POLITECNICO DI TORINO

Dipartimento di Ingegneria Meccanica e Aerospaziale
Master Degree in Mechanical Engineering

Creation of a preventive and predictive maintenance system on automatic test benches for Stellantis transmissions

Advisor:
Prof. Francesca Maria CURA'

Candidate:
Nikole BALLA

Supervisors at FCA Italy Spa:
Ing. Alessandro GIAZZI
Paolo ROGNONE

ACADEMIC YEAR 2020/2021

Abstract

Present work goal is the know-how acquisition of structure and operation of an NVH test bench for Stellantis transmissions, with the aim of building its Quality Maintenance system by applying the 7 Steps of Quality Control Pillar (WCM).

Throughout the study, two main benches' chronic loss factors are detected and faced:

- Bearings overheating on "primary shaft" group;
- Tripods joint unscrewing and elastic joint breakage on "secondary shafts" group.

In both cases the Advanced Kaizen tool is implemented to analyse the issues, to verify the system according to the State of Art, and finally to make proposals of alternative layouts, in order to eradicate the loss factors.

After the Opening Chapter, the first Chapter is devoted to the presentation of Stellantis plant (Mirafiori Meccanica in Turin), the transmission C5.14 produced there and the stage activity run from March to September 2021 linked to the project; the following two Chapters contain information about the test bench and the theory of WCM applied in the study. In Chapters 5 is depicted the application of the 7 QC Steps to the case study and in Chapter 6 are set out the two Advanced Kaizen's development.

Final Chapter contains the results of the analysis, together with the impact quantification of the corrective actions implemented at Mirafiori Meccanica: it is proposed a focus over the beneficial effect on the Quality KPIs, which are affected by the excessive noise level recorded during the NVH test and caused by the two chronic loss factors attacked. It is shown the stable decrease of fake scrap after the issues resolution, and regarding the improvements which have yet to be realized, is proposed a road map for future works towards a further test benches' enhancement.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Study herein presented is the result of a Stage experience run in Mirafiori Meccanica PWT Plant, in Turin, from March to September 2021.

As a Quality Engineer Trainee, a work based on Quality Maintenance principles (WCM) have been done over plant's automatic test benches, used to assess the compliance of 100% Stellantis transmissions, model C5.14. The goal of the work is to acquire a strong *know-how* on test benches, creating an efficient maintenance control system of the machines, enhancing their mechanical structure and reliability.

Particularly, there's been taken care about chronic loss factors affecting the quality of NVH signals. The *Noise Vibration and Harshness* system is installed on every test bench and was introduced in the plant in 2015, in order to objectively detect products' defects, thus delivering to the Costumer only compliant items.

The work is organized in seven chapters: excluding the present one, aiming in introducing the reader to the Thesis' theme, they intend to clarify tools and theories applied -where needed- and to show adopted solutions and following results, judgmentally evaluating their impact over the plant's efficiency.

After a brief introduction of Mirafiori Powertrain Plant and an overview of transmission C5.14, in Chapter 3 is reported a detailed description of automatic test bench's: basis of NVH and Shift-ability tests, performed during a standard gearbox check, are described through hints, then a complete list of detectable C5.14 defects is reported, and finally some measurement issues are highlighted, focusing on the ones related to the background noise normally or *abnormally* produced by the bench.

In Chapter 4 it will be described the theoretical *World Class Manufacturing* principles and tools used during the study, giving special attention to Quality Control Pillar steps and to the concept of *Quality Maintenance*.

In Chapter 5 is proposed the practical application of QC steps to the specific case study, namely all *Quality Maintenance* tenets are implemented over a single test bench, *Thyssen5*, to be used as bench-mark and model for future test benches improvements. While analyzing possible machine criticalities, two design chronic loss factors are recognized and faced. To their punctual discussion is dedicated Chapter 6.

Here two Advanced Kaizen, corresponding to the two issues detected at previous step, are developed as they were carried out in Mirafiori Meccanica, acquainting the reader to the logic process behind the study and introducing him or her to the solution proposed, in order to permanently solve the issues.

Finally, in Chapter 7 are drawn the conclusions of the work, showing how the permanent corrective actions already implemented over Mirafiori Meccanica test benches have had a positive impact over Quality KPIs and over the fake scrap reduction, thus resulting in time and maintenance costs savings by the plant.

Chapter 2

Mirafiori Powertrain Plant

FIAT Mirafiori is and industrial complex in south Turin, in the self-titled area of Mirafiori. My stage experience took place in Mirafiori Meccanica - Gate 20, where the transmission C5.14 is produced.

As a trainee in Quality Engineering Department, whose role I covered for three months, I experienced the activity of the Quality Engineer, related to the measure of plant performances and the resolution of product's issues, arisen during weekly warranty meetings, moreover I followed preparation and conduct of the external Audit ISO IATF 16949, run by DNV Agency for the re-certification of FCA Plants.

Figure 2.1: Top view of the industrial complex of Mirafiori

The following four months, from the early June to September, were devoted to the study and the improvements implementation on the ThyssenKrupp automatic test benches, subject of the present thesis and deeply described from Chapter 5.

2.1 Plant throughout the years

Born in the early 1934, the industrial complex was needed to replace and enlarge the production lines previously set in Lingotto Plant [1]. After World War II the production of engines and transmissions started (1958); in 1991 the plant was completely devoted to the manufacture of transmission C5.14, the model actually produced and placed in many low-powered vehicles, such as Fiat 5oo and 5ooL, Lancia Ypsilon, Fiat Panda and Panda 4x4 [2].

Figure 2.2: Fiat Mirafiori in the 60s - coach-building at Gate 16

Since 2001 the 6 speeds version has been introduced, while the torque engine production was completely dismissed (2004). By 2008 the plant reached the goal of 10 millions C5.14 made and sold, nowadays it counts more than 22 millions of transmissions produced [2].

FIAT Spa grew through the years and modelled itself by joining other companies, gradually getting bigger and international. Here are briefly reported the milestones [3, 4, 5] characterizing the development of the company, focusing on the Mirafiori industrial area history:

- *1939*: Mirafiori Plant was inaugurated, having 22.000 employees on two shifts.

- *1956*: expansion of Mirafiori Plant (doubling the covered area) named "Mirafiori Sud".

- *2000*: joint venture of FIAT Spa with General Motors, the world's largest car-maker.

- *2014*: after the economic crisis of 2008, which caused severe troubles to the Chrysler Group, FIAT Spa concludes the acquisition of the American company, creating FCA Italy Spa and FCA US Spa.

- *2021*: having announced in 2019 the intention of merging with the french auto-maker PSA Group, FCA and PSA created the corporate named Stellantis at the beginning of 2021.

Figure 2.3: Stellantis brands

2.2 Plant today

Nowadyas Mirafiori Powertrain Plant has a total area of 437000 m^2, of which 288000 m^2 covered. It has 1090 employees, divided into white collars and blue collars [2].

The only product made by the plant is the Stellantis transmission C5.14, available in four different version, each having several fittings possible: further information are given in Section 2.3.

The main components and spare parts produced at Mirafiori Meccanica are the following:

- gears of each speed (from 1^{st} to 6^{th}) and sleeves
- primary and secondary shafts
- differential group
- tulips and shift levers
- housing boxes (Aluminum machinery)

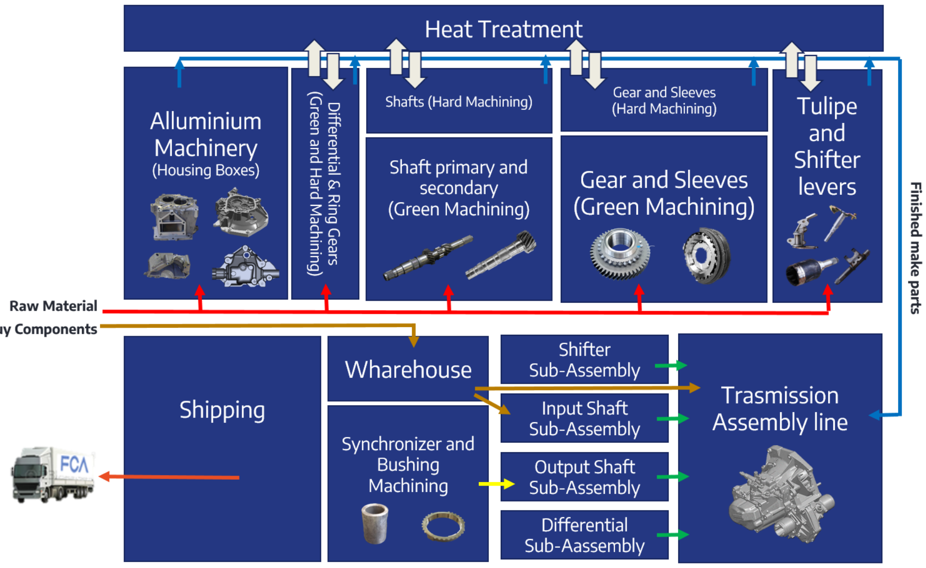
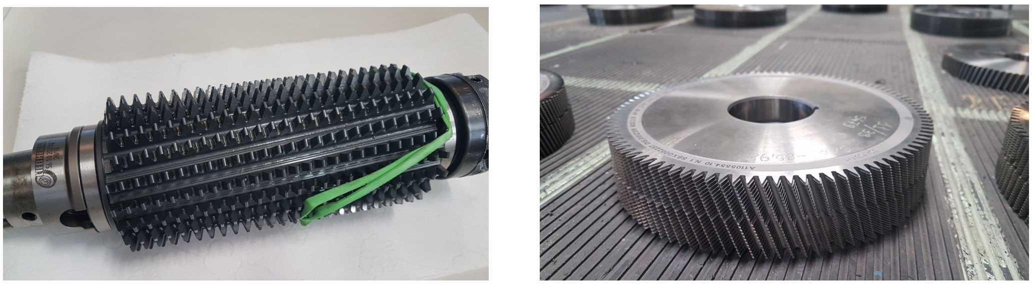


Figure 2.4: Production flow of Stellantis transmission C5.14

The production flow of C5.14 is reported in Figure 2.4 and here are summarized the main working steps for a generic spare part:

1. Raw components arrive at the machining UTE (*Unità Tecnologica Elementare*, i.e. elementary production centre) in which gears' teeth, shafts and bushing are created by hobbing machines and lately refined by shaving cutters.

2. The so called *pezzi in bianco*, i.e. components before heat treatment, are driven towards the furnaces in which they undergo oil quench and, according to the specifications required by the part, eventually they go into the shoot peening machine.



(a) Hobbing machine tool (b) Shaving cutter tool

Figure 2.5: Gears machining tools

3. Being in the furnaces long enough to complete the heat treatment, the so called *pezzi in nero* (components after heat treatment) are brought back to the Machining Unit to be processed by a grinder machine.

4. Once the spare parts have been completely machined and refined, they are shipped to UTE 2.06 and UTE 2.07, which are the assembly lines; here an almost fully automatic system manages to assemble the transmissions, each having the right characteristics for the specific fitting required. Throughout the whole mounting process, a Statec memory linked to the pallet on which the transmission is placed, collects all the information regarding the assembly status of the C5.14 together with any repair or flag signals.

5. The transmission is now fully assembled and filled with lubricant oil; once it successfully passes the seal test, it is shipped to the Thyssen automatic test benches where the driving conditions are faithfully reproduced to discover damages, defects and mismatches inside the transmission. The check cycle is (mainly) an NVH test, getting information about the product from vibration analysis.

6. If the transmission is marked as non-compliant with respect to the thresholds of the NVH test, it is sent to UTE 2.10 to be thoroughly checked and eventually repaired or totally scrapped.

7. Shippable transmission are appropriately put in packages and sent to the body-shop plants in which the C5.14 is assembled on the vehicle: Pomigliano in Italy, Tychy in Poland and Tofas in Turkey.

By looking at Figure 2.6 it is possible to give a glance to the Mirafiori Meccanica layout.

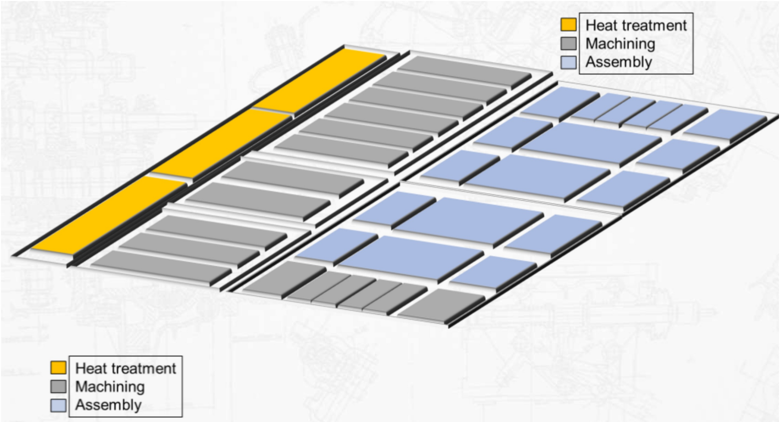


Figure 2.6: Layout of Machining, Assembly and Heat Treatment Units in Mirafiori Meccanica

2.3 Mirafiori transmission C5.14

As previously mentioned, the C5.14 transmission is mounted on low-powered vehicles of the FCA Group and it is available in four different versions; the combination of vehicle and transmission is shown in Figure 2.7 [2]:

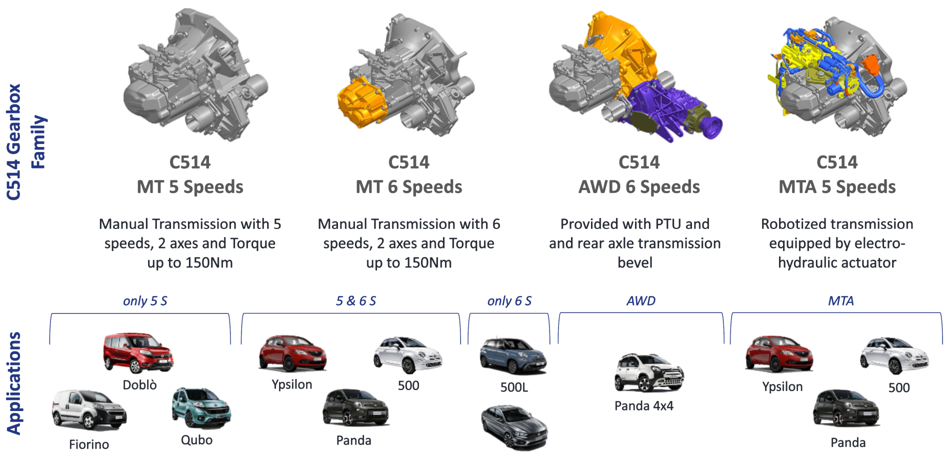


Figure 2.7: C5.14 versions and corresponding vehicles mounting it

The versions depicted above have the following features:

- **MT 5 speeds:** basic version, made of five gear couples for the forward driving and a group of three gears for the revers motion (conduct and conductor gears plus an idle gear); it is available in 12 variants, i.e. different gear ratios that can be combined.

- **MT 6 speeds:** an evolution of the previous model, it has an additional case to house the 6^{th} speed's gears; it is produced in 7 different variants.
- **MTA 5 speeds:** Manual Transmission Automated, is a robotized transmission equipped with an electro-hydraulic actuator; produced just in a single variant, this model is getting dismissed.
- **AWD 6 speeds:** All Wheel Drive, is mounted on 4x4 vehicles and has a rear transmission bevel to motorize rear wheels too; it is made in 4 variants.

Despite the different arrangements each C5.14 may have, the main structure of the transmission is the one shown in Figure 2.8:

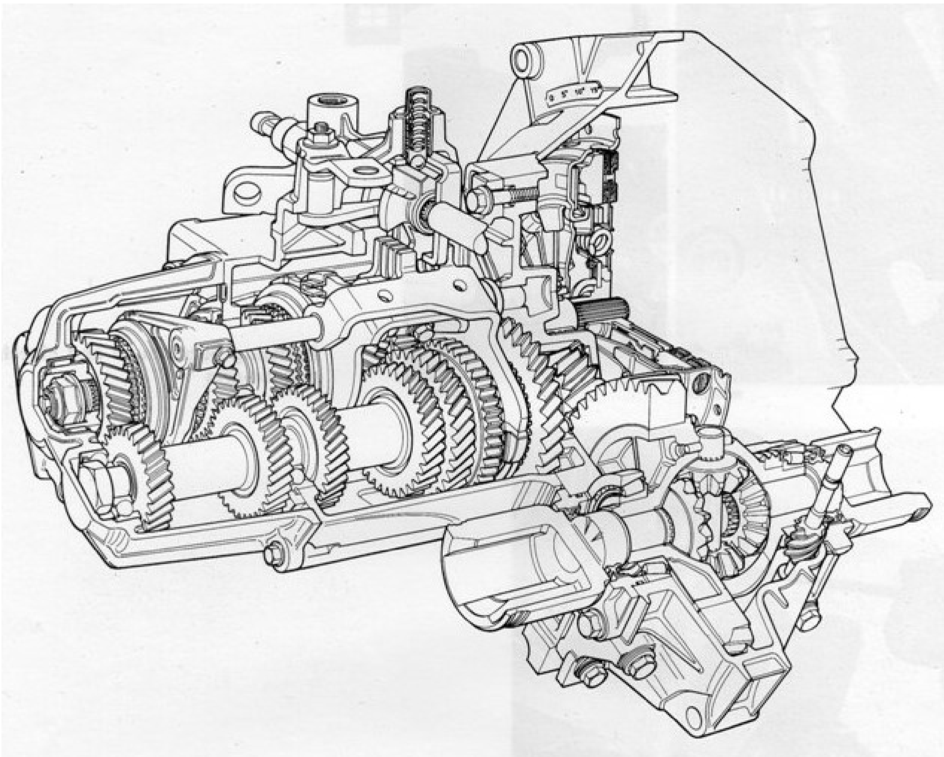


Figure 2.8: Transmission C5.14 scheme - MT 6 speeds version

To clearly describe the C5.14 structure, here are identified five macro-groups which will make easier to understand the functionality of the Stellantis transmission.

Primary Shaft It is the shaft connected with the vehicle engine through the transmission puller (a portion of splined shaft able to transmit the rotational motion, visible at right end of Figure 2.9). On primary shaft are placed the six driving gears: 1^{st} and 2^{nd} speeds are machined directly on the shaft, together with the rear gear, while 3^{rd}, 4^{th}, 5^{th} and eventually the 6^{th} gear are machined separately and then mounted on the shaft. Note that forward speeds are made of helical gears, while the rear gear has straight teeth.

Figure 2.9: Primary shaft of transmission C5.14

Driving gears have an engagement system which allows the vehicle to change speed even if the two shafts are not completely still: thanks to a braking system made of a thread on the synchro-rings and a rough conic surface, as the engagement sleeve is moved up and down towards one speed or the other, the thread comes in contact with the conic surface, restraining it. Then the two gears, driven and driving, are engaged thanks to their teeth, suitably shaped to hang on without loosing contact during driving.

(a) Gear (b) Synchro rings (c) Assembled system

Figure 2.10: Engagement system - double synchro ring

According to the gear's size, the engagement system may have a single or a double synchro ring: for bigger gears, which have a grater rotational inertia, braking is ensured by a double frictional contact, since the two synchro rings are both threaded and they grip over two conic surfaces (the internal and the external surfaces of an intermediate ring, the gear is not conic, see Figure 2.10a); smaller gears are restrained by a single synchro ring, which grips over the gear's conic surface.

Secondary Shaft Secondary shaft receives motion by the primary one and transmits it to the two drive shafts, thanks to the differential group. In this case all gears are machined separately with respect to the shaft itself as they are bigger. In this case there are only driven gears, recognizable because of the absence of engagement teeth crown.

