfied when the tool wear does not guarantee the new Standard tollerances. This point, in particular, is still not completely defined because the costs of scraps must be compared to costs of more frequent retooling of shaving machines and restoring of cutting tools, before establishing officially a new standard. The Period of Check is twelve weeks long for this reason. After the monitoring period, all modification will be standardized and the problem will be considered as solved.
- **Introduction of periodical checks of machines parameter in AM cycles:** Defect modes are tabled in form of X-Matrix. The target is to identify the entire chain of causes and effects, from defect to machine parameters to be monitored in order to avoid the generation of defects.

6.1.1 X-Matrix for Shaving Machine

To better monitor process quality, it is useful to build an X Matrix for each shaving machine. This tool allows to correlate the defect modes to the phenomena, to machine component, to machine parameters. The target is to identify the correct values of measurable machine parameters, and correlate them directly to defect modes. The Matrix includes defect modes related to Noise percieved in Functionality Test, and machine parameters to check. As already mentioned, the main defects related to noise are non compliances on measured parameters Cα, fHα, Cβ, fHβ on teeth profiles concerning involute profile and helix, errors on circular pitch and error on concentricity. These defects are directly correlated to several phenomena related to shaving machine, as an eccessive backlash on supporting bearings, or a wrong restoration of cutting tool. These phenomena are directly connected to certain components of the machine and verification of their correct functionality. The role of this Matrix is to identify a list of periodical checks to perform during Autonomous Maintenance cycles, or during Professional Maintenance preventive cycles, to guarantee product quality by Quality Maintenance on Shaving machines.

6.1.2 QM-Matrix for Shaving Machine

After X-Matrix it is useful to build related QM Matrix. This tool helps scheduling preventive maintenance cycles and understanding the effectiveness of these checks. Starting from Machine components and related parameter to measure, QM Matrix specifies for each control the measuring instrument to be used, required Compliance tollerances, frequency and the responsible that must perform the check. In the end, QM Matrix also integrates 5QFZD for each check, to evaluate its effectiveness.

6.1.3 5QFZD – Five Questions for Zero Defects

WCM requirements specify a Score of at least 80% for 5QFZD, but QM Matrix shows that this score is reached only for an automatic Check performed by machine to verify the funcioning of Machine positioning system, which surely is not the root cause of pinions analysed in this project. When score obtained with 5 Questions For Zero Defects, the applied countermeasure is not Robust. This means that, even if introduced modifications are effectively solving the problem, it is possible that these conditions of respected Quality could change over time, and the defect could be generate again. To improve 5QFZD score it is required the purchase of expensive measuring systems to be installed on the machines. This represents an investment greater than the damage caused by defects that could be again generated. In this case, the final decision is driven by the negative Benefits / Costs ratio, which imposes to accept this solution despite not being strong enough to solve the problem permanently.

6.2 Noise of 5th gear couple

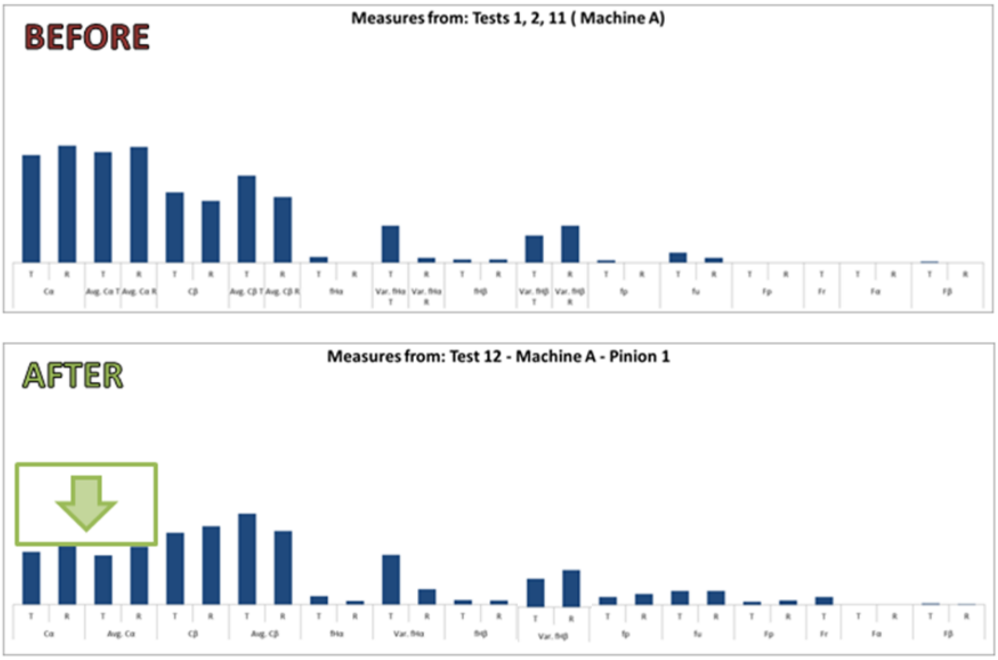
The same identical procedure is applied also to Shaving machines destined to 5th Gear Wheels. Technology of process, and constructor of the machines are common, for this reason X-Matrix and QM-Matrix can be directly applied to all similar Machines without performing other analysis. The only different between pinions and 5th Gear Wheels is the current status of shaving machines. Pinions machined with Machine B evidenced high fraction of non-compliances for circular pitch and concentricity, while this problem is not evident on 5th Gear Wheels. This is strictly correlated to non-compliances of Headstock, Tailstock and Cutting Tool rotating axes of Machine B, whose restoration should give an immediate improvement for these parameters. Other expected results are a reduction of $C\alpha$ values out of New Standard requirements, for both pinions and 5th Gear wheels, and finally, a reduction of defects together with an improvement of FTQ index.