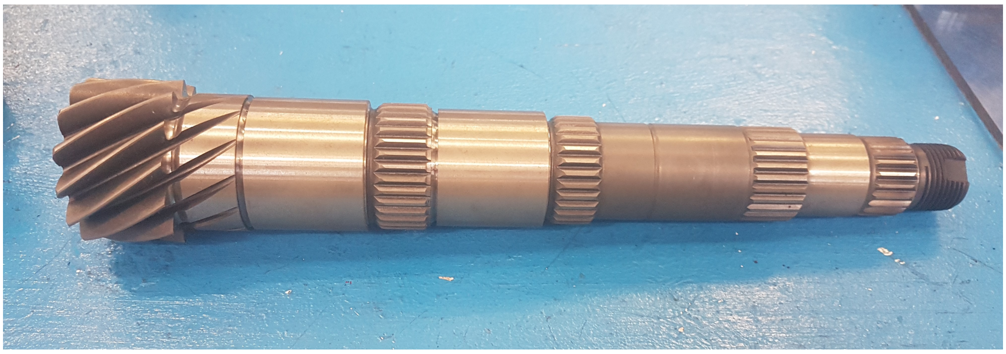
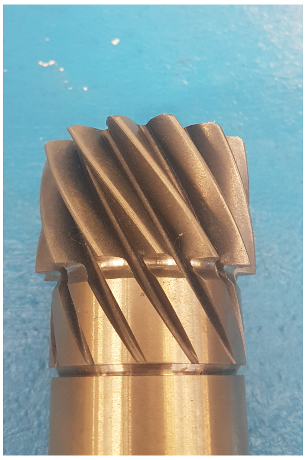


Figure 2.11: Secondary shaft of transmission C5.14

Rear speed group As during reversing, the vehicle's drive shafts rotate in the opposite direction with respect to normal driving, the rear speed group is the only one made of three gears: driving rear gear on primary shaft, driven rear gear on secondary shaft and between the two the idle gear, which is responsible to reverse the angular motion direction. Since rear speed is not synchronized, all the three elements have straight teeth instead of helical ones.

Differential group The pinion at one end of secondary shaft (see left end of Figure 2.11) puts in rotation the differential crown, which in turn puts in rotation the system of fifth wheel and planetary: these latter elements are connected with two tulips (from the french *toulipes*, due to their bell-shape), in which the two drive shafts of the vehicle are engaged to transmit motion to the wheels. As said before, in case of front-wheel drive models, the system is as simple as the one depicted above; for all-wheel drive vehicles, the differential housing is slightly larger, in order to accommodate the shafts shunting the motion to rear wheels too.



(a) Pinion

(b) Differential group

(c) Tulip

Figure 2.12: Motion transmission system: from secondary shaft to drive shafts

Engagement Leverage System Speeds are engaged mechanically thanks to a leverage system made of gear selection forks and sleeves (Figure 2.13b). Gear lever inside the cockpit is linked to bowden cables, which thanks to traction actions are able to move up and down, left and right the gear selection forks.

(a) Sleeve of 1^{st} and 2^{nd} speeds

(b) Sleeve and engagement forks

Figure 2.13: Sleeve and engagement forks system

Each sleeve can engage and dis-engage two consecutive speeds (1^{st} - 2^{nd} sleeve on secondary shaft, 3^{rd} - 4^{th} and 5^{th} sleeve on primary shaft): by sliding on the shaft towards one speed, the sleeve forces the engagement system to brake down the rotation and a the same time it makes that gear speed become jointly liable with the shaft, so that the secondary shaft angular speed will be dependent from the specific gear ratio engaged.

As for any item made of gears and mechanical joints, the contact between metal surfaces, clearances and possible small or big defects of machining, create a certain noise during functioning. Transmission vibrations can be louder or softer according to gears tolerances and different gear ratios combined together. What is of key importance is the *feeling* the driver has while sitting on his or her car: if the transmission system results to be too noisy, constantly clicking, the costumer will have a bad perception about the vehicle quality. To take care about driving feelings and also to catch possible serious defects on transmission components, 100% of C5.14 items are checked on automatic test benches.

As stated in the very first chapter of this work, the thesis goal is reduce as much as possible vibrations and noise not coming from the transmission itself, which are due to the mechanics of test benches: having a stiff and correctly designed structure, it will be possible to clearer identify C5.14 issues and defects, without resolving to fake scraps and production wastes.

To do so, it is fundamental to understand which transmission features are measured by the Thyssen test benches, how the vibration sensors are placed on them and how an NVH test (i.e. *Noise Vibration and Harshness*) works and has to be run for a correct results interpretation.

Chapter 3

Automatic test benches

Present chapter will be devoted to a basic description of Thyssen automatic test benches, in order to make the reader acquainted with their function, structure and main issues: everything is related to measurement cycle aspect and transmission features to be checked, while the mechanical description of test benches will be detailed in chapter 5.

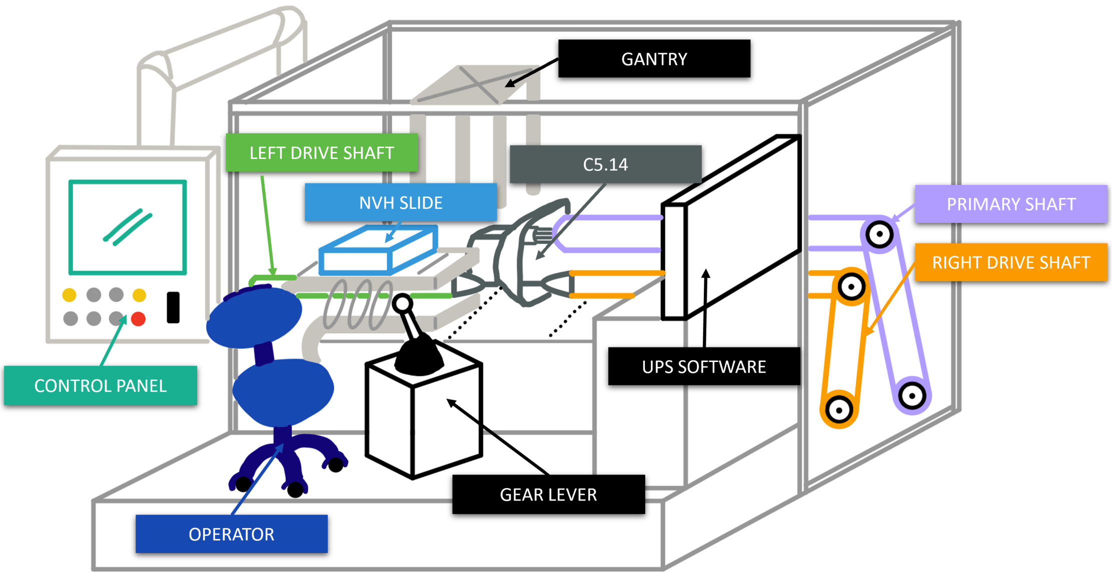


Figure 3.1: Sketch of Thyssen test bench

3.1 Test benches layout and main features

To test C5.14 transmission performances, Thyssen test benches are designed in order to faithfully reproduce driving conditions and excitation which produce a mechanical response of the gearbox, making able the test bench to record and analyse vibrations coming from it.

In Figure 3.1 is depicted a simplified scheme of a Thyssen test bench: the machine covers a rectangular area bounded by glass shelters, equipped with open-close sensors to ensure employees' safety during functioning. Operators are sitting in the front part of the test bench, nearby the gear lever, which is exactly the one assembled on FCA group vehicles; maneuvering the gear lever, attached to transmission's engagement and selection levers through bowden cables, allows the speeds changing during check cycles (note that two test benches are equipped with cobots, while the other four are still maneuvered manually).

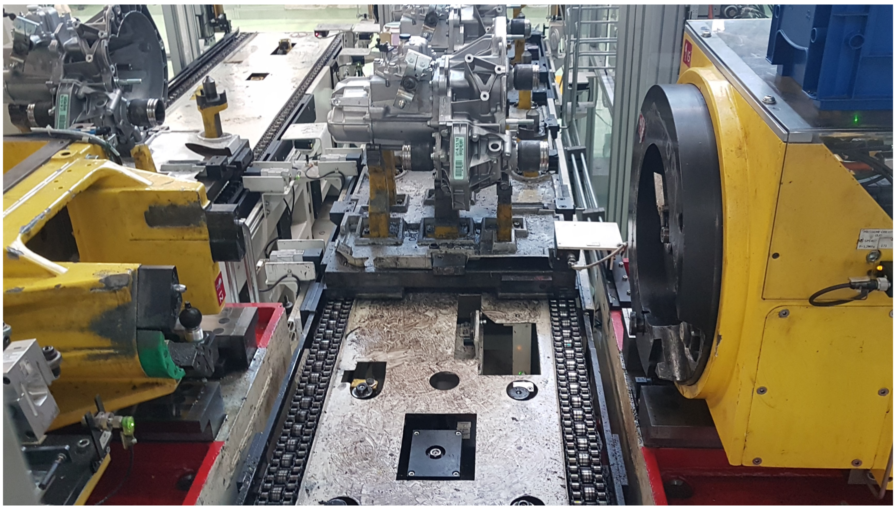


Figure 3.2: Secondary shaft slides with transmission locking system

Main mechanical sub-systems simulating the on the road test conditions are the following:

- Primary shaft: positioned on the test bench right end, the sub-system plays the role of vehicle motor shaft, having an electric motor which transmits torque and speed to the transmission's primary shaft, in order to reproduce drive mode conditions, i.e. drive torque on primary shaft and resistant torque on secondary shafts.
- Two secondary shafts: placed on the right and left sides of the test bench, the two sub-systems have a double task, on one hand they play the role of

vehicles drive shafts, simulating wheels rotation and producing a drive torque during coarse mode (i.e. condition in which the vehicle engine is not giving any thrust and torque is transmitted by the rotational inertia of wheels to the motor shaft), on the other hand a system of hydraulic cylinders allows the closure of the two sub-systems over the transmission, to lock it during the cycle in a safe and functional position; the two yellow slides are shown in Figure 3.2.

(a) NVH slide (b) Gantry (c) Stamping system

Figure 3.3: Functional sub-systems

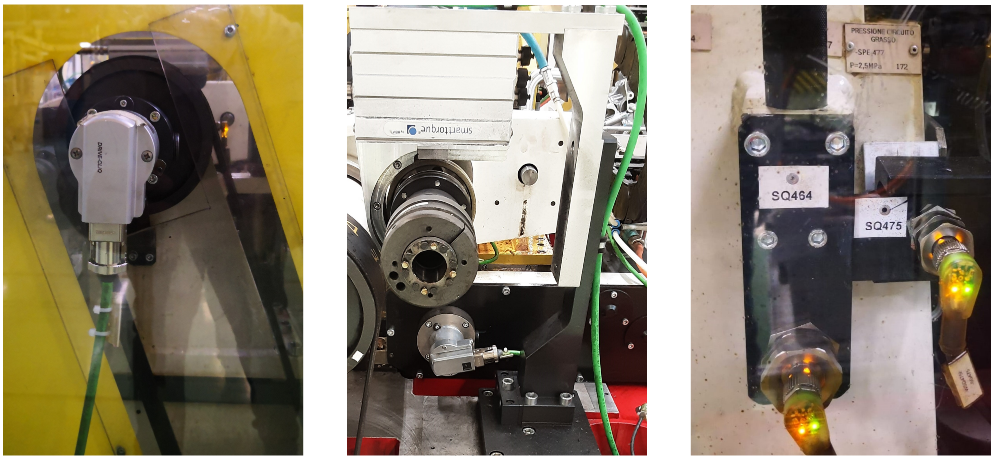
While these principle sub-systems simulate driving conditions, other groups are designed for functional purposes:

- NVH slide: sensors useful for NVH data collecting and maneuver levers are placed on a slide, which is able to approach the transmission to be tested by moving left and right, on proper slide-way powered by hydraulic cylinders, and back and forth thanks to a system of pneumatic cylinders, able to engage selection and engagement levers directly on transmission's control cover (see Figure 3.3a).

- Gantry: thanks to four hydraulic cylinders, the cage-like gantry is able to lift the transmission from the test spot to the delivery line, so that automatically C5.14 are moved in and out from the test bench site.

- Marking system: at the end of the checking cycle, each compliant transmission is marked OK by a structure made of pneumatic cylinders; moreover the transmission is put in neutral position, in order to be correctly stock in delivery pallets.

To perform NVH and shift-ability tests, further described in the next two paragraphs, the test bench is equipped with many sensors, which are both necessary for vibration and force data collecting as well as for Thyssen correct functioning, constantly checking torque and speed conditions, components and transmission position and lubricant levels.



(a) Encoder (b) Torque transducer (c) Pressure transducer

Figure 3.4: Sensors on Thyssen test benches

Here are listed main sensors mounted on Thyssen test benches:

- **Accelerometer:** placed on the left slide, over a spherical and elastic support, it is the main NVH sensor used to collect transmission's vibration. Acceleration measured are directly elaborated by UPS software installed on test bench's PC and noise levels are instantaneously compared with fixed thresholds to judge transmission compliance (further details are reported in paragraph 3.1.1).

- **Load cells:** two force sensors mounted respectively on selection lever and engagement lever, used to evaluate the shift-ability of the C5.14 under investigation; data collected are compared with fixed thresholds, in order to detect whether the force applied by the operator or the cobot exceeds limits of comfort maneuverability conditions. Note that human operators are not able to repeat always the same movements to engage and disengage a speed, so instead of having a shaped thresholds, only force peaks are detected.

- **Encoders:** on each of the three axis (primary shaft, left and right drive shafts) is placed a sensor to verify angular speed set on each shaft; the information is used to elaborate vibration data from UPS software and to check the correct gear ratio of every gear couple, which is important to ensure the correct transmission fitting to respect emission requirements.

- **Torque transducer:** similarly to encoders, there is a torque transducer installed on each axis, used to check correct test performances and eventually detect abnormal transmitted torques, symptom of stuck elements, absence of lubricant, foreign bodies inside the gearbox and so on.

- **Pressure transducer:** to continuously verify the correct functioning of lubricant system, delivering grease to slide-ways and bearings all over the test bench, a pressure transducer is positioned in the farthermost spot along system's tubes.

3.1.1 Hints of NVH test

Noise Vibration and Harshness test is the main tool used by Thyssen test benches to evaluate transmissions compliance. With respect to a complete vehicle, NVH test is applied to assess what follows:

- *Noise:* referring to high frequencies, vibration measurements are used to spot noise and abnormal vibrations coming from the product.

- *Vibration:* with respect to low frequencies, amplitudes of mechanical oscillations coming from product's components are checked in order to spot structural issues, misalignment and mechanical defects which may affect the vehicle functioning.

- *Harshness:* all vibration measured during NVH test are evaluated through a qualitatively assessment system, which is built according to experience about comfort feelings and perceptions over the vehicle.

While what is pointed out above is fully true for a vehicle, regarding transmissions what matters the most is *Noise*: a compliant and comfortable gearbox is the one producing the minimum level of vibration during driving.

Following this idea, in Mirafiori Meccanica the NVH test is run using a single accelerometer positioned in the bottom of the transmission's aluminum case: the sensor is mounted on a spherical and elastic support (Figure 3.5), which allows the accelerometer's sensitive part to come solidly in contact with the gearbox, as it is lowered (and afterwards lifted up) by an hydraulic elevator.

When the transmission is clamped between the two slides, i.e. the right and left sub-systems engaging the gearbox and locking it with hydraulic cylinders, the elevator on which the transmission is positioned is lowered by an hydraulic

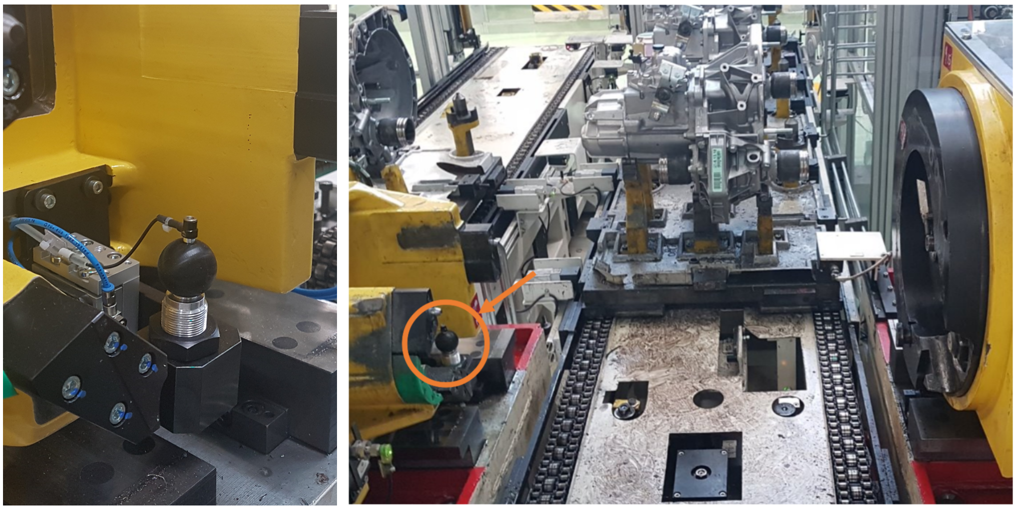


Figure 3.5: NVH accelerometer on Thyssen test benches

cylinder, making the accelerometer come in contact with the aluminium surface, a wide spot under the C5.14 suitable to measure noise as it reverberates vibrations coming from all other components.

Using a single record, the UPS software installed in Thyssen PCs is able to perform three analysis, which are described here below:

Track order Every time a speed is engaged, two different meshing are present within the transmission and they can be clearly spot in Figure 3.6.

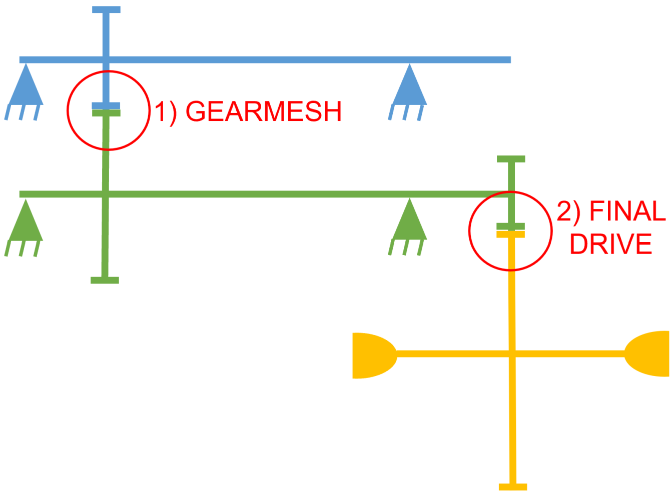


Figure 3.6: Meshing scheme of a generic speed engagement

1. Gear-mesh: meshing of driving gear (represented in blue on the primary shaft) and of driven gear (represented in green on the secondary shaft); the gears coupling determines the gear ratio of the speed engaged, which changes during driving as the gears couple engaged is changed.
2. Final drive: in order to transmit the motion to the wheels, a further mesh is needed, involving the pinion (right end of the secondary shaft) and the differential crown (represented in yellow, together with the tulipes sketched as two semicircles).

Each meshing has a specific vibration frequency. Ideally having only compliant components and having engaged that specific speed, the two meshing produce a vibration at a specific frequency, which can be evaluated as follows:

$$f = \frac{Z \cdot n}{60}$$

- f [Hz]: meshing frequency
- Z [-]: meshing order, it represents the number of gear's teeth referred to primary shaft, which means that for gear-mesh it corresponds exactly to the number of driving gear teeth (z_c), while for final drive it is the number of pinion teeth referred to primary shaft's speed:

$$Z_{gear\ mesh} = z_c$$
$$Z_{final\ drive} = \frac{z_c}{z_{cc}} \cdot z_{pinion}$$

- n [rpm]: angular speed of primary shaft

Note that having determined the meshing order, namely once the teeth number of driving gear (z_c), of driven gear (z_{cc}) and of the pinion (z_{pinion}) are fixed, speaking about frequencies f or angular speeds n is exactly the same thing. That's what usually happens during NVH track order test, since for each speed tested a graph like the one reported in Figure 3.7 is produced.

The vibration amplitude is measured in decibels, computed from the recorded accelerations:

$$A = 20 \cdot \log\left(\frac{measured\ m/s^2}{reference\ m/s^2}\right) \quad [dB]$$

Amplitudes are plotted with respect to different primary shaft angular speeds, i.e. for different meshing frequencies. The transmission white noise measured in this way is compared with a fixed threshold (represented in blue). If NVH track order curves exceed blue bounds, it means the specific gear coupling tested produces an excessive noise, probably due to machining or assembly issues occurred during operations.