Chapter 7 CHECK: Monitor of Obtained Results

After the application of countermeasures, Kaizen procedure suggests a period of result monitoring to ensure the effectiveness of introduced actions. This period should last twelve weeks, if the results are satisfactory and improvement is stable, after the Check period the problem is considered completely solved and automatically enters the Act Step of Deming Cycle.

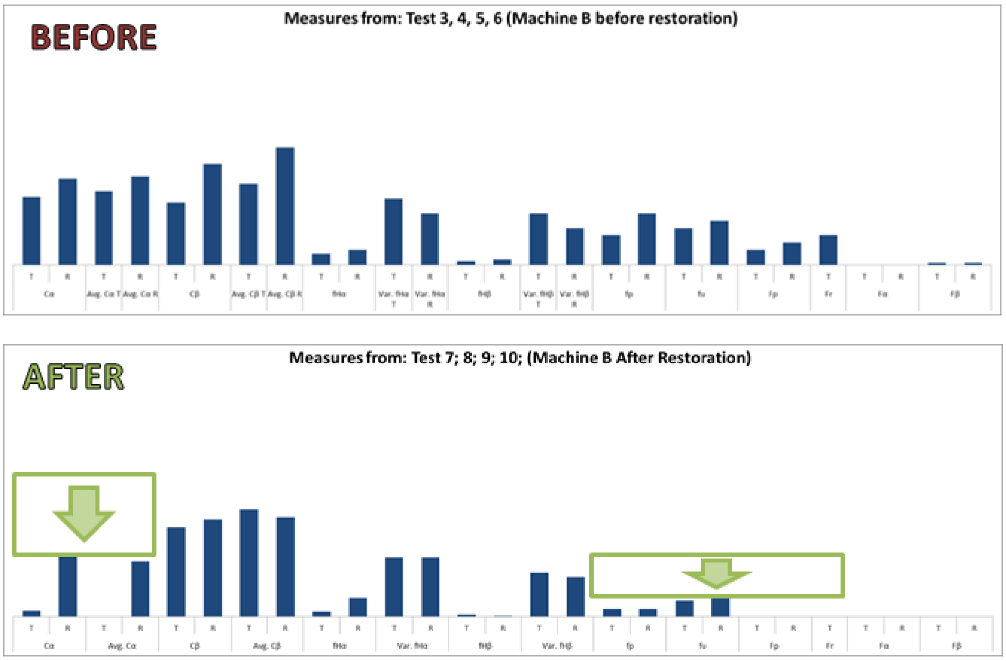
7.1 Noise of secondary shaft pinion - differential crown wheel couple

First results to monitor are the microgeometrical measures of Pinions, evaluated trough a new sample population of 50 components of Pinions 1 finished using Shaving Machine A. Charts represent the fraction of measures not respecting the proposed New Standards. First is presented the initial situation before modifications. Second chart shows the changes after corrective actions. As expected, parameter Cα is reduced, while other parameters does not show interesting variations.