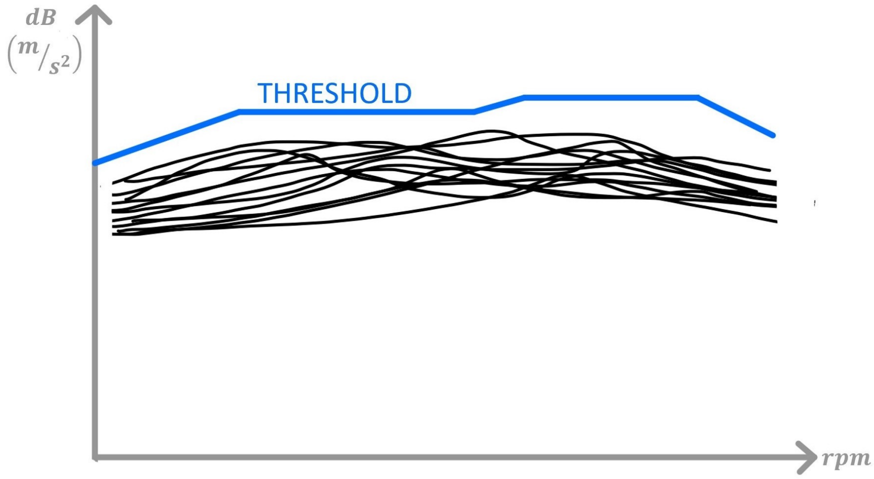


Figure 3.7: NVH curve example: track order

Order spectrum While the analysis described above is related to known and specific frequencies, checked just by looking at vibration amplitudes, plotting the order spectrum of the recorded signal means investigate anomalies showing up at different frequencies, not directly belonging to the transmission. This procedure allows to discover other defects, not directly related with gears dimensional compliance, for example is possible to detect bearing noise, missing elements, uncorrected lubrication and so on.

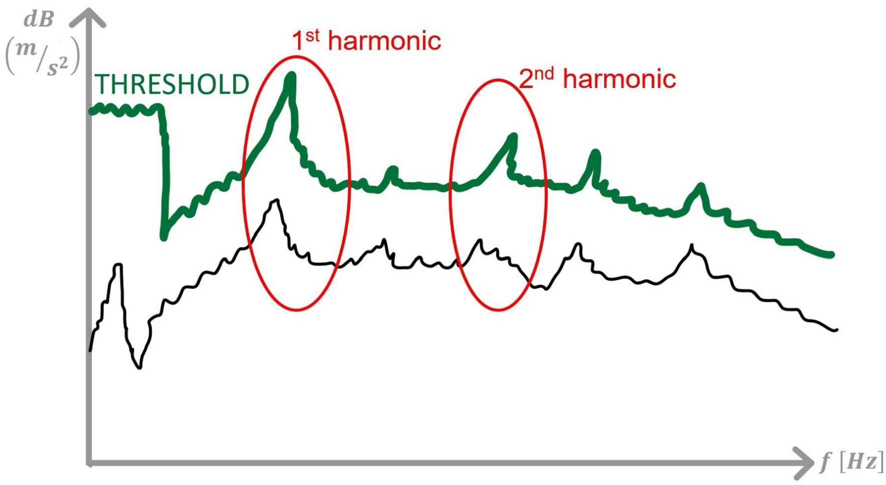


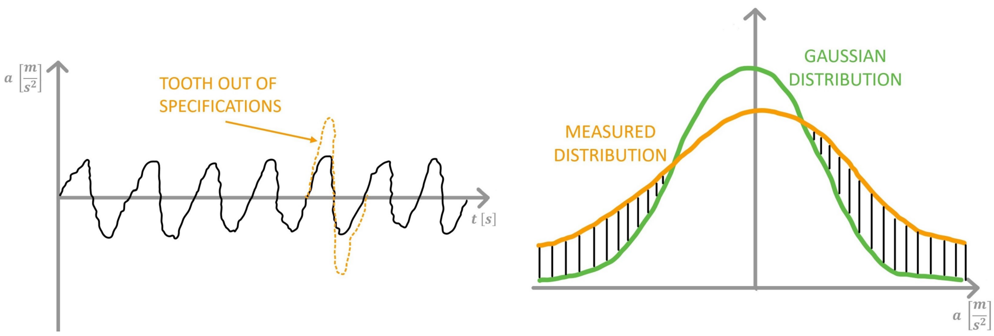
Figure 3.8: NVH curves example: order spectrum

Signal spectrum is built considering vibration collected during both drive and coarse modes of excitation and a threshold fixed by experience, makes possible to verify transmission compliance: if a spectrum portion overcomes the thresholds or there are sudden peaks in the diagram, the transmission is marked as KO regarding the specific maneuver tested.

The diagram trend in Figure 3.8 shows regular peaks, corresponding to the harmonics of the vibration; the most significant one is the first harmonic (first peak), while at regular intervals are present all multiples of signal's first harmonic.

Kurtosis analysis While the two previous checks are carried out in frequency domain, Kurtosis analysis is a check implemented over time domain to spot nicks on gears' crown (defects details are given in paragraph 3.2).

Main reasoning of Kurtosis analysis can be described by looking at diagrams depicted in Figure 3.9a: every time a new couple of teeth come in contact during shafts rotational motion, the acceleration recorded by the test bench increases and decreases as the contact point moves along teeth profile; ideally what is recorder is a trend like the black one in Figure 3.9a, made of (almost) constant up and down on recorded signal. By plotting the accelerations distribution (Figure 3.9b) , in case of perfectly compliant gears what is obtained is a Gaussian distribution. Since every gear is different from others, because of tolerances, or material or possible defects, the actual distribution elaborated by UPS software differs from the ideal Gaussian one: what is done during Kurtosis analysis is evaluate the deviation amount between measured distribution (in orange) and the reference one (in green), so that if this value exceeds fixed limits, it means there is a nick over gear's crown.

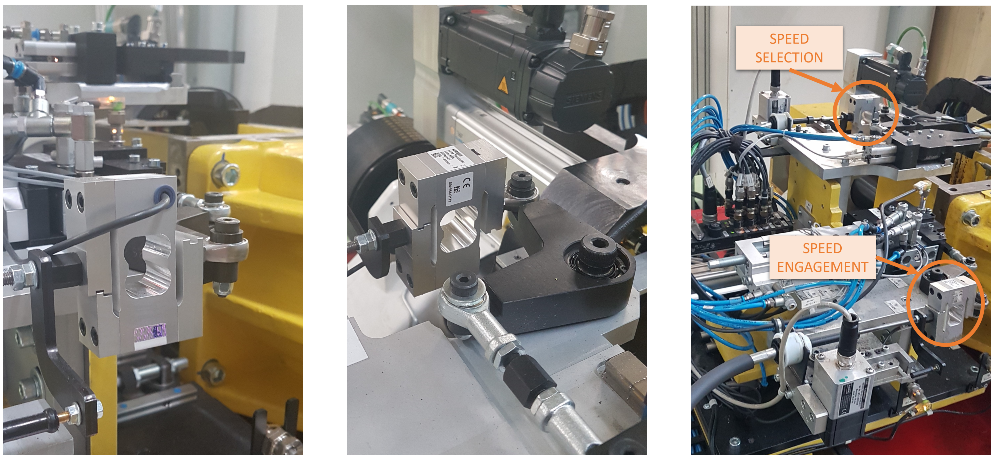


(a) Acceleration trend (b) Acceleration distributions

Figure 3.9: Theoretical principles of Kurtosis analysis

3.1.2 Hints of shift-ability test

With respect to NVH test aiming in spot abnormal vibrations produced by transmission C5.14, shift-ability is about comfort driving performances and eventually stuck gearboxes detection. On NVH slide sub-system are mounted two load cells (Figure 3.10), one related to speed selection, moving the gear lever from left to right, and the other related to speed engagement, moving the gear lever up and down: not all speeds excite simultaneously the two load cells, for example going from the 3^{rd} speed to the 4^{th} one, the gear lever is moved up and down but not left and right; selection load cell is excited only when the driver changes between two speeds not associated to the same engagement sleeve.



(a) Selection load cell (b) Engagement load cell (c) Load cells location

Figure 3.10: Load cells used for shift-ability test

Typical force trend recorder during speeds shifting is the one depicted in Figure 3.11, where three areas can be clearly distinguished, each related to a force peak.

A. **Disengage Load:** smoother peak, due to the force necessary to disengage previous coupled gears.

B. **Synchronization Load:** the greatest force recorder by the load cell during shifting, it is related to the braking action performed by synchro rings, grasping over the rough gear conic surface; maximum load is reached when the gear is completely stopped.

C. **Engagement Load:** final peak in the trend can be statistically more or less pronounced, since it is due to the reaction forces generated between engagement sleeve's teeth and gear's teeth, which can be already aligned to be engaged correctly or could be "out-of-phase", producing a grater force while coming in contact.

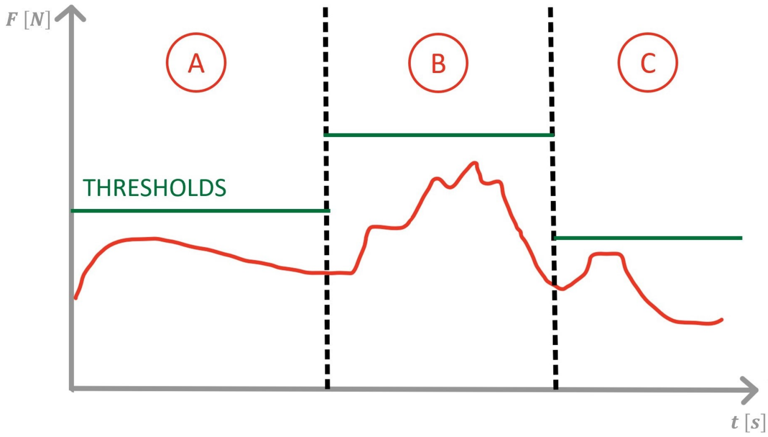


Figure 3.11: NVH curves example: shift-ability

Since shift-ability trends strongly depends on the operator running the test, it is not possible to compare the force measured with a shaped threshold, that's why in Figure 3.11 there are straight thresholds for each area.

The test is completed by a timer (internal to the UPS software) and a strain gauge, which allow the operator to check on the monitor if the lever stroke is the designed one.

3.2 Control cycle and C5.14 measured features

As explained in paragraph 2.3, C5.14 transmission is made of several gears and components, each one machined and undergone a specific heat or strengthening treatment: metallic elements coming in contact one with the other create a certain vibration (noise) during operation. The enormous number of possible gears' features combinations, due to tolerances ranges, makes impossible to have a single and defined NVH curve: it is more likely to have a range of decibels representing compliant gearboxes, where every curve is slightly up or down with respect to an average noise trend. Using as example the order track diagram, in Figure 3.12 is shown how gearboxes may be more or less noisy, and what matters in the end is that curves must be solidly below the fixed thresholds.

Thresholds can be overcome by the full curve or just by noise peaks, in some other cases the curve may be below the threshold having an irregular trend: in all these events the transmission should be considered as non compliant and the

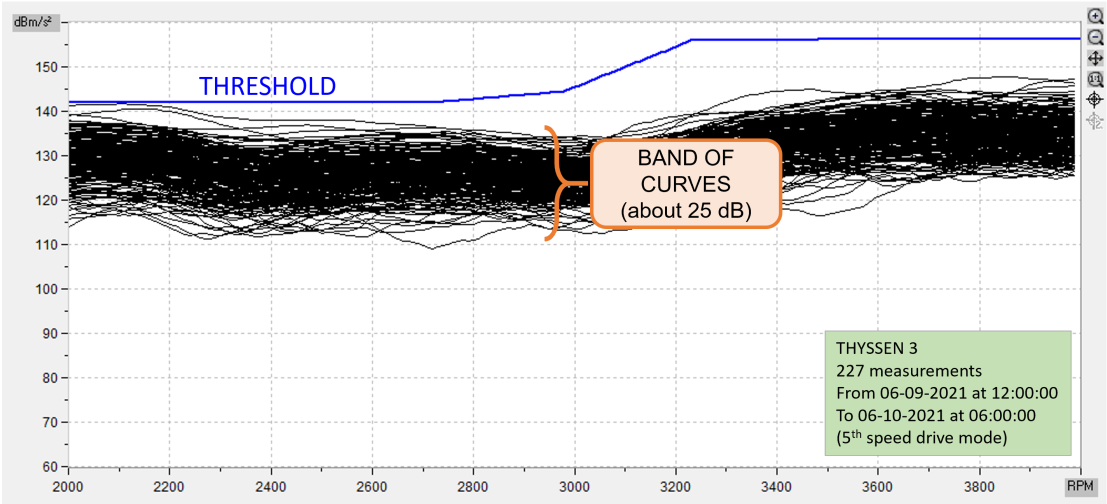


Figure 3.12: Example of NVH curve

UPS software, installed in each automatic test bench, gives an error signal to the operator, who uniquely marks the faulty gearbox and sends it to diagnosis lines.

3.2.1 Detectable defects

Having described how an NVH test is performed and which are main diagrams and evaluation system used to analyse them, here are listed some of the most common and important defects a transmission may show during final checks:

- **Nicks:** plastic deformation of the gear's teeth, which produces a metallic ticking during driving, due to the presence of excessive material on the gear's crown that comes constantly in contrast with its matching gear; the defect may be caused by wrong machining operations, bad gears handling or bumps during assembly operations.
- **Hiss:** on the contrary with respect to nicks, hiss noise is due to lack of material on gear's teeth, which produces an air flow that results in a constant hissing during driving; the defect may be caused by wrong machining or assembly operations, by material issues (e.g. occlusions).
- **Hard engagement:** often detected on specific speeds, which can be hardly engaged or in some cases not even engaged correctly to test the transmission in that configuration; typically signaled by excessive force on load cells, it could happen because of many components defects, like smaller or bigger diameters machining of components involved in engagement operations, wrong elements lubrication, abnormal components breakage inside the gearbox.

- **Stuck gearbox:** detected as the cyclogram cannot be performed at all or just in some steps; it could be due to many component's defects, like wrong machining operations, out of specification elements, lack of lubricant or missing components.

- **Noisy gearbox in all speeds:** usually it is due to nicks or other geometrical defects on the differential crown, which is always engaged during driving, so that it makes noisy not a single speed but all of them; in some other cases it may happen that a foreign body has fallen inside the gearbox, damaging the gears during driving and producing noise and excessive metallic debris.

From the retrofit of test benches in 2016, when Thyssenkrupp introduced the NVH system, the control cycle implemented in UPS software to catch all these defects was changed several times, each time refining it to detect more precisely some C5.14 issues or modifying sequence and/or duration of ramps to reduce the lead time. Last modification was performed in June 2021, so that in the next paragraph the control cycle will be described using the previous version, while excitation and stress data will be taken from the latest version of it.

3.2.2 Visual control cycle

To properly detect transmission issues, it is important to faithfully simulate on-the-road conditions, so that the gearbox is excited in the most similar way to actual driving conditions. What mainly influences transmission noise is the specific speed engaged, transmitted torque and angular speed of the two shafts. A basic step to reproduce real operating conditions is to excite the gearbox through ramps and shifts at every speed and mode. In Figure 3.13 is depicted the control cycle, expressed referring to the angular speed of test bench's primary shaft.

To introduce the reader to specific checks performed and making him or her acquainted to the terminology used, here are reported some basic concepts regarding transmission tests:

- *Drive mode:* condition in which the drive torque is given by the vehicle engine and it is transmitted by the motor shaft to the C5.14 primary shaft; on the test bench the mode is simulated by the primary shaft's electric motor action, which generates a resistant torque on the two secondary shafts, i.e. the two drive shafts of the vehicle.

- *Coarse mode:* when the vehicle's engine doesn't provide any thrust to the forward motion, gearbox's shafts keep rotating because of the drive torque transmitted by the wheels (inertia effects); on test benches the condition is obtained by faking the drive torque through two identical electric motors connected to right and left secondary shafts, which in turn transmit the torque to the gearbox's secondary shaft and through it to the primary shaft of C5.14 and of the test bench itself. Changing mode means changing the gears contact surface, since their teeth meet in their opposite faces.

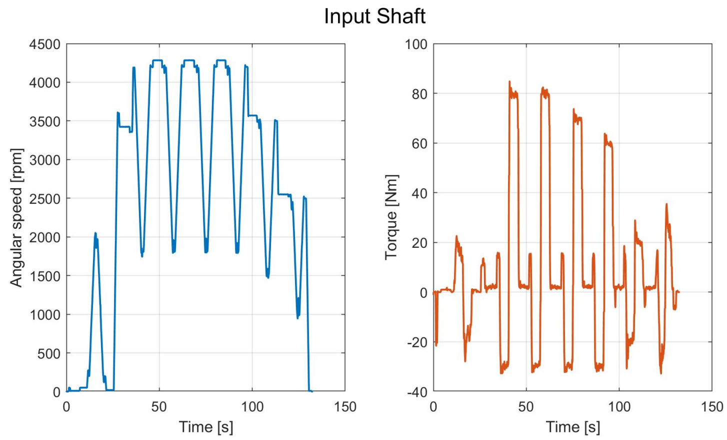
- *Shifting:* while previous two modes are tested through ramps, namely by increasing or decreasing shafts rotational speed, shifts are characterized by constant angular speed (set to the maximum value used to excite the speed checked) and increasing transmitted torque; shift phase is also characterized by speed change, meaning that selection and engagement levers are used to pass from one speed to the previous one.

By testing at each condition described above all gearbox's speeds, ideally every defect should be detected over transmission C5.14.

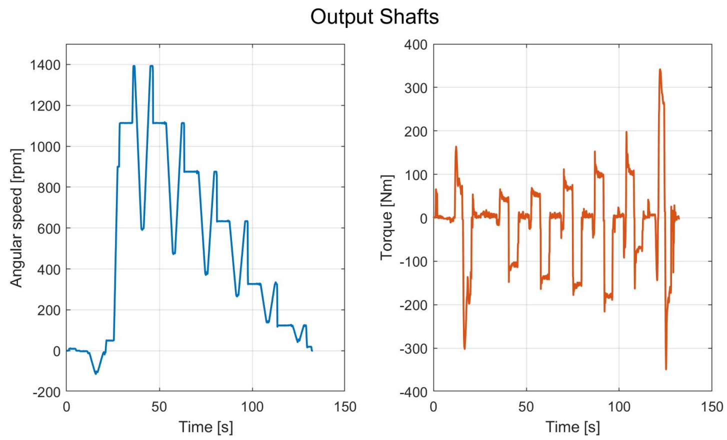
Figure 3.13: Visual control cycle on Thyssen test benches (version till May 2021)

As mentioned before, from June 2021 the control cycle has been upgraded by reducing the test duration of about 40 seconds. In Figure 3.14 is reported the latest cyclogram, in terms of angular speed and transmitted torque of both Thyssen's primary shaft and two drive shafts.

What is important to point out is that changing the cyclogram may seriously affect test benches structure and mechanical responses. For example, if the transmitted torque during shifting from 4^{th} to 3^{rd} speed is increased to refine the Kurtosis analysis and catch even slight nicks on gears teeth, the modification will reverberate over the test bench, meaning that the daily time of excitation at that specific torque at which shafts, bearings, and all other components over the machine undergone is increased, and if the torque rise is not negligible, it may cause



(a) Primary shaft



(b) Secondary shafts

Figure 3.14: Visual control cycle on Thyssen test benches (latest version)

a drastic shortage of components life; in more sensitive cases, it may produce a critical element wear, which eventually could produce a test bench breakdown.

To avoid unforeseen machine stops, while PLC programmers modify the control cycle on UPS software, maintenance specialists should verify that new excitation conditions do not interfere with correct functioning of test benches' sub-systems, checking at least components marked as critical.

Since a punctual deconstruction of Thyssen test benches and a list of critical components does not exist at the moment, the goal of the present thesis is to analyse the machine mechanical structure, in order to highlight the so called machine Q-Points (see definition in chapter 4) to be carefully handled and to solve immediately main issues discovered on the machine regarding these critical elements.

3.3 Measurement issues

To ideally catch only the body under investigation noise, it should be isolated from the external world; in laboratories this can be reached by applying *"free-free"* boundary conditions, simulated by hanging the body to the ceiling through thin cables positioned nearby structure's nodes [6].

Unfortunately *"free-free"* BCs cannot be applied during transmissions' NVH test, since the gearbox has to be checked while simulating driving conditions, i.e. while the transmission is solidly connected to the test bench, whose elements and sub-systems play the role of crankshaft, drive shafts and so on.

Actual test conditions imply that all test benches vibrations, which may come from different sources, reverberate on the transmission itself and consequently the accelerometer placed on it, collects on one hand noise actually coming from the gearbox and on the other hand an additional noise coming from the test bench and the plant's floor. Note that under stable conditions, test bench's noise determines just an offset to the measurement, which can be easily managed by setting the NVH thresholds to an appropriate level, typically suggested by experience.

Measurement issues may rise when test bench's noise increases with respect to normal levels, due to a component and/or sub-system malfunction or due to a growing element's wear, which produces a noise measure drift. To understand the reason why these abnormal vibrations may arise, let's briefly list main noise sources of the test benches:

- moving mechanical part, such as slides, pistons, mechanical limit switches and so on;
- mechanical couplings, both between test bench's components and between test bench and gearbox (elastic joints, screw joints, etc);
- motion transmission systems, like pulley and belt system, splined shafts, screw joints and so on;
- clearances, misalignments, loosening of mechanical joints due to components wear.

The first three items of the list above can be considered as "normal" vibration sources, namely they do belong to the test bench structure and cannot be eliminated nor reduced under a certain volume: these stable conditions, if preserved, represent the stable off-set mentioned before, which keeps constant in time and (almost) constant between different test benches.

Last point, related to mechanical issues, if not properly managed and maintained, may become sources of noise drifts and "abnormal" vibrations: in this instance the NVH curves off-set may be:

2. constant, but higher with respect to other test benches and to previous test bench status;

3. drifting, getting louder and louder during time, so that NVH curves are no more comparable with other test benches or with previous test bench status.

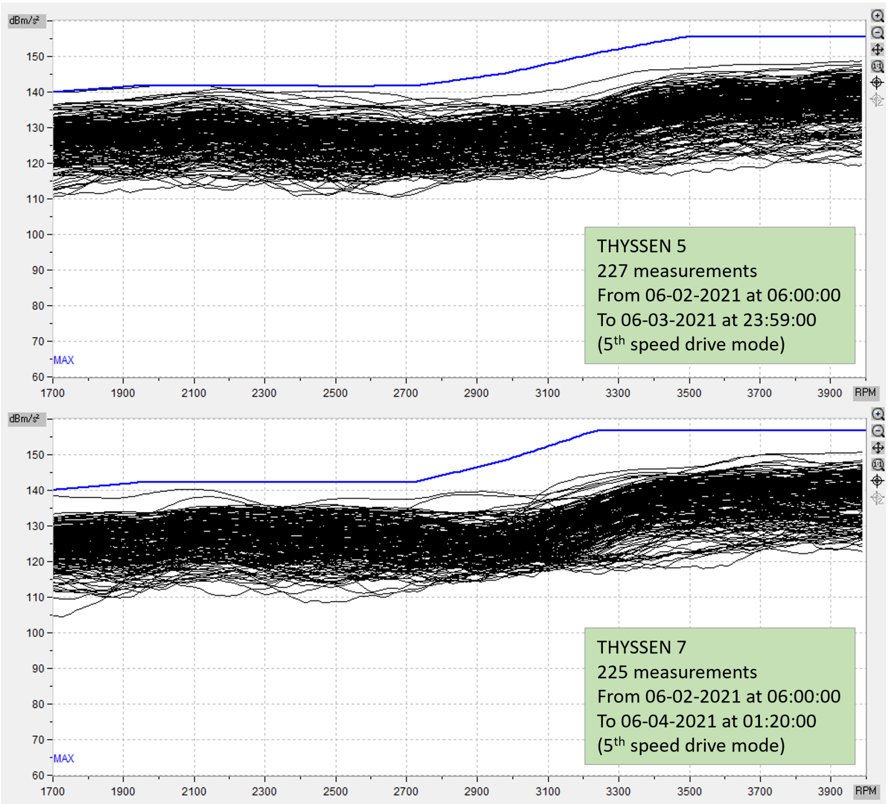


Figure 3.15: Comparison between NVH curves collected in the same period on two different test benches

In Figure 3.15 is reported an example of drifting off-set: the NVH curves are related to the same acquisition period, namely transmissions have been produced in the same days and having almost the same machining and assembly characteristics. By comparing noise recorded on TH5 and TH7 (automatic test benches number 5 and number 7), it is possible to clearly spot a greater noise off-set on TH5: *Thyssen5* test bench was the very first retrofitted machine and probably its components have a wear and deterioration (not identified during actual maintenance operations and checks), which badly affects NVH measures.

Having identified a difference between test benches noise, it is important to evaluate the risk of vibration drifts and to understand the reasons behind abnormal components' wear, since bad test benches performances during test cycles may produce a double type of failure:

1. Transmission damage: since during the test, primary shaft and two drive shafts are put into the transmission case, to respectively engage the primary and the secondary shafts of C5.14, some test bench's fault may happen, resulting in a wrong or misaligned or missed engagement, which could produce a damage on the item; moreover test benches are equipped with some motorized slide-ways, that are approached to the gearbox in order to feel its response through sensors, and if these mechanical groups are not properly calibrated or designed, a collision might occur with the product.

2. Fake scrap outcome: the NVH system, used by test benches to verify the gearbox performances, collects noise and vibration information from the transmission and compare them to known thresholds, in order to declare a product compliant or not; since the transmission is placed on the test bench itself, vibration caused by mechanical clearances and couplings may fake the measurements, adding an extra noise to the one of the gearbox and putting it out of the fixed thresholds.

During last year Thyssen test benches have shown some important structural issues, that often resulted into one of the two defects described above. In order to attack and solve the problem, the goal of the present work is to apply the 7 Steps of Quality Control Pillar (see chapter 4), which through Quality Maintenance tools and principles, aims in improving test benches mechanical structure, reducing at the same time the amount of fake scrap and time and energy resources employed by Maintenance Department to repair test benches as needed.

Next two chapters will give to the reader respectively some hints about WCM tools used to accomplish the task and the application of QC Pillar proofs, focusing on problem solving procedures and obtained results.

Chapter 4

WCM: principles and pillars

Present chapter is devoted to the explanation through hints of the methodology applied to address the issues outlined in Chapter 3 related to Thyssen automatic test benches.

A brief introduction of the *World Class Manufacturing* and its pillars is presented, followed by a focus on the WCM tools developed in this work.

4.1 Rise and development

WCM can be considered as an evolution of *lean manufacturing* and *Total Productive Maintenance* (TPM), both introduced and developed by the Toyota Motor Corporation from the 30s to the 80s of XX century [7, 8].

Initially the two philosophies were aiming at improving the Japanese industrial production system, by bringing the concepts of Waste-Minimization and Quality to a key priority: the production system must be as *lean* as possible, meaning that wastes in terms of time, scraps, handling and re-work should be minimize, favouring a plant structure that optimizes the usage of space and time, and it should be easily adapted to different demands or products, flexibly changing its layout and features. This is the period in which the ideas of JIT (*Just In Time*), pull logic, *kaizen* and zero-waste process were born and applied.

Together with the intention of creating a production system clear of defects and time or material wastes, it was important to create a production flow made only of added-value: it was necessary to implement actions and apply strategies aiming on making the product *perfect* [9].

Pursuit of perfection was developed by investing on Quality, so that both the product and the production lines were designed to avoid human errors or machine failures, ideally making it impossible to produce a non-compliant component.

These are the fundamentals on which the *World Class Manufacturing* is based on and that were developed by Professor Hajime Yamashina, the Japanese founder of WCM and its major promoter all around the world. He exported the concepts learned at Toyota, where he worked for many years as a consultant, in some of the most important and international companies, as it happened for Fiat Automobiles Group in 2004.

As it will be better described in paragraph 4.2, WCM is structured in several pillars, each referring to a specific productive area that has to be managed and controlled.

4.2 Technical & Management Pillars

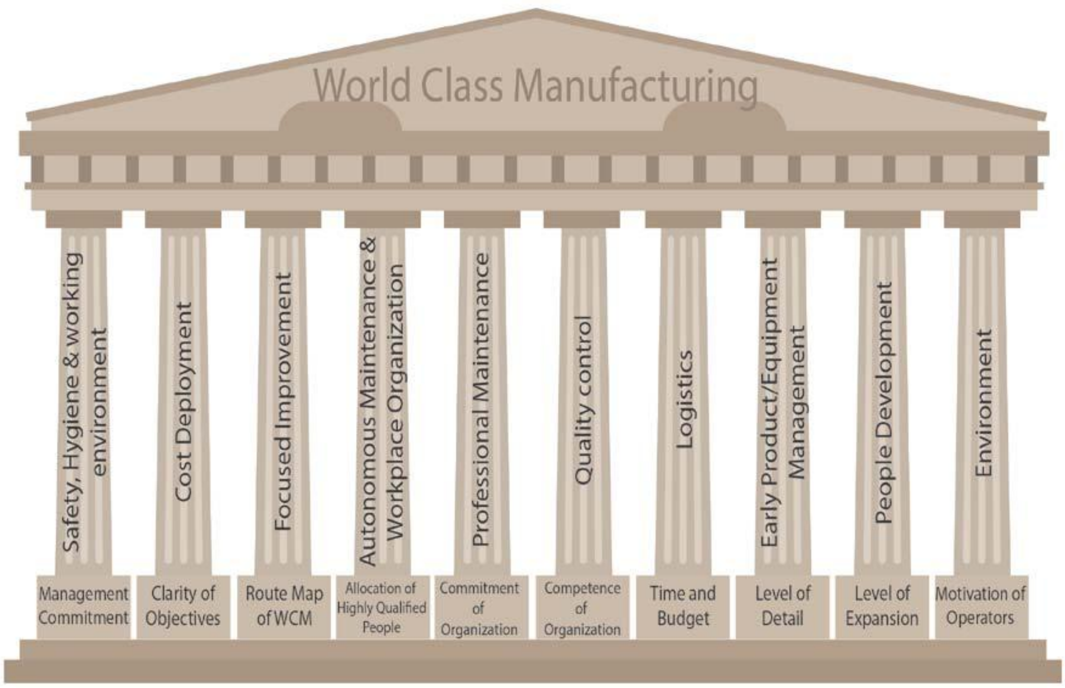


Figure 4.1: WCM pillars

In Figure 4.1 is depicted the so called WCM temple: it summarized the basic structure of Yamashina's philosophy. There are 10 managerial pillars on which 10 technical pillars are built on, each couple of pillars covers a specific productive area of the company that has to be managed. In Tables 4.1 and 4.2 are briefly described the principles and the functions of each pillar [10, 11]:

Table 4.1: Managerial Pillars of WCM

Management Commitment	It is the base of WCM system, which guarantees that the company moves towards the right direction by persuing WCM principles and pillars
Clarity of Objectives	It fixes the plants targets, making sure they are followed and respected to reach company's goals in time; general targets are de-constructed throughout each organization's level
Roadmap to WCM	Once targets has been fixed, it provides a clear strategy to be followed in order to accomplish the company's goals
Allocation of Highly Qualified People	To be sure of reaching targets and full deploy the resources of the plant, it is important to put the right employee in the right role, to fully develop his/her skills
Commitment of Organization	To ensuring the involvement of every plant's employees, it is important to have a strong management checking on the lower portion of the organization's pyramid
Competence of Organization	Continuous improvement requires a continuos research, making sure the plant has the right and newest knowledge to improve its know-how and its skills
Time and Budget	To fully employ the plant's resources, it is important to properly manage them especially in terms of cost and time
Level of Detail	To further improve the production system, it is important to deeply analyse issues and sources of waste, to remove them from the root cause
Level of Expansion	To reach the maximum profit from WCM system, it is important that this philosopy permeates all plant's productive areas
Motivation of Operators	Once WCM philosophy has been spread all over the plant, to keep the system going on it is important to keep constantly motivated workers and employees, to make them be actively part of the improvement

Table 4.2: Technical Pillars of WCM

SAF	*Safety*	Focus on the ergonomics and working safety conditions, to prevent the worker from any injury or repetitive and exhausting operations
CD	*Cost Deployment*	Its aim is to manage the company's economy by connecting spending and revenues directly to improvements/ issues of the productive system
FI	*Focus Improvement*	Strictly related to CD pillar, its purpose is attacking major losses/spending causes inside the production system, to positiveley manage the available resources
AM / WO	*Autonomous Maintenance Workplace Organization*	AM pillar focuses on enhancing both plant's efficiency and products quality by involving employees in maintenance activities for a daily improvement; WO pillar consists in designing and building the best workplace possible, by applying the 5S and the safety prescriptions
PM	*Professional Maintenance*	It regards machines showing frequent or repetitive breakdowns, not having an established maintenance routine
QC	*Quality Control*	Created to reduce scraps and non-efficiency spending, it focuses on product's compliance in order to fully satisfy the costumer's needs
LOG	*Logistics*	Base on JIT philosophy, it manages plant's logistics and warehouse to avoid excess of stock and to reduce economic losses due to items' aging
EEM / EPM	*Early Equipment Product Management*	Regarding the start of a new product and/ or production line, to analyse in advanced any issue or technical inefficiency that could potentially affect the production system

PD	*People Development*	Aiming at improving employees skills and knowledge, it concerns all the aspects related to workers' abilities and training
ENV	*Environment*	Keeping an eye on environment savings and "green" topics, this pillar is used to analyse and plan a strategy to successfully use the company's resources

What clearly comes up by looking at these pillars is that the WCM fundamental rule is the pursuit of efficiency and defects-free production system, which is only achievable by involving all workers in the process towards *perfection*. Making everybody aware of the importance of correctly handle the production process is the company's success key, the basis of any possible improvement, that could lead to an increase of efficiency and earnings form the activity.

Even dough the WCM system is fully interconnected and sometimes it is not easy to make a clear distinction among pillars and specific aspects of them, the present work will focus mostly on the 6^{th} Technical Pillar, i.e. Quality Control.

To clarify this choice is important to understand the different approaches one may have while analyzing the performances of an industrial machine. In Figure 4.2 is presented a scheme listing all the institutions (Pillars) involved in the machine's care.

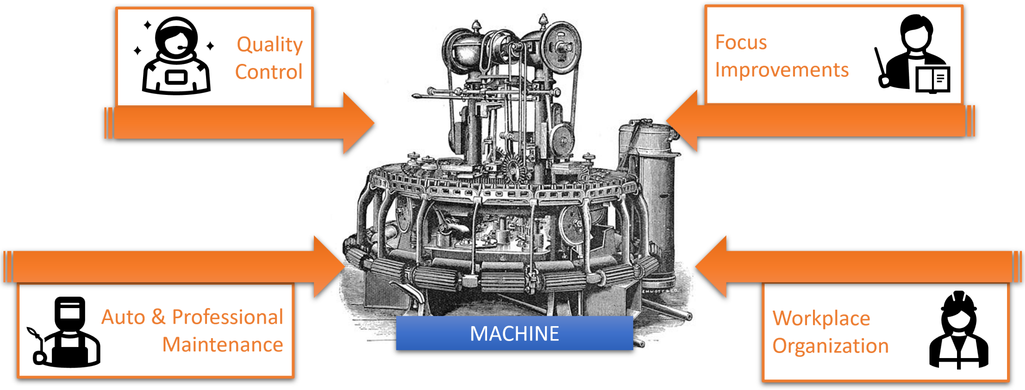


Figure 4.2: Scheme of machine's care improvements perspectives

- **WO view:** industrial machines, especially manual ones, must be designed in order to respect ergonomics requirements and to ensure the employees most comfortable working position possible; Workplace Organization Pillar is strictly connected with Human Resources department, which supervises the working conditions and eventually attends the machine's changes to meet the ergonomics requirements. At this point productivity and capabilities of the machine are not taken into account.

- **FI view:** with respect to the theoretical machine capacity, the real production accomplished is lower than that and affected by many issues, e.g. tools' damages, unforeseen stops, lack of energy, components misalignment, softwares errors; the goal of Focus Improvement Pillar is to reduce as much as possible these loss factors, reducing the lead time while enhancing the machine structure by making it stiffer with respect to possible malfunctions.

- **PM & AM view:** maintenance perspective about the machine is focused on making it continuously working, performing the minimum number of check / repairing operations to fix it. Ensuring a constant production flow is a target independent from efficiency or quality constrains: maintenance point of view does not consider the way in which the machine produces parts, namely it doesn't take care about the possibility to improve the machine structure or layout to increase is efficiency (as FI Pillar does) and similarly it doesn't mind about the conformity of the produced pieces (as QC Pillar).

- **QC view:** Quality Control Pillar looks at the machine to ensure it produces 100% compliant components, even if at the expense of production or machine stops. Theoretically speaking, the machine could produce just a single component per day, but if it is compliant the QC point of view is satisfied.

Obviously an efficient and performing industrial area should manage its machines -both automatic and manual- considering all these aspects at once, even if the requirements of one perspective flies in the face of other's. As it frequently happens in engineering field where several ingredients for the perfect machine recipe have opposite trends, the best thing to do is to find the *optimum*: optimal solution represents the condition in which the machine works in compliance with all different perspectives' minimum requirements and embraces the strategy ensuring the best combination of them, balancing positive and negative aspects.

Perfect results can be reached only by teams made of managers and workers coming from all Pillars, each promoting the important aspects of its technical area. For this reason, even if the present thesis is focused on QC perspective, my reasoning was made in close cooperation with the Maintenance Department of Mirafiori Meccanica, which helped me -Quality Engineering Department representative- not only in understanding the Thyssen test benches structure and features, but also in looking at it at 360 degrees, deeply analysing its issues and permanently solving them.

In order to make clear to the reader the WCM tools I've applied to perform such a research of *optimum*, next paragraphs are devoted to the explanation of basic Quality Control instruments.

4.3 Quality Control Pillar

The 6^{th} Technical Pillar of WCM is Quality Control: as explained in paragraph 4.2, the main purpose of this pillar is taking care about Costumer Satisfaction with respect to the products the company makes. The QC vision is perfectly condensed in the WCM *V.N.O.T. Introduction* [12]:

- *Vision:* full Customer Satisfaction through excellence in Quality.
- *Needs:* systematical increase of Costumer Satisfaction and making costumers perceive over-expectation value from the product.
- *Objectives:* working according to the rule of "Zero Defects", increasing workers' skills to solve quality issues and reduction of non-quality costs.
- *Target:* create and respect a system of indexes and targets to evaluate the effectiveness of QC actions.

It is important to highlight that Quality activities are not *value-added* ones, because no machining or improvements are performed over the product. Nevertheless Quality Department is fundamental to ensure that all other activities within the plant do respect standards and produce compliant components, avoiding losses in terms of waste material and re-work time, which will inevitably follow the scrap creation.

Having this idea clear in mind, it seems natural to consider that Quality activities should be focused on checking the production compliance in the very first steps of the production flow. In Figure 4.3 is reported the chart of non-quality costs [10].

The chart highlights that discover a defect at an early stage of the process will cause a lower expenses with respect to find it out at the end of several processes, because during the *value-added* chain of production, energy and time are wasted over a non-compliant product. Moreover it's important to consider that a row component nonconforming can be eventually re-worked and being put again in the production flow, while a defective item reported by the costumer will be pulled down and probably an extra cost will be charged to the plant in order to pay back the warranty.

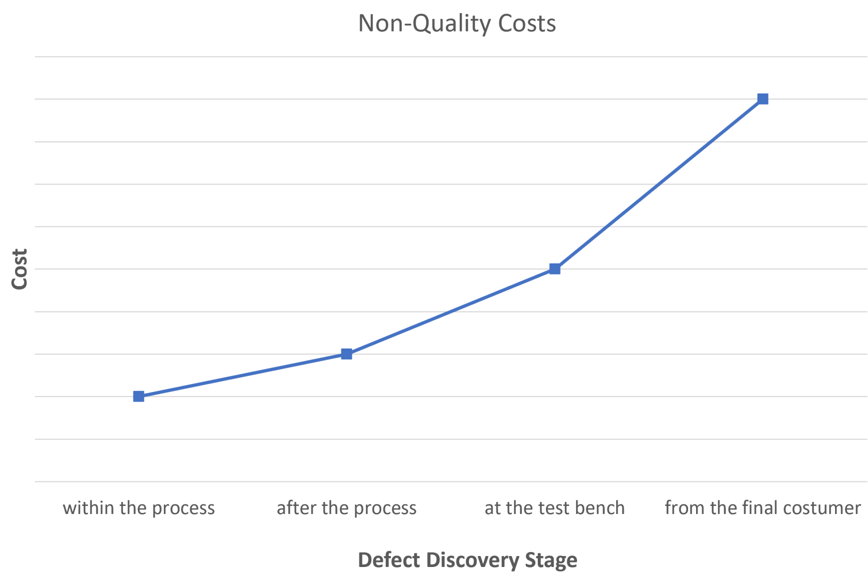


Figure 4.3: Chart of Non-Quality Costs

Ideally Quality Control should operate just in the early stages of the production flow, discovering defects at the beginning of the process and making almost useless the final functional tests, because there is an high probability of having assembled only compliant components. While this should be the goal of Quality Department, it is impossible to exclude final checks and preserve a good Costumer Satisfaction rate.

This goal being clear, it gets of key importance to create a monitoring system of all the plant activities in order to have the highest rate possible of *good at first try* items (see Quality KPIs definitions). To achieve it, the primary Quality task is represented by the analysis of issues and non-conformity happening in the plant's floor: it is called the *Root Cause Analysis*.

To definitely take out issues and avoiding their future show up, it is crucial to deeply understand the problem's source and to directly attack it. The WCM offers a strong tool to do so and it is call *kaizen*: taken from *lean manufacturing* philosophy applied by Toyota Production System, it is a procedure allowing the *kaizen* Team to analyse the issue through determined steps and to implement corrective action that eventually will become the new production standard, avoiding future production mistakes. As a *kaizen* will be proposed in the present work too in order to solve performances issues related to Thyssen test benches, in paragraph 4.3.1 is proposed a detailed description of the *Root Cause Analysis* procedure.

All Quality activities devoted to identify, analyse and solve plant's issues, should have a positive impact on Quality KPIs, i.e. *Key Performance Indexes*.

In Mirafiori Meccanica the Quality evaluation system is based on the following indicators:

- **3MIS Warranty**: computed monthly and expressed in ppm (i.e. parts per millions of units), it expresses the weight of final costumers claims reported during the first three months from the car selling; it is computed as:

$$3MIS\ Warranty = \frac{N^\circ\ claims}{Monthly\ Production\ Volume} \cdot 10^6 \quad [ppm]$$

- **Zero Mileage**: computed monthly and expressed in ppm, it regards complains coming from shop floors where the transmission is shipped to be mounted on vehicles. A further distinction is made with respect to the type of complain: *Assy* represents a transmission only repaired by the shop floor plant, while a *Pull* is a transmission completely replaced, and so it represents a more serious issue. The indicator is computed as:

$$0\ Mileage = \frac{N^\circ\ Assy + N^\circ\ Pulls}{Monthly\ Shipped\ Volume} \cdot 10^6 \quad [ppm]$$

- **Scrap Ratio**: computed monthly and expressed as a percentage, it quantifies the loss due to scraps of single components and totally equipped items, referring the resulting economic loss to the monthly revenue coming from selling compliant transmissions:

$$Scrap\ Ratio = \frac{Scraps \cdot Average\ Item\ Price}{Monthly\ Revenues} \cdot 100 \quad [\%]$$

- **DRR**: Direct Run Rate is a subset of Scrap Ratio and it is computed daily and expressed as a percentage of the total number of transmission produced. It represents the number of *good at first try* transmissions delivered OK from the test benches:

$$DRR = \frac{Good\ at\ First\ Try\ Transmissions}{Daily\ Production\ Volume} \cdot 100 \quad [\%]$$

Note that the present work should have a positive effect particularly over the DRR value (and consequently on the Scrap Ratio): as presented in paragraph 3.3, many Thyssen test benches' issues are related to fake scrap, i.e. transmissions marked as KO and resulting compliant after a second level diagnosis, that could eventually require the dis-assembling of the transmission itself. This occurrence is a source of a double loss:

1. Negative impact on DRR value: even if the transmission is actually OK, it cannot be considered as *good at first try*, as after the test cycle it can't be directly shipped to the shop floors.

2. Time and energy waste during second level diagnosis: following the scrap procedure determined by Quality Department,each suspected transmission has to be double checked by a manual test bench, if no sign of defectiveness is perceived the item is re-tested on automatic test benches. If one of this two checks give a suspicious response, the transmission has to be dis-assembled looking for the non-compliant components, even if at the end no defect is found.

As a result, the delivery procedure gets more tricky and time-consuming: proving what was said previously, finding out a defect in the final productive stages represents a considerable loss for the plant. Hopefully the enhancement activity over Thyssen test benches will sharply decrease these negative effects.

In order to permanently solve Thyssen's issues, in Chapter 5 will be applied step by step the QC Pillar: like all other WCM Pillars, Quality Control consists in developing seven steps towards the *optimum* achievement. In Table 4.3 are briefly describe these steps [12], further explanation will be given in Chapter 5 where they are practically applied.

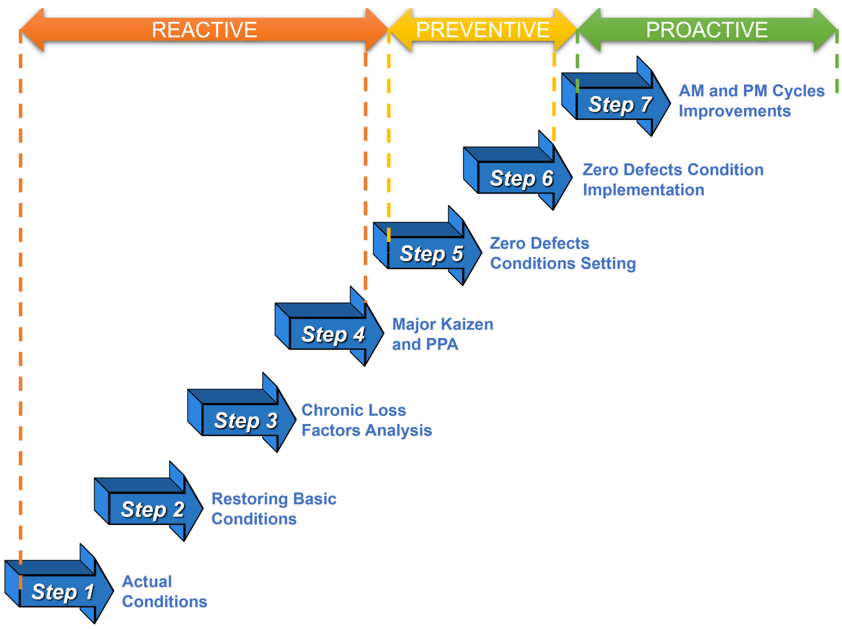


Figure 4.4: Seven Steps of Quality Control Pillar

Table 4.3: Seven Steps of Quality Control Pillar

STEP 1	*Actual Conditions*
	Analysis and inspection of actual machine's conditions
STEP 2	*Restoring Basic Conditions*
	If any loss or damage is spotted during Step 1, it is repaired and brought back to basic conditions
STEP 3	*Chronic Loss Factors Analysis*
	If after basic conditions restoring some malfunctions keeps showing up, a further analysis is performed looking for sources of chronic losses; investigation is performed by observing the machine operations, even doubting about the design choices
STEP 4	*Major and/or Advanced Kaizens*
	For each chronic loss factor identified, a kaizen is realized, whose complexity depends on the faced problem (it goes from a Standard Kaizen to a Process Point Analysis)
STEP 5	*Zero Defects Conditions*
	Once optimal working conditions are identified, all possible issues affecting the machine are written using X matrix tool, in which defective components are linked to their failure cause and conditions for Zero Defects are set down
STEP 6	*Application of Zero Defects Conditions*
	Using the QM Matrix tool, Auto-Maintenance and Professional Maintenance Cycles are elaborated to achieve and keep over time the Zero Defects conditions; if some machine's components shows a critical Impact Factor, the maintenance cycles should be revised to reduce its failure risk
STEP 7	*Improvements of AM and PM Cycles*
	The final step is devoted to the enhancement of AM and PM cycles previously set, improving the checking span and simplifying control procedures to make them faster and leaner

4.3.1 PDCA Technique and Kaizen

Kaizen is one of the WCM instruments presented in previous paragraph that will be used in this work to enhance Thyssen automatic test benches' mechanical structure. The term *kaizen* comes from the Japanese *kai* that means "changing" and *zen* that stands for "good" [13]: kaizen tool represents a structured procedure to investigate and analyse productive issues, to solve them and create new standards.

Kaizen's structure is modelled on the *PDCA Technique* (Figure 4.5):

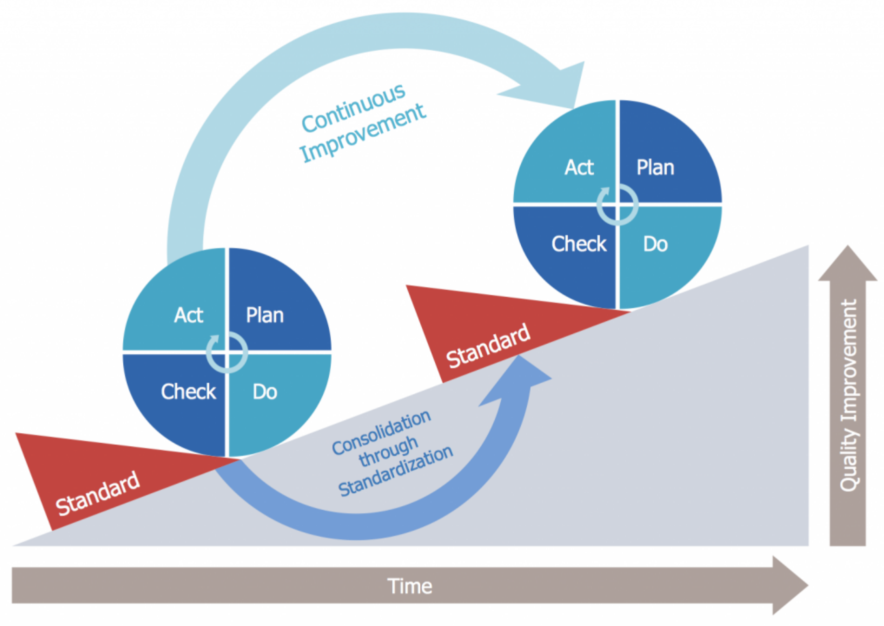


Figure 4.5: Deming Cycle

- **Plan:** once an issue comes up, the first thing to do is understand it and analyse all possible causes that contributes to the defect's creation.

- **Do:** having found out the issue's source, the kaizen team can think about possible solutions to fix it; corrective actions can be intermediate, to temporarily contain the defect, or permanent, changing some structural or organizational aspect of the production flow.

- **Check:** in a period of three months the corrective actions created at previous step are checked about their feasibility, their actual implementation and their ability to definitively stop the issue.

- **Act:** if the check period gives a positive result, corrective actions should become the new productive standard of the plant (in Figure 4.5 ideally represented by the wedge); but the goal accomplishment does not represent the end, as the plant's attitude should be of continuously improving the products quality, so that the Deming wheel can keep climbing.

Quality Team in Mirafiori Meccanica has developed a standard form for the kaizen. In Figure 4.6 is reported a fac-simile of it; in following paragraphs will be given a detail of the most important tools used in it.

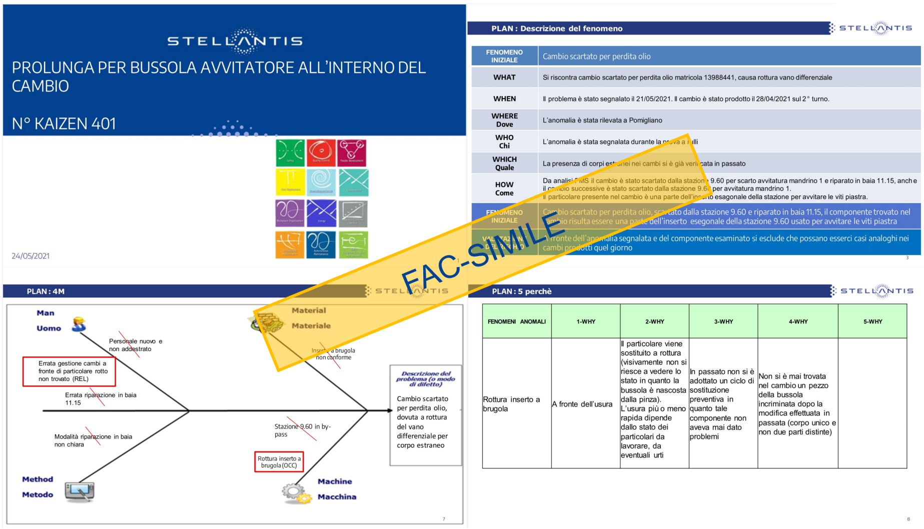


Figure 4.6: Kaizen template used in Mirafiori Meccanica

PLAN First thing to do while facing a defect in the production line is to isolate the machines on which the nonconformity has appeared and define the risk perimeter: the kaizen Team can only do it by asking itself questions which help understanding the issue's nature. The **5W and 1H** is the tool typically applied first:

- *What?* Description of the defect and the component on which it is present.
- *When?* Point out when does the defect was detected and when probably it occurred.
- *Who?* Define which entity or employee found out the issue and reported it.
- *Which?* Identify the type of defect, eventually correlating it with past issues occurred on the same line.
- *How?* By putting together the information collected in previous questions, make an hypothesis about the ways of defect's occurrence.

Having defined clearer the defect, it is possible to fill in the last two form's boxes:

- *Initial Phenomena:* probably after the analysis proposed the defect presented at the beginning has slightly (or totally) changed in its shape and it is now something lighter to work on.

- *Risk Perimeter:* guessing a possible issue's occurrence helps the Team to define if the defect is repetitive or not; if so, it is important to check carefully all other components made in the same tool machine, during the that critical shift or made of the same row material (it depends on the specific risk perimeter evaluated), to find and isolate all possibly compromised components around the plant.

This first review help the Team understand a bit more the issue and at the same time is use-full to immediately implement containment actions to avoid defect spread and consequently an high number of scraps.

A further investigation is performed over the *Initial Phenomena* that has been identified, in particular it is important to detect the issue source nature. At this point it is typically applied the **Ishikawa diagram** tool (sometimes simplified in *4M method*).

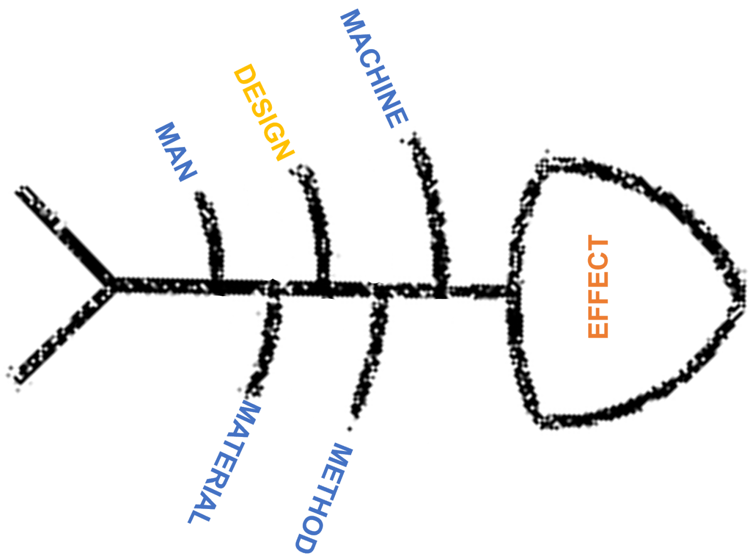


Figure 4.7: Ishikawa diagram

Fish-bone like diagram, filled out to reason about the main cause that could have determined the defect: usually the kaizen Team has a brainstorming and everybody, according to its skills and experience, proposes a possible failure cause. These ones has to be be sought within the five fields, which are:

- *Machine:* possible troubles related to the machine's functioning, for example a misalignment, part program's failure, mechanical components damages.

- *Material:* some defects may appear because of material's fault, so that its nonconformity may affect the mechanical properties of the product, causing and unforeseen breakage of it.
- *Method:* in other cases the product's damage may occur because a inappropriate handling or working procedure have been applied by operators.
- *Man:* frequently issues on production flow are caused by human errors, who can fail the operation for many reasons; typically root causes like this are addressed using the *H.E.R.C.A.* tool (which stands for Human Error Root Cause Analysis), where the worker who caused the failure gets an interview to understand reasons behind his wrong behaviour.
- *Design:* it may happen that product's failure is caused not by an accidental event, but for some designing mistakes; it is a typical situation of new products, whose correct functioning has yet to be run in.

Once the brainstorming ends, all Team members examine the proposed failure causes, erasing the ones which does not seem plausible to have happened: what is left at the end of this process is written in the fish head.

Notice that when a product's failure happens, the kaizen Team has to reply to a double question:

- **Occurrence:** why the product was machined and/or assembled in the wrong way? Why does it failed?
- **Release:** why the damaged product was not intercepted inside the production line or at the final check of the process or at the test benches (according to the product flow's point in which the failure was discovered)?

If it is necessary, the Team performs two different inquiries to solve both occurrence and release problems.

Having identified the failure cause, the final tool to be applied is the **Why-why Analysis**: the Team keeps asking itself "why?" about the failure cause, till the investigation goes so deep that probably it identifies the real root cause of the defect.

DO Previous step left the kaizen Team with a single (or multiple) root causes that are reasonably the source of the defect under investigation. At this point it is important to search and create some effective countermeasures to avoid two basic things:

1. The defect is produced in future: acting on the occurrence root cause, corrective actions should make the process stiffer (change machine's tools, apply a different productive procedure, modify the production line).

2. The defect is detected again by the costumer: acting on the release root cause new or better detection instruments and/or procedures can be made-up to catch non-compliant components in time (poka yoke, revised thresholds, added cameras or sensors).

CHECK The third kaizen's step is represented by a check phase, in which kaizen Team and all other operators involved verify that the the defect they want to eradicate is actually gone. In Mirafiori Meccanica this check period is closely supervised by Process Quality Department, a branch of Quality Department that performs internal audit and inspections to verify the goodness of the process and the procedures applied.

If at the end of these 3 months check the permanent corrective actions result to be properly followed and effective, kaizen goes in the next step. If not, kaizen Teams are invited to work again on the issue, looking for a deeper root cause or simply reinforcing the corrective actions.

ACT Last step of the kaizen is create and/or update the standards including the corrective actions applied and checked at previous points. With the aim of pursuing continuous improvement, this step is quite important, as it guarantees that the new quality standard is respected and at the same time it builds the basis of a further improvement of the same standard.

At Mirafiori Meccanica, like many other industrial plants, the two main normatives the Quality Department has to update are the P.F.M.E.A. and the Control Plan.

P.F.M.E.A. stands for Process Failure Mode Error Analysis, it is a document created by the plant and the tool machine maker, where all possible kind of defects are listed and weighted. Usually the P.F.M.E.A. is filled in during the tool machine design phase, later according to the experience of its working conditions, the costumer (in this case the plant) can update it, contemplating new defects too or changing weights of existing ones.

All defects detailed here regards component's features machined by that specific tool machine, which can possibly be worked in a wrong way, causing the component failure. Note that not all features has the same importance about functional reasons, that's why the most critical ones are marked as "Q-Points" (meaning Quality-Points), that operators must be take care of to avoid dangerous product's failure.

The logic sequence to fill in the P.F.M.E.A. form is the following:

- List of components features to be machined on that productive station;
- Corresponding machining operation that the tool machine activates to produce that specific feature;
- Determination of Relevance Index, by multiplying the following indexes:
  - PROBABILITY of occurrence: on a scale from 1 to 10, rate the probability of producing a component having that feature out of specifications
  - DETECTION: rate from 1 to 10 the reliability of the detection system present on the productive station to catch the defective component
  - SEVERITY: rate from 1 to 10 the risk related to that specific failure (in this case 9 points are given for a vehicle stop, while 10 are given to safety issues arising from the defect)

The **Control Plan** is directly dependent from the P.F.M.E.A., as it represents the list of quality checks to be performed on the productive station to avoid the components failure. Ideally features are checked at 100% according to the failure modes evaluated in the P.F.M.E.A., in order to ship ahead only compliant components.

If this total check cannot be performed for several and various reasons, then it is important to carefully control at least features marked as Q-Points.

The kaizen structure depicted above can be obviously extended with further analysis and information, but the steps described in this paragraph are common to all kaizen projects.

According to the defect harshness and its resolution toughness, kaizen projects can be classified as follows:

1. **Quick Kaizen:** applied for generic improvements, typically regarding issues of which the root cause is well known by operators and easy to eradicate; in this case corrective actions can be implemented immediately and autonomously.
2. **Standard Kaizen:** with good approximation it has exactly the structure depicted above and it represents the common procedure to face up problems in the production flow.
3. **Major Kaizen:** it has a structure very close to the one of Standard Kaizen, but the kaizen Team is typically made up by managers (so employees that has an higher rank with respect to operators); it is employed when standard kaizen responses shows to be ineffective.

4. **Advanced Kaizen:** plants usually resort to this kaizen level only while facing chronic problems, that corrective action by corrective action keeps showing up; in this case a PPA (Process Point Analysis) is performed, namely all tool machine components that come in contact with the product are deconstructed and analysed in their structure, looking for a possible issue to be solved.

4.3.2 Maintenance stages

Focusing on the main topic of this work, i.e. Thyssen test benches mechanical improvement, it is important to describe the so called *Quality Maintenance*, which is halfway between Quality Control and Maintenance Pillars. This subject is particularly significant when it comes to Machine problems (first voice of Ishikawa diagram): as a matter of fact, it represents the maintenance principles applied to guarantee the product quality. Back to the representation given in paragraph 4.3 (Figure 4.2), it is like making merging the two perspectives, so that now the machine care is implemented to make it work as close as possible to its theoretical capacity load, at the same time producing only compliant components.

This speech has to be declined for the peculiar machine, centre of this thesis analysis: test benches cannot be considered as tool machines, as they don't perform a *value-added* process nor make any change to the transmission structure. In any case test benches come in contact with the product (eventually damaging it) and they simulate the on-wheel conditions to try the transmission performances. As explained in paragraph 3.3 wrong mechanical designs, excessive clearances and bad mechanical coupling may result in an unfair reading of NVH curves, consequently creating a fake scrap, which is time and energy consuming. To avoid or at least reduce this productive waste, it is important to carefully act on the test benches maintenance.

At first it is necessary to clarify the following distinction between maintenance phases:

1. *Reactive:* maintenance activities comes "to failure", namely intervention are performed after the machine breakdown, to repair it and restore its initial conditions.

2. *Preventive:* planning suitable inspection cycles, maintenance activities foresee machine issues and breakdowns, replacing or adjusting in advance components and features that in the near future will fail; in this way productive stops are largely reduced, as repairing activities are all planned during expected production stops.

3. *Proactive:* last and more complex maintenance phase, it consists in study the machine structure to make some changes and improvements of it, extending components life.

Being this maintenance activities classification common to most companies, WCM makes a further distinction between maintenance stages: two are represented by the Technical Pillars 4 [14] and 5 [15], the last stage, i.e. Quality Maintenance [16], is embedded in Pillar 6, that is Quality Control.

Autonomous Maintenance AM represents a peculiar approach to maintenance, according to which all operators do take care about their workstation and processes by doing simple repairing actions, checks and part replacing. The more the worker is skilled the better he or her masters the process, well handling and improving his/her productive area.

Correctly applying AM means create a knock-on effect of improvement: better and properly managed equipment means creating a better and pleasant workplace, a good workplace means improve plant's performances and quality.

Note that this goal, summarized by concepts already introduced like Zero Defect and Zero Breakdown Conditions, can be achieved only if all operators are made aware of the importance of their actions: this awareness and sensitivity must be instilled by managers, who makes the plant follow step after step the AM prescriptions.

Professional Maintenance PM is the complementary aspect of AM: in this case interventions on machines are performed by skilled and professional employees, the Maintenance Department workers, who are able to take care and properly fix even the most serious machine's breakdowns.

To do so it is fundamental to precisely organize maintenance activities: at first it is necessary to analyse the machine and understand its functioning, in order to identify all possible criticalities; then a maintenance standard has to be set down for all plant's machines and obviously respected.

Once these key steps are achieved, maintenance can go further by building up periodic maintenance cycles for each machine and furthermore their preventive maintenance cycles, so that inspections and components' replacements are planned to (almost) avoid completely machine brake-downs.

Quality Maintenance Previous two steps are only under Maintenance Department control. The last additional step of Quality Maintenance mixes together actions of Quality and Maintenance Departments, which work together to ensure not only that machine's load capacity is fully exploited, but also that 100% of components produced are compliant.

Main focus of QM is to permanently set down Zero Defects conditions, which is only possible by acquiring a deep machine knowledge, usually achieved by deconstruct it and analyse its main sub-systems and components.

Having became skilled with respect to the machine, it is necessary to periodically check its conditions and measure the produced components, to identify immediately a possible drift of machine's features which lead to non compliant components: as soon as the operator advises some malfunctions of the machine, the Maintenance employees can be activated to restore basic conditions.

4.3.3 Quality Maintenance Tools

Having already reached the basic steps of AM and PM on Thyssen test benches, the goal of this thesis is to go further on QM theory, creating the foundations for preventive and proactive maintenance cycles implementation.

While doing that, the seven steps of Quality Control Pillar will be promptly followed, and since at steps 5 and 6 it is required the application of two crucial instruments of Quality Maintenance, the present paragraph will give some hints about the *X Matrix* and the *QM Matrix* tools.

X Matrix The first tool employed by Quality Maintenance is called X Matrix (because of the table structure and the possibility to read it in many directions). With respect to a single machine, it is used to analyse the correlations between the following four concepts :

$$DEFECTS \times PHENOMENA \times COMPONENTS \times PARAMETERS$$

The goal of the X matrix is to define and establish Zero Defects Conditions by identifying the cause-effect relationship between the defects a product may show with the specific machining operation needed to produce it: if there's a mistake in the parameter settings or a damaged machine's component, the working operation may go wrong. To immediately identify this kind of defects sources the X matrix is a valuable tool. Note that these activities refer mostly to *reactive* and *preventive* maintenance phases.

The typical structure of the X matrix is depicted in Figure 4.8; following the coll-outs here are the passages to fill in the matrix:

1. *Failure Modes:* the first column to fill contains the list of all possible defects which may appear on the product.

2. *Phenomena:* all failure modes are linked with the phenomena in charge of causing them.

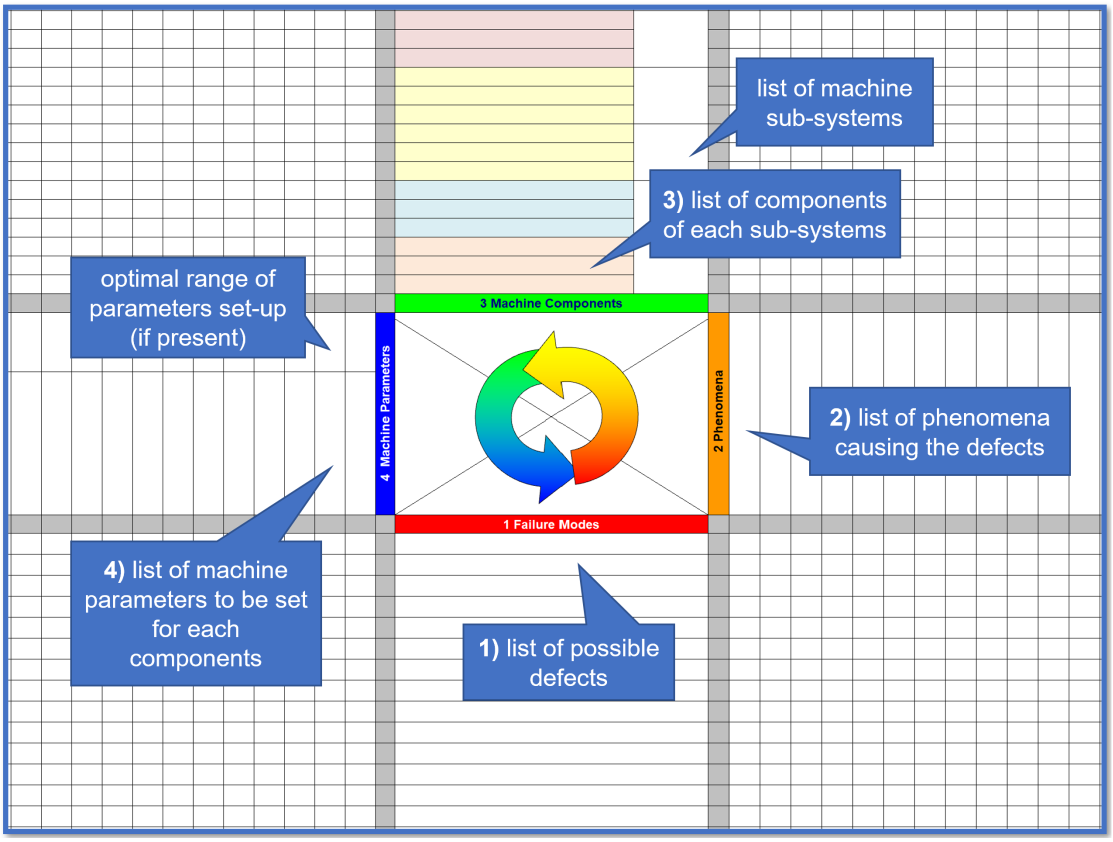


Figure 4.8: X Matrix structure

3. *Machine Components:* phenomena listed before are related to specific machine parts, that could result damaged and consequently cause the defect.

4. *Machine Parameters:* probably the machine component malfunction is due to a wrong set-up of machine parameters, here are reported the correct or optimal values they should have to ensure Zero Defects Conditions.

As previously pointed out, test benches are not like tool machines and so they require a slightly different analysis approach; let's see how the columns meaning has to be reinterpreted:

1. *Failure Modes:* instead of product's defect, here are listed all possible damages, issues and malfunctions the test bench may have, which may cause an alteration upon the NVH test results.

2. *Phenomena:* same as before.

3. *Machine Components:* same as before.

4. *Machine Parameters:* since defects here are due to wrong design or non optimal working conditions, instead of make a list of correct parameters settings, it will be useful to specify the right set-up conditions together with correct working ranges (like speeds, temperatures, preload, clearances and so on), if present.

QM Matrix and 5QFZD Every X Matrix must be always followed by the QM Matrix: this tool displays and clarifies checks which have been identified at previous step, making them the maintenance standard for that specific machine. Theoretically, by following the check cycles and their procedures, the machine works always in Zero Defects Conditions.

This instrument can be applied not only in *reactive* and *preventive* maintenance phases, but in *proactive* phase too, since it should report all optimal machine parameters' checks, taking into account even those ones which didn't cause any failure yet.

As did for the X Matrix, in Figure 4.9 is reported the scheme of a QM Matrix:

1. *Machine Sub-Systems:* the first part of the matrix resumes elements of X Matrix, listing all machine sub-systems and components involved in the maintenance checks; for each group are specified:
   - *Machine Components:* main machine parts of that sub-system.
   - *Machine Parameters:* one for each component, it expresses the parameter to be set up on the machine for its correct work (here are not reported values, just the physical quantities involved).
2. *Check:* the core part of QM Matrix is made of clarifications about the maintenance cycles and how they should be performed:
   - *Measuring Tool:* it is the instrument of measure with which it is possible to quantify the corresponding parameter.
   - *Specifications:* it clarifies how to judge the measurement: it is OK or not? Note that it is important to express numerical values or ranges, to clearly objectify the measurement result.
   - *Frequency:* here are reported how often the checking cycle has to be performed (once a week, twice a year and so on).
   - *Responsibility:* it shows the name of the Department in charge of the control cycle; here is also specified if it is an AM or a PM check.
   - *Standard:* if a standard document is present to regulate the maintenance cycle performance, here is reported its name or code to be immediately found.

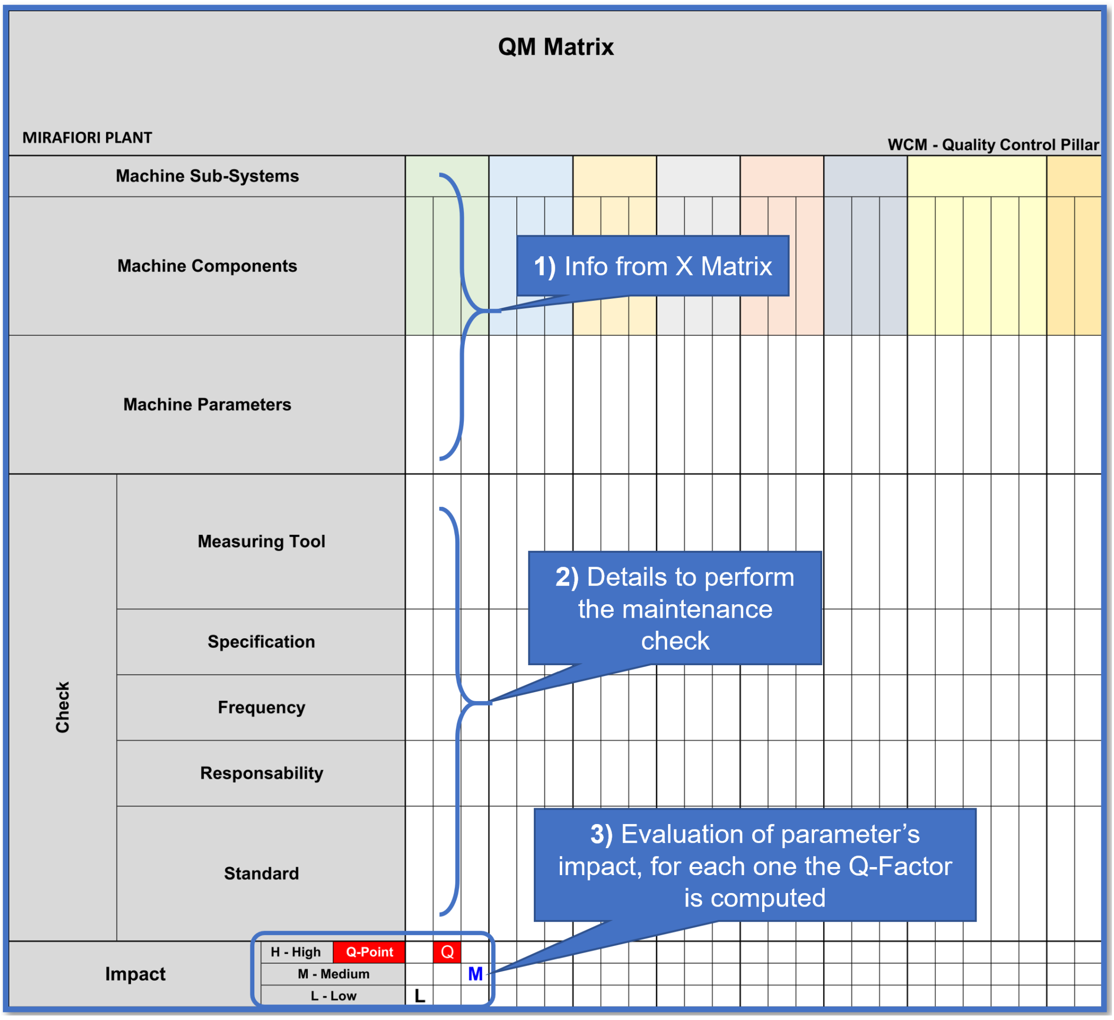


Figure 4.9: QM Matrix structure

3. *Impact:* this final section, preparatory for the compilation of 5QFZD module (5 Question For Zero Defects), assigns a label to each component/parameter:

   - **H** or **Q-Point**: high level of importance, if the component's feature is particularly critical for quality issues, it is marked as a Q-Point, i.e. Quality-Point to take care of.
   - **M**: medium importance feature, since only in some cases its wrong machining could end up in quality issues.
   - **L**: low importance about quality standards, even if that component's feature is out of tolerances the product preserves its conformity.

Having filled in the QM Matrix, last analysis step consists in evaluate the efficacy of the maintenance cycles, eventually improving them. To verify it the *5 Question for Zero Defects* tool is applied. Imagine it as the continuation of the QM matrix, in Figure 4.10 is reported the 5QFZD scheme:

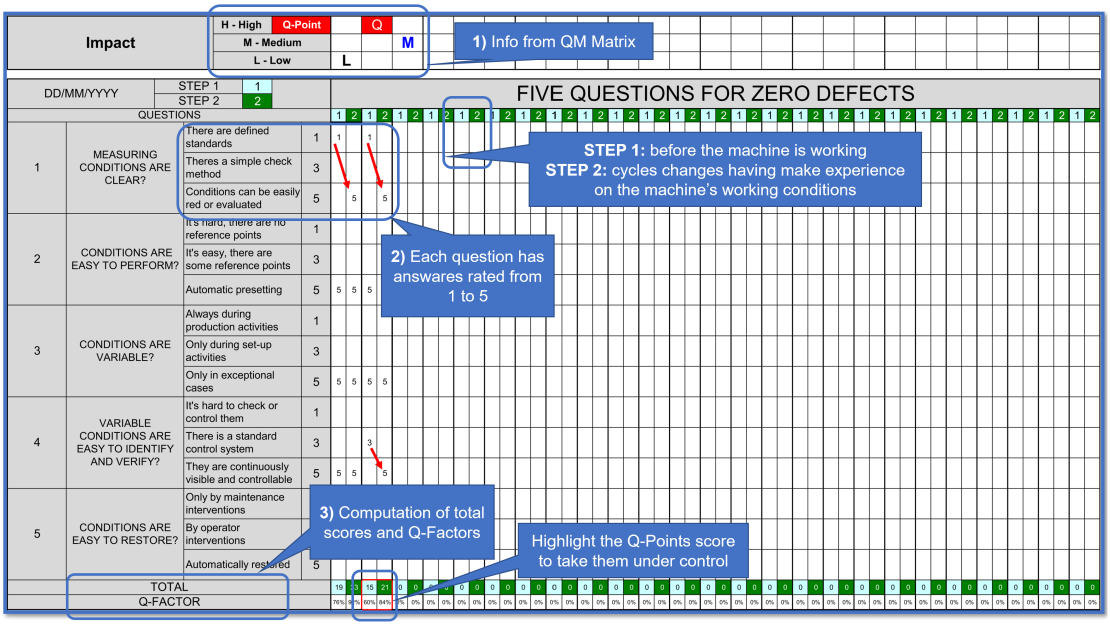


Figure 4.10: 5 Questions for Zero Defects structure

The five questions reported in the scheme refers to the easiness with which control cycles can be performed: the more the quantity to measure is clear and easy to read, the higher is the reliability of the check.

1. *Impact:* same rows taken from the QM Matrix.

2. *Questions:* five questions about the machine's conditions are listed here, each declined for the specific machine component present in the QM Matrix. The generic term "condition" refers to the circumstance in which the cycle should be performed, for example:

   - 1) *It is clear which measurement instruments and in which conditions you have to evaluate that parameter?*
   - 2) *It is easy to preform the measurement? Do you know how to do it?*
   - 3) *Machine working conditions are stable or not? Is there any difference to perform the check in a condition with respect to another one?*
   - 4) *Can you immediately get aware of dealing with variable working conditions?*

- 5) *Is it easy to restore design working conditions of the machine?*

  Each questions has three possible answers rated from 1 to 5, where 1 means very bad check reliability and 5 is the best way to reach Zero Defects Conditions on the machine.

3. *Scores:* for each component/parameter taken into account, the summation of all points is performed (the maximum is 25 points) and then the reached score is expressed as a percentage of the maximum rate the listed item may get, this percentage represents the parameter called Q-Factor.

With respect to the scheme in Figure 4.10, note that for each listed item there are two different scores columns: column of step 1 refers to the early compiling of the 5QFZD, performed during the design stage of the machine; step 2 refers to answers coming after a refinement of the maintenance cycles, modified according to the experience made on the machine working conditions. After revising the cycles, the Q-Factor of many components is expected to grow as the reliability of those cycles gets higher.

As previously stated, **Q-Factors** are computed as:

$$Q\ Factor = \frac{Total\ Score}{25} \cdot 100 \quad [\%]$$

Ideally, getting 5 to each question leads the component to reach a Q-Factor of 100%, namely the corresponding maintenance cycle is effective and cannot be improved more than that: ensuring its execution the machine won't create a defective component (with respect to that specific feature considered). Actually reaching 100% value for all machine's components may result in an excessive cost, without real major quality advantages, so WCM fixes the optimum Q-Factor rate to 80%: by making sure that at least all Q-Points reaches this target, the machine will work almost without creating non compliant components.

Chapter 5

Application of Quality Control Steps

As introduced at the end of Chapter 4, here will be detailed the application of Quality Control Pillar steps, declined for a special industrial machine, i.e. a transmission test bench.

Note that the subject of the present analysis is different with respect to a common tool machine, which is why WCM instruments will be adapted to the specific case, making the reader well aware of these adjustments as the speech will proceed.

Consider that in Mirafiori Meccanica are installed six test benches, which have been retrofitted in different periods, making the machines having slight equipment differences. For this reason the analysis will be performed over a single test bench, which is the *Thyssen5*, as it was the first retrofitted machine, and having accumulated more service hours than all test benches, it probably shows issues that other machines are not expressing yet: it is considered a safety choice to investigate over TH5.

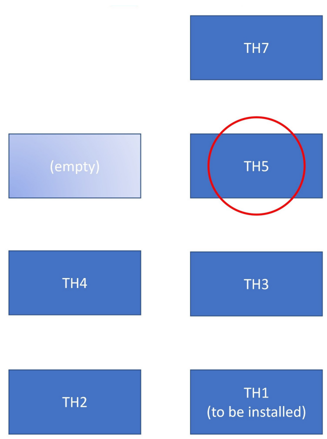


Figure 5.1: Test benches layout in Mirafiori Meccanica

5.1 Step 1 & 2: Actual Conditions and Basic Conditions Restoring

The very first thing to do to apply Quality Maintenance over an industrial machine, is to assess its actual conditions, eventually restoring basic conditions suggested by the machine maker.

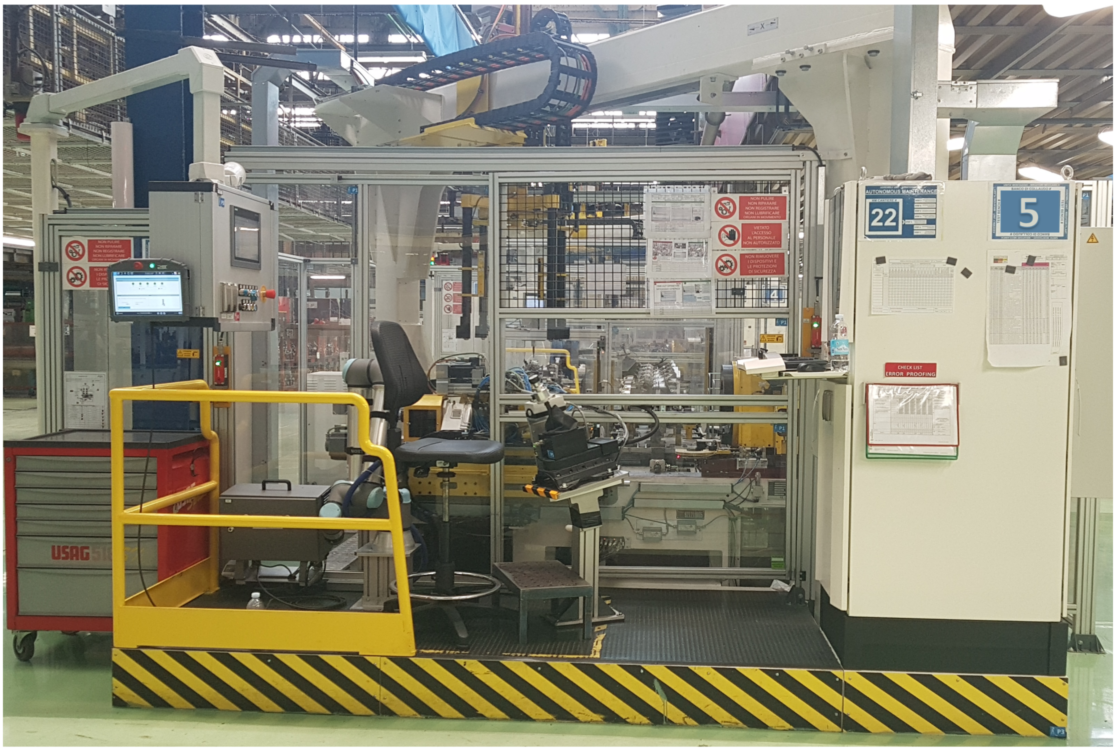


Figure 5.2: Picture of test bench *Thyssen5*

STEP 1: Actual Conditions In Figure 5.2 is shown the test bench number 5 installed in Mirafiori Meccanica. By comparing it with the sketch proposed in Figure 3.1, the reader could easily spot the operator station nearby the gear lever, the test bench PC on which the UPS software elaborates the NVH analysis, the control panel and over these elements the test bench's core, made of slides, rotating shafts and motors, enclosed by glass shelters, able to handle the transmission and to analyse it in a fully automated way.

While checking actual machine conditions, it is important to understand the operation of the test bench, knowing how the control cycle is performed and which are the main machine groups or sub-systems involved. While outer elements,

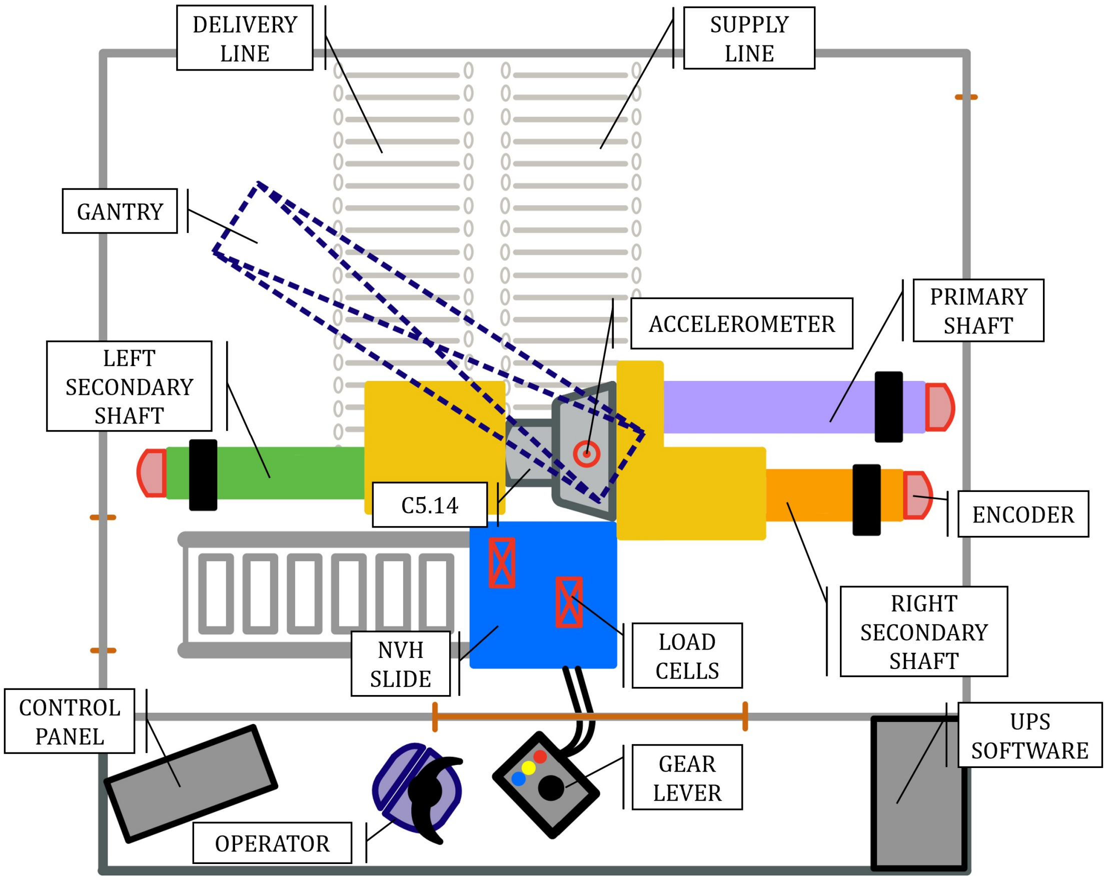


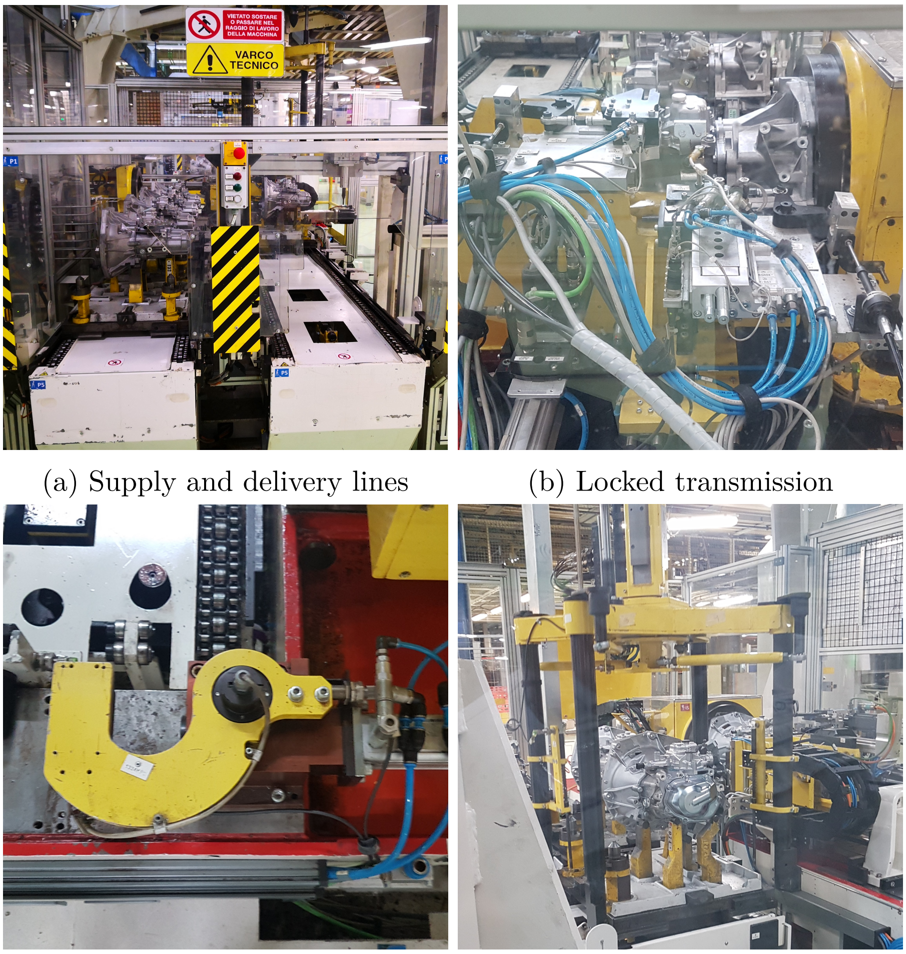
Figure 5.3: Sketch of test bench top view

mainly needed for collateral operations and machine status checks, are sufficiently described by the scheme already presented in Chapter 3, here there will be a focus over the test bench's elements inside the glass shelters. In Figure 5.3 is proposed a sketch (top view) helpful to catch the cycle steps described afterwards.

1. The AGVs, guided by magnetic strips under the plant's floor, bring the transmissions to be tested on the supply line (see left path of Figure 5.4a), motorized to make the product flow towards the test spot;

2. The elevator plane, positioned at the end of the supply line, lifts up the transmission to allow the right and left slides (respectively corresponding to the ends of right and left secondary shafts groups) to lock the C5.14 under investigation thanks to an hydraulic system;

3. While the transmission gets locked by the slides, electric motors and pneumatic cylinders present on left and right slides and on the NVH slide, allows



(a) Supply and delivery lines (b) Locked transmission

(c) STATEC memory reader (d) Gantry robot

Figure 5.4: Elements of Thyssen test bench directly involved in the checking cycle

these sub-systems to come nearby the gearbox, engaging its two shafts and the elements over its control cover, necessary to maneuver the speeds during the test: the test setup is achieved (Figure 5.4b);

4. In the present position the C5.14 undergoes all the various checks implemented to spot gearbox's issues (see paragraph 3.2 for visual control cycle and detectable defects details);

5. During the test, some gearboxes may result non compliant: in this case the magnetic memory under the transmission pallet (called STATEC memory, whose reader can be seen in Figure 5.4c) records the non conformity and at the same time the operator manually affixes a tag on the product;

6. At the end of the control cycle, both compliant and non compliant gearboxes are released by the locking system of the test bench and are lifted up by a gantry robot (Figure 5.4d), which thanks to four hydraulic cylinders grasps the transmission and brings it to the delivery line;

7. Once the product is put on the delivery line, another elevator plane takes it, and using a pneumatic cylinder brings down the C5.14 on the conveyor roller, which will store four gearboxes along its length, waiting for and empty AGV to take the transmissions away;

8. Before being loaded on the AGV, a system of pneumatic cylinders marks the C5.14 to be delivered.

Understanding the control cycle and identifying the main mechanical groups involved, has been fundamental to acquire a basic *know-how* of the machine, essential to perform next steps of QC Pillar.

STEP 2: Restoring Basic Conditions The present step has been easily applied by performing a visual check of the test bench TH5: Maintenance Department constantly monitors test benches' status, performing *breakdown maintenance*, namely maintainers act most of the time directly on issues and breakdowns arising. The main operation they do is to properly bring the test bench back to the prescribed conditions, following the machine maker book, so that no critical declines have been detected during Step 2 inspection.

Since the basic conditions restoring is not sufficient to make the test bench number 5 work properly for longer productive periods nor to eradicate chronic machine's issues, it was necessary to proceed the analysis by going through steps 3 and 4.

5.2 Step 3 & 4: Chronic Loss Factors Analysis

These two further steps aim to detect and solve chronic loss factors of the machine: they are represented by every test bench's issue which may produce an excessive level of noise on the transmission checked. To go deeper in the investigation, it was not only necessary to comprehend test bench's operation and shape, but to understand which elements compose it and how they are assembled together.

Initially the machine maker documentation was analysed, discovering how they decompose test bench's structure and which names (ID numbers) are given to its groups. By reading the mechanical drawings available in the machine's documentation, the groups identified are reported in Table 5.1.

Table 5.1: Thyssen test bench's nomenclature and groups

GROUP ID	DESCRIPTION	GROUP ID	DESCRIPTION
202	basement	203	NVH attachment system
204	primary shaft electric motor	205	right secondary shaft electric motor
206	left secondary shaft electric motor	207	NVH slide
208	primary shaft slide	209	primary shaft linear electric motor
211	right secondary shaft slide	212	left secondary shaft slide
213	primary shaft - transmission puller side	214	primary shaft - torque transducer side
215	right secondary shaft motion transmission system	216	left secondary shaft motion transmission system
217	gearshift system	218	bowden cables system
219	STATEC memory slide	220	NVH sensors
221	tripod joints (mounting details)	222	torque transducer (mounting details)
223	load cells (mounting details)		

Note that the way in which mechanical elements are assorted by Thyssenkrupp is strictly linked with the machining and assembly operations needed to retrofit and mount correctly the new test bench version (Thyssen one instead of ZF). For the purpose of the next QC Pillar step to be applied, a further study has been performed, by recognising all the groups listed in Table 5.1 and associating them to elements on the physical test bench. Since not all components can be clearly spot on the machine, it has been of key importance to analyse the mechanical drawings, picturing the element's shape and associating to each a specific role.

This journey towards test bench structure's *know-how* acquisition, made possible the production a document called *Scomposizione Banchi di Delibera Thyssen*, given to the Maintenance Department, in which are listed all main functional sub-systems and their main components, noting both their shape/typology and mechanical purpose. Since not all sub-systems will be involved in the next study, in Table 5.2 are summarized all of them, together with a useful indication of components' commercial ID (where present).

Note that each sub-system is made of several components, including screws, spacers and so on: having in mind the need to discover and classify possible critical elements present on the test bench, for each group are presented only those components which undergo stress conditions or that could be damaged during functioning.

Table 5.2: Thyssen test bench's sub-systems and main components

sub-system	**main components**	**commercial code**	**qty**
HYDRAULIC SYSTEM	cylinder Φ22/5 (secondary shaft slides actuation)	/	2
	cylinder Φ80/25 (secondary shaft slides locking)	/	2
	cylinder Φ25/50 (lift table)	/	1
	cylinder Φ48/32 (gantry's grippers)	/	4
LUBRICATION SYSTEM	oil tank	/	1
	grease tank	/	1
	pressure transducer	*DS-W 12 179 990 034* (VOGEL)	2
	oil pipes	/	several
	grease pipies	/	several
MOTION TRANSMISSION SYSTEM (primary shaft)	belt	*11L2020-12* (POGGI)	1
	deep groove ball bearing	*6007.2Rsr* (FAG)	2
	elastic joint	*Modulflex 920-4,5-003* (BSD KUPPLUNG)	1
	electric motor	*1FT7108-5FS70-3NK3* (SIEMENS)	3
	encoder	*6FX2001-5FD13-0AA1* (SIEMENS)	1
	poly-V pulley	*11L2020-12* (POGGI)	1
	pulley clamping unit	*serie 1003* (BIKON)	1

MOTION TRANSMISSION SYSTEM (secondary shafts)	belt	*11L2020-20* (POGGI)	2
	deep groove ball bearing	*6007.2Rsr* (FAG)	4
	elastic joint	*Modulflex 920-4,5-003* (BSD KUPPLUNG)	2
	encoder	*6FX2001-5FD13-0AA1* (SIEMENS)	2
	poly-V pulley	/	2
	pulley clamping unit	*serie 1003* (BIKON)	2
	electric motor	*1PH8165-1MD03-0DA1* (SIEMENS)	2
NVH SLIDE and SENSORS	accelerometer	*KS813B* (MMF)	1
	elastic support	/	1
	engagement load cell	*S2M* (HBM)	1
	locking nut	/	1
	selection load cell	*S2M* (HBM)	1
	sensors cables	/	3
PNEUMATIC SYSTEM	cylinder $\Phi16/40$ (STATEC slide)	/	1
	cylinder $\Phi40/500$ (horizontal motion engagement slide)	/	1
	cylinder $\Phi40/150$ (transverse motion engagement slide)	/	1
	cylinder $\Phi16/30$ (NVH slide)	/	1
	cylinder $\Phi40/50$ (marking system)	/	1

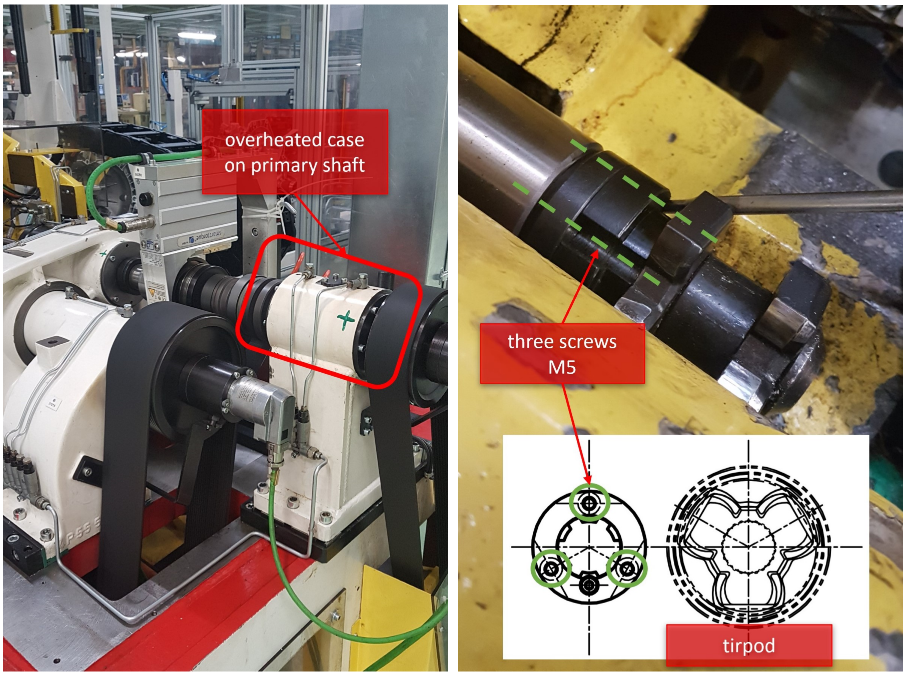
PRIMARY SHAFT	angular contact ball bearing	*7210AC P4* (SKF)	1
	deep groove ball bearing	*3210 C3* (FAG)	1
	elastic joint	*226.525.01* (HEIDENHAIN)	1
	roller bearing	*NU 2210 C3* (FAG)	1
	safety clutch	*EAS 496.714.0* (MAYR)	1
	shaft	/	1
	tapered roller bearing	*HR 30210J* (NSK)	1
	torque meter	*T12* (HBM)	1
SECONDARY SHAFTS	deep groove ball bearing	*3210 C3* (FAG)	2
	elastic joint	*Modulflex 920-4,5-003* (BSD KUPPLUNG)	2
	roller bearing	*NU 2210 C3* (FAG)	2
	splined shaft	/	2
	torque meter	*T12* (HBM)	2
	tripod joint	/	4
	tripods splined shaft	/	2

STEP 3: Chronic Loss Factors To identify factors and elements of the test bench which cause a chronic loss in the machine performances, it have been possible to follow two ways:

a. Visual inspections: together with a mechanical specialist belonging to the Maintenance Department, the test bench was visually analysed, looking for suspect working conditions.

b. Machine Ledger and SAP system: the two instruments are used to record all maintenance activities over the test benches and represented a useful resource to discover chronic defects and frequent component's breakdowns; knowing that *Thyssen5* was retrofitted in 2015, the list of recorded issues is quite long and accurate.

Crossing the information coming from Maintenance records and what was perceptible directly on the machine, several loss factors have been evaluated, but because of the occurrence repeatability and of the direct impact on the NVH system, only two of them will be developed and solved in the present work:



(a) Bearings' case overheated (b) Tripod joints' unscrewing

Figure 5.5: Elements of Thyssen test bench directly involved in the checking cycle

I. **Bearings' overheating**: by inspecting the test bench, an high temperature was discovered on the case shown in Figure 5.5a, in which are present the primary shaft and its two bearings; to confirm the suspect, some observations were done:

   - a thermometer was used and a temperature of around 100°C was recorded;
   - looking at the Machine Ledger of TH5, during the last year too frequent maintenance interventions were discovered, aiming in replacing the bearings because of their excessive wear;
   - searching within the machine maker documentation, no information about the optimal working temperature range of the bearings was found, but bench-marking the case's temperature of other test benches, it emerged that older ones (TH5, TH4 and TH3) showed a temperature between $80 \div 90\ °C$, while test benches retrofitted during the last two years had a lower temperature, around $60 \div 70\ °C$.
   - performing a second visual check of the primary shaft's case during operation, grease stains were discovered on it, even if the lubricant housing should be perfectly stemmed by o-ring seals.

   All the circumstances suggest the primary shaft of *Thyssen5* is not working in the right conditions, probably due to an excessive wear of some elements not immediately recognizable.

II. **Tripod joints unscrewing** and **elastic joint damage:** in this case the test bench weak sub-system turned out to be the "SECONDARY SHAFTS" one, which simulates the action of the vehicle's drive shafts. Two chronic losses were discovered, both regarding a mechanical joint along the secondary axis:

   - Tripod joints unscrewing: in order to engage the transmission, the end of each secondary shaft is equipped with two tripod joints, having different sizes to fit both in large and small tulips (see Figure 5.5b); the tripods are mounted on a smaller splined shaft (for easiness of notation called *tripods splined shaft*), which in turn is joined to the secondary shaft (the longer shaft of the sub-system, which is splined too, so that it will be called just *splined shaft*) through an internal splined connection and three screws M5.

     By looking at the Machine Ledger, it came out that once a shift, a team of two maintainer had to intervene on the test benches to tight the screws, thus avoiding excessive vibration of the mechanical joint and the screws breakage.

- Elastic joint damage: the *splined shaft* mentioned above is connected to a smaller shaft that transmits the motion from the electric motor to the gearbox (simply called *secondary shaft*); the two are linked by an elastic lamellar joint, useful to recover misalignment.

  By talking with the test benches' maintainers, it turned out that frequently the elastic joint has needed to be replaced because of unforeseen breakages.

By facing the two issues, it was needed to re-design the two mechanical joints in order to make them work properly, without constantly requiring Maintenance Department interventions.

At this point the key issues to work on have been discovered: in the next step they will be deeply examined, and possibly solved, by suggesting some proposals for improvement.

STEP 4: Advanced Kaizen After an initial discussion with the maintenance mechanical specialists, the best tool to attack the chronic loos factors has been recognized in the Advanced Kaizen: both issues are frequent and repetitive, despite the restoring of basic test bench's conditions according with the machine maker documentation, which means that their root cause goes deeper in the test bench's structure and a Standard or Major Kaizen won't be appropriate to solve them.

Being the Advanced Kaizen features complex and quite long for both the issues faced, the reader will found all details in Chapter 6. To be coherent with the present speech, a summary of the two Advanced Kaizen is proposed here. They will be described together, following the natural structure of the Kaizen; for easiness of notation, bearings' overheating and secondary shafts' joints will be indicated using the same roman numbers seen before (so there will be the issue I and the issue II, respectively).

- **Defect Origin**

  I. Torque and speed modifications on the cyclogram were introduced in October 2019 in order to refine the nicks detection during shifting (Kurtosis analysis); this event exasperated loading conditions over primary shaft, and in conjunction with a bad lubrication system, it produced an overheat of the system, thus causing the premature wear of shaft's bearings.

  II. During the control cycle, the gearbox is run both in forward and rear modes, to detect defects on both sides of the gears' teeth: the continuous reversal of motion increases the clearances between teeth of the internal splined connection (between *splined shaft* and *tripods splined shaft*), thus creating abnormal vibration over the joint and making the three screws M5 undergoing shear stress; as a consequence it was induced their unscrewing and eventually their breakage.

About the elastic joint damage, it is important to notice that every time the test bench encounters a stuck gearbox (defect described in paragraph 3.2.1), the only sign of it, consists in the UPS error the operator receives once the test bench recognizes itself not able to make the C5.14's shafts rotate: day by day the excessive effort made by the secondary shafts, trying to perform the control cycle, creates small damages in the elastic lamellar joint, that after some time brings it to breakage. In this case the root cause should be sought in a bad managing of stuck gearboxes at design level.

- **Analyses and Calculations**

  I. To verify the correct operation of "PRIMARY SHAFT" sub-system and not having precise indications from the machine maker documentation, it was necessary to calculate and verify the following parameters:
     - Belt pull and frequency;
     - Bearings rating life, re-sizing one of them to respect the SKF life specification;
     - Lubricant viscosity ratio.

  II. The root cause identification was performed through a visual analysis of the test bench, comparing it to the machine maker drawings (both of ZF and of Thyssen) and observing the typical transmission flow on the test bench during a productive day.

- **Proposed solutions**

  I. The belt pull was checked and verified, while the bearings arrangements was considered to be not appropriate for the actual application: the mating *angular contact ball bearing* and *tapered roller bearing* is not recommended by the SKF catalogue [17], followed for the computations, and the *tapered roller bearing*, lubricated with grease, does not respect the maximum angular speed requirements of the test bench.

     For these reasons the arrangement was modified and the lubricant was changed by adopting a more suitable grease for bearings undergoing high torque loads. Together with the lubricant change, the lubrication system was modified too, avoiding the continuous pumping of grease inside the primary shaft case.

II. The unscrewing of the tripod joints seems to be solvable in three different ways: not having yet some further information about the type of wear occurring on the splined connection teeth, the three ways have been all analysed:

   - bolt securing washers;
   - modified splined profile;
   - *splined shaft* re-design in a single piece.

   To solve the second issue related to this sub-system, a safety pin connection was introduced, in order to preserve the test bench from serious damages when a stuck gearbox is tested. The fusible element has been sized according to Niemann theory [18].

Notice that the very first issue faced, starting from the end of April 2021, was the bearings overheating, since it was the more serious and possibly impacting defect for the test bench. Closely collaborating with the machine maker, issue I was solved before the delivery of the newest test bench *Thyssen1*.

Regarding the secondary shafts re-design, the Maintenance Department and Manufacturing Engineering received the new design proposals, but being a radical change of the test bench, it has to follow a specific procedure to be approved and finally applied.

5.3 Step 5 & 6: X and QM matrices

At this point of the analysis, it is necessary to create *standards* to align employees actions and unify tools applied to verify test benches conditions. To do so, Quality Control Pillar provides two powerful tools, called X Matrix and QM Matrix, known to the reader for what said in Chapter 4. Speaking about steps, they correspond respectively to Step 5 and Step 6, hereafter described.

It is important to underline that such instruments are mainly matter of Maintenance Department, so that as Quality Engineer Trainee, skills of the author are not sufficient to properly deploy the maintenance cycles. This is why in the present work it will be presented just an initial version of the X Matrix, built with the help of test benches' maintainers, while only a few hints will be given about the QM Matrix.

STEP 5: X Matrix Main goal of this WCM instrument is to relate the product's issues to specific machine parameters, in order to avoid item's damages or wrong machining operations: by carefully take parameters under control and inside the correct working range, ideally the machine is works in *Zero Defects Conditions*.

In the X Matrix, a good maintenance team should not consider just issues already showed by items produced, but it should consider all possible defects which could appear on the product, thus moving a first step towards *preventive maintenance*.

As explained during the theoretical presentation of the tool in Chapter 4, dealing with a test bench is slightly different with respect to fill-in the Matrix for a common tool machine: here operations performed are not *value-added*, so they cannot actually compromise the compliance of the item. For the specific machine, the X Matrix goal is to highlight and attack all possible machine defects that could badly affect the NVH measurement system, thus reducing to zero the sources of *abnormal* noise on the test bench.

For the sake of completeness and to fully take advantage of the instrument, Maintenance Department decided to add also machine failures not directly linked with noise levels, but concerning unforeseen machine stops. This is why besides bearings and joints failures, attacked by the two previously mentioned Kaizen, there are also entries like «air leakages from pneumatic circuit» or «missing signal from encoder»: such failures usually produce warnings on the UPS software, so that actually the test cycle is not run at all.

Without showing the entire X Matrix, that would be meaningless for the aim of the present work, here is described the logic connections of the entries related to Advanced Kaizen I - *Bearings' overheating*, to make a practical example of how the Matrix should be filled in and interpreted.

As the reader can see form Figure 5.6, the two main *Failure Modes* observed over the test bench during the Advanced Kaizen I analysis are:

(1) **abnormal noise** from "PRIMARY SHAFT" sub-system;

(2) **abnormal wear** of primary shaft (due to overheating).

The two issues are listed separately, since they do not necessarily appear together, but their origin is common, which is why the *Phenomena* related to them are all marked. In particular, such noise or wear might be caused by following events:

(1) wrong bearings **preload** application;

(2) - (3) wrong amount of **lubricant grease**;

(4) **worn bearings**, if they are working beyond their service life limit.

As mentioned before, the X Matrix should be a document as much complete as possible, also contemplating issues not emerged yet. It is the case of «wrong bearings preload», which was not the root cause of primary shaft's overheating,

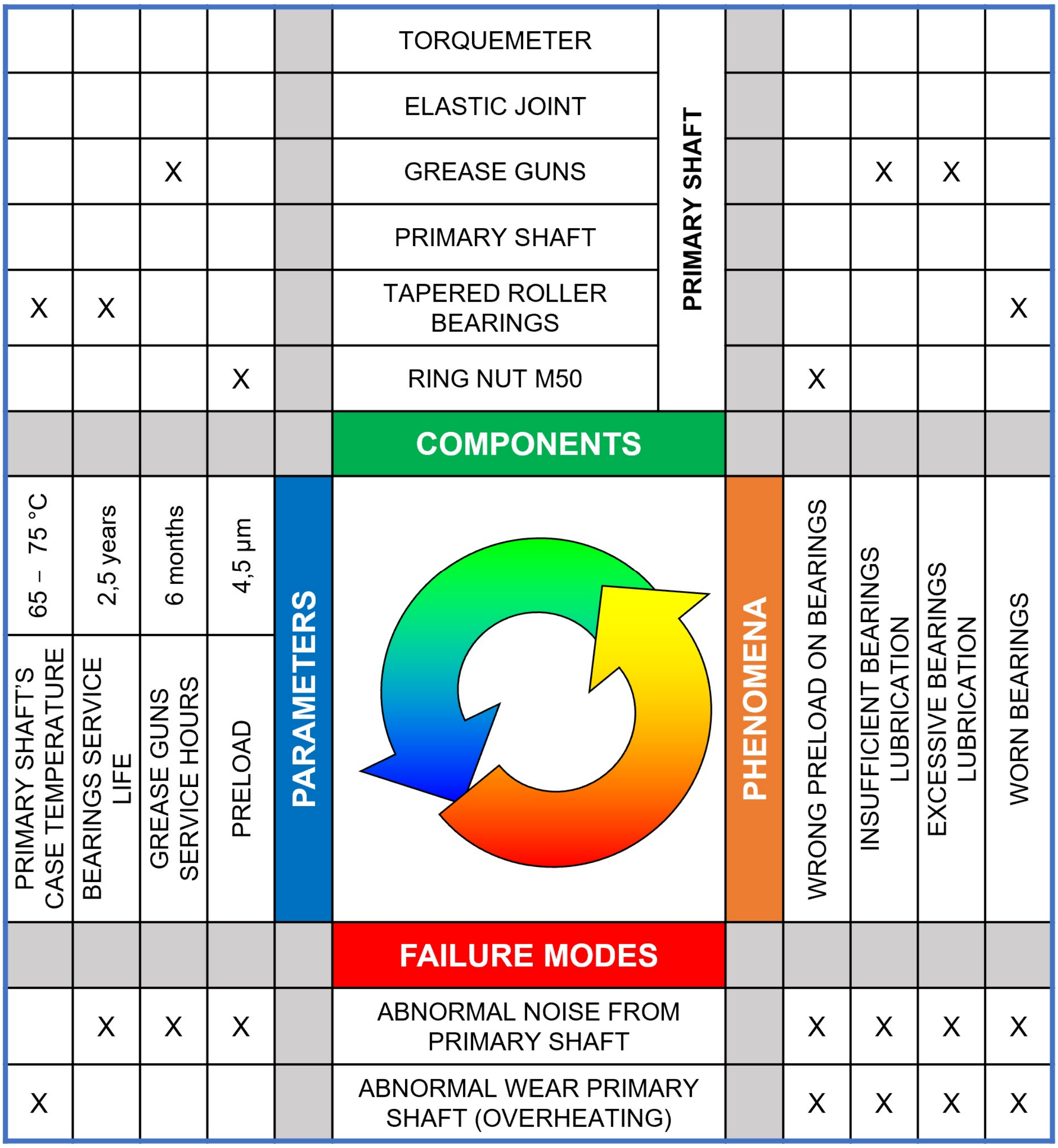


Figure 5.6: Example of X Matrix building

but it is a phenomena that eventually could appear on the system, thus making necessary to keep an eye on it.

At this point, each *Phenomena* has to be connected with the machine *Component* it may arise on. This passage is deeply linked with the test bench deconstruction performed at Step 3, which allows the Team to know which are the main components and systems of the machine and how they work. In this example, it is reported a partial list of "PRIMARY SHAFT" sub-system's components, to show how entries connections are created. Here issues are related only to three test bench's elements:

(1) **ring nut M50**;

(2) the couple of **tapered roller bearings**;

(3) **grease guns**, which replaced the centralized lubrication system as permanent corrective action of Advanced Kaizen I.

About the three components involved, final building step requires the identification of a control parameter, and consequently of its optimal value, that will be periodically checked over the machine to ensure the *Failure Modes* detected won't show up again. That is why the Maintenance Department, thanks to the computation presented in this work, identified four *Parameters*:

(1) **preload** of bearings, to apply through the ring nut displacement, suggested by maintainers experience;

(2) - (3) **service hours** of both grease guns and bearings, since these components need to be replaced after a well determined period, which has been computed and that will be carefully monitored;

(4) **working temperature range**, to be controlled in order to preserve bearings and lubricant optimal working conditions.

Using the logic herein described, it is possible to fill in the entire Matrix, listing all important defects the maintainers should care about and giving them a clear reference of the control parameters to look after.

STEP 6: QM Matrix Having just a list of control parameters is not enough to efficiently run the machine, because checks to be done in order to assess parameters settings are not yet standardized.

To do so, Maintenance Department uses the QM Matrix, where are collected all *Parameters* itemized before and each of them is:

- scheduled to run, by defining the frequency of the check;
- associated to a measurement instrument, with which the parameter's value will be correctly assessed;
- accompanied by a standard procedure, explaining how to collect the measures and how to interpret them (it is actually the definition of AM and PM cycles).

Typically after a certain checking period, maintainers revise the cycles, using the experience acquired in the meantime to improve the cycles itself (see paragraph 5.4). The machine is now arrived at the *Zero Defects Conditions* status: obviously it doesn't mean that the machine never stops nor its components never gets worn before the scheduled time, but the know-how acquired over the test bench can make the maintainer well confident about the machine management. Everything is now under control, well defined and standardised, so that the machine care is no more a prerogative of the machine maker, it is something easily affordable by the plant itself.

5.4 Step 7: Further Improvements

Final QC step brings the machine maintenance into a further maintenance stage. Before the start of the present work, test benches were at the **reaction stage**, meaning that interventions were based on machine failures, with only a few components and/or sub-systems checked regularly through a planned schedule. Having arrived till the building of QM Matrix, it ends the path towards **predictive stage**, which was the goal of the Thesis: the *know-how* acquired during the journey, here proposed and described, allows the Maintenance and the Quality Departments to get a deeper awareness of Thyssen test benches, being able to recognize sources of a certain defects, to attack effectively them and to constantly monitor benches status in a structured way.

Last rung would be a step ahead into the **proactive stage**: it means improving the actual maintenance cycles, creating a benefit not only for the machine correct operation, but also their maintenance efficiency, thus saving time and money.

There are two ways to enhance AM (*Autonomous Maintenance*) and PM (*Professional Maintenance*) cycles:

i. <u>Elongate the checking period</u>: experience may suggest that some components are replaced too soon with respect to the wear level they show, for example it could happen because of overestimated loading conditions, frequently done for safety reasons.

   Typically such an improvement is possible only after a consistent break-in period, usually not shorter that 1 or 2 years.

ii. <u>Turn a PM cycle into an AM one</u>: some smarter solutions may be found to check components' parameters, thus relieving professional maintainers to verify it and making possible the monitoring directly by the machine operator.

   It is typically accomplished by making the measurement very easy (e.g. look a value on a fixed display) and putting the sensor or the component to be checked in a way it can be readily reached, without removing the machine shields or displacing other test bench's elements.

This Thesis is the result of a study lasted 6 months over TH5 test bench, so that it would not be possible to apply any enhancement of type (i). But still, afterwards are proposed some ideas of type (ii) to ease a couple of control cycles.

Unscrewing of accelerometer ring nut: In Figure 5.7 is shown a focus of the accelerometer placed under the gearbox to be tested. The system is made of the sensor, a ring nut that ensure its mounting on the support and the support itself. Maintenance Department introduced a PM cycle to periodically verify that the ring nut is actually well tighten on the support: time to time it happened that not well positioned accelerometers are used to perform NVH tests, so that gearboxes results to be much more "noisy" than they were, producing fake scraps. The issue has been detected especially on test benches on which the sensor cable was replaced with a new one.

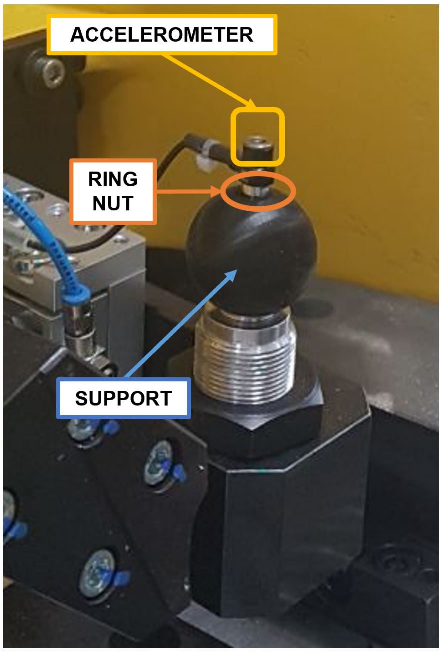


Figure 5.7: Accelerometer system details

To eliminate the PM cycle or at least to try to elongate the checking frequency, it could be an idea to reinforce the joint by using a **magnet**. Accelerometers are usually placed on the object to be inspected through magnetic connections: this time the magnet would be placed in the opposite direction (not between sensor and body, but between sensor and support). The gearbox's surface on which the accelerometer is placed is made in aluminium, so that the magnets won't affect the vibration transmitted by it.

The two magnets would be placed respectively in the bottom part of the ring nut and on the top part of the support, eventually creating a proper shaped spot on it, in which the ring nut will fill perfectly. To overcome high levels of vibration producing the unscrewing, the magnetic force produced by the magnets should be accurately verified.

Grease flow check: As the most part of greases, the lubricant grease used for slides and some bearings groups all over the test bench, changes its physical status according to the external temperature. It is particularly difficult to assess if the grease is actually flowing within the pipes during hot season, when some air bubbles arise inside the grease tank, creating void. Visually the system seems to work normally, since the tank's window is covered by residual grease and hides the air bubble inside.

Also in this case, maintainers had set up a specific PM cycle to verify the grease texture and if it is effectively flowing in the pipes, particularly during summer season.

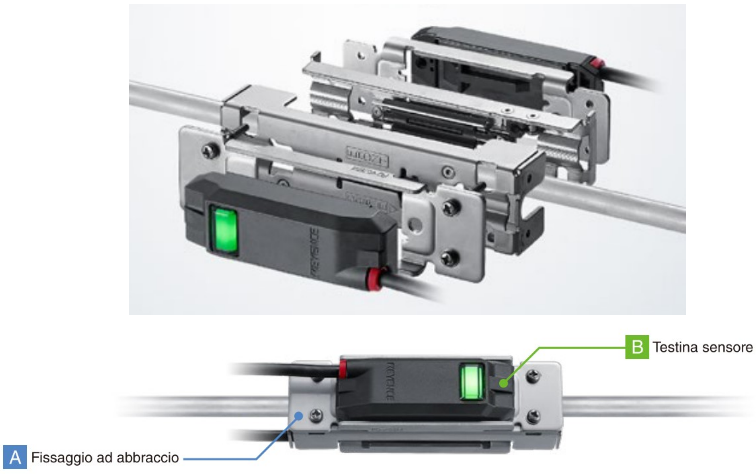


Figure 5.8: Embrace flow sensor from Keyence [19]

In this case the cycle could be not only turned into an AM cycle, but even eliminated, putting a **flow sensor** on