7.1.0.1 Improvements on Machine A Pinion teeth microgeometry

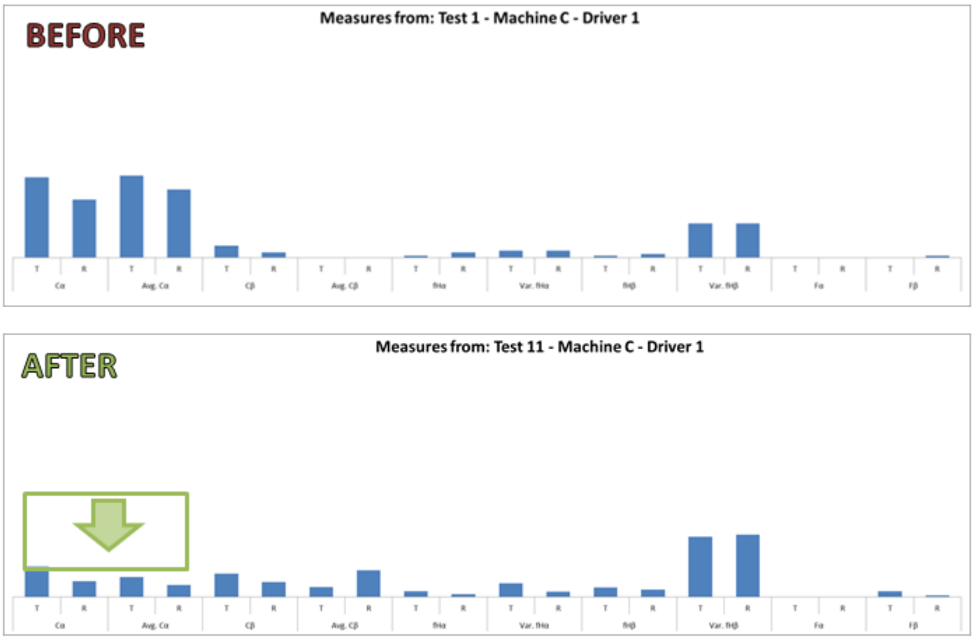
Same comparison is performed also for Machine B before restoration of machine rotating axes, and after introduction of all countermeasures. Four tests are included in a single diagram, one for each model of pinion finished using machine B. Before actions, machine non-compliances were causing low performances for what concerns circular pitch and concentricity. This problem is solved with machine restoration of support bearing of rotating axes of Headstock, Tailstock and cutting tool. Also in this case, changes on restoration cycle of cutting tool allow a reduction of Convexity of involute profiles on pinion teeth. This result confirms the expectations, the behavior of Machine B becomes identical to Machine A after restoration, and overall Cα parameter is reduced.



7.1.0.2 Improvements on Machine B Pinion teeth microgeometry

7.2 Noise of 5th gear couple

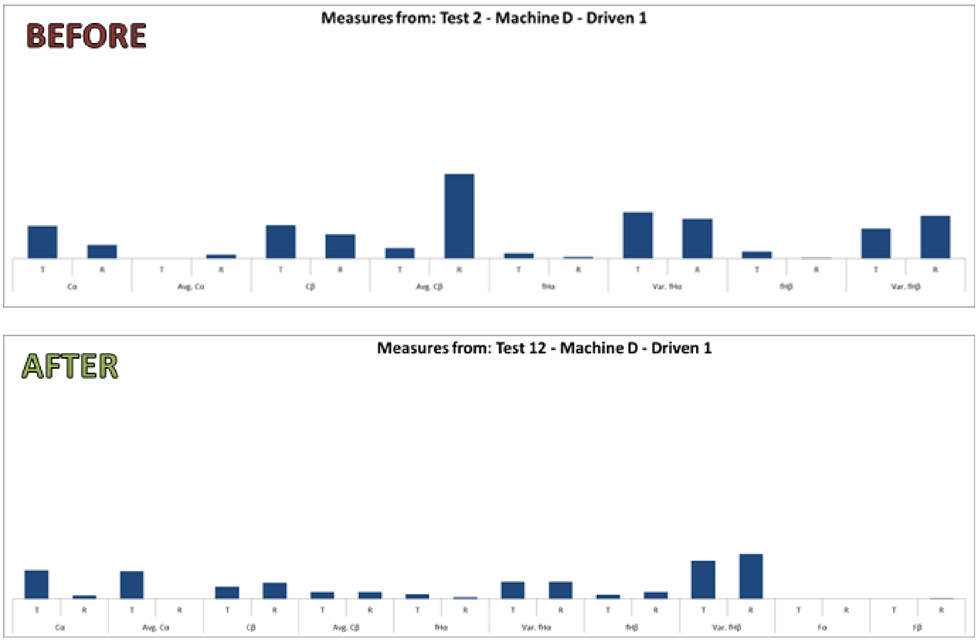
For what concerns 5th gears, only parameters not respecting New Standard requirements are Cα, Cβ and variations of fHβ. It was sufficient to tune shaving tool restoration cycle to improve microgeometry of teeth and reduce Convexity of Involute profile Cα.



7.2.0.1 Improvements on Driver 5th Gear wheel teeth microgeometry

It is interesting to show that Test 12, representing a population of 5th Gear Driven wheels finished using Machine D does not show improvements on Cα, because in this case, Convexity of Involute profile values before countermeasures were already similar to final results obtained during other tests. Diagram of Test 12 also evidence a reduction of

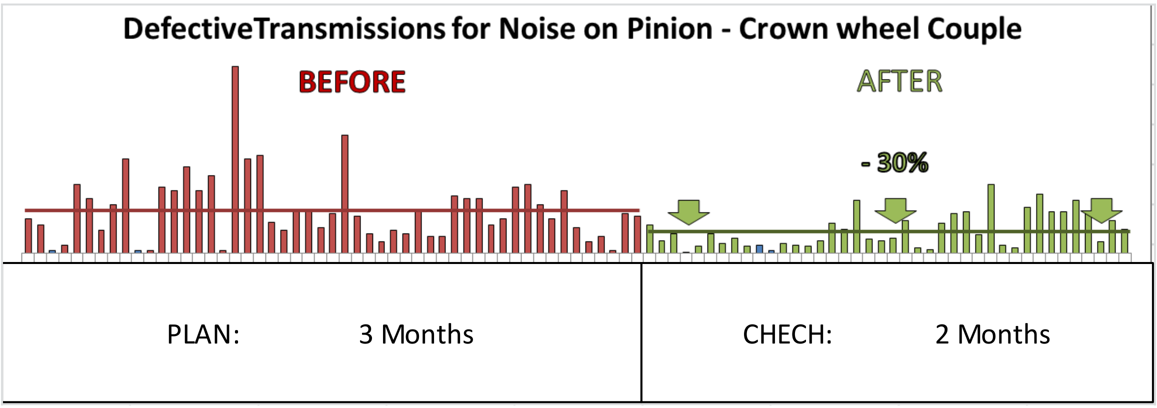
Cβ, but it cannot be associated to restoration cycle of cutting tool, but on random and uncontrollable variability of heat treatment.



7.2.0.2 Improvements on Driven 5th Gear wheel teeth microgeometry

7.3 Reduction of Defects

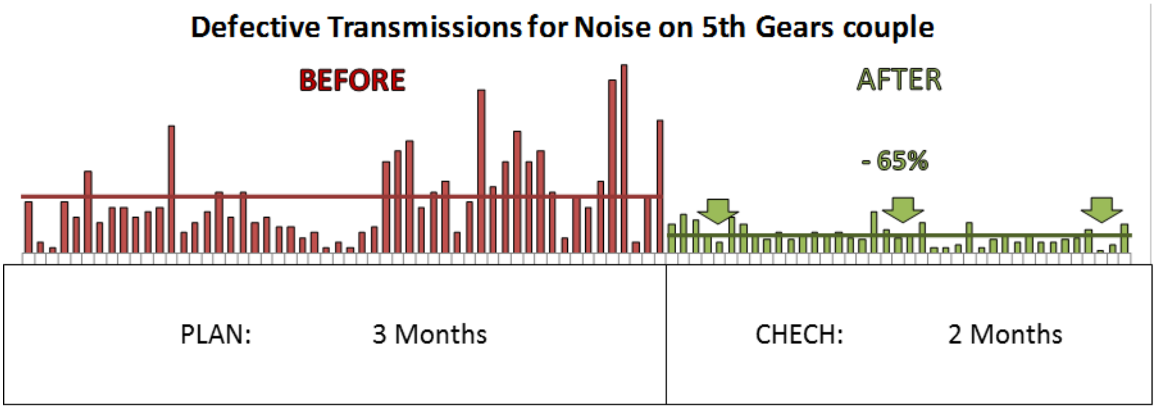
Finally, after considering modification of teeth microgeometry, it is interesting to monitor the history of defects. Project Plan phase required 3 months. For both problems analyzed, countermeasures were applied in the same period. Afterwards, it follows a part of Check phase of 2 months that will last for 12 weeks.



7.3.0.1 Reduction of defects for Noise on Crown wheel – Pinion couple

Chart evidence a reduction of scraps for Noise detected on secondary shaft and differential coupling immediately after countermeasure introduction. However, production process of pinions is very complex, as the gear is integral with secondary shaft, and in particular, shape and dimensions of pinion teeth cause an high sensibility to process variations, with consequences on product quality and number of defects. Applied countermeasures allowed an average reduction of scraps by 30%, lower than the target of 60%. This is due to the fact that defective pinions are generated also by other causes still under analysis.

Profiles of 5th Gears are simpler, production process achieves better results if compared to pinions. For this reason, number of defects generated by Noise on 5th Gear couple are effectively reduced with introduction of countermeasures. Defects are reduced of 65%.



7.3.0.2 Reduction of defects for Noise on 5th gear couple

The initial target of reduction by 60% of number of defects was achieved for noise on 5th gear wheels, while for pinions, the problem still remains as the root cause corrected was not dominant, and defects can be riconduced also to other problems that still require an analysis. Together, solutions found for two faced problems top on FTQ QA Matrix list has brought to an overall improvement of Plant FTQ. This represents an important result for quality and production, as reduction of scraps allows a higher productivity, a reduction of False scraps and number of functionality tests, together with a reduction of wasted money.

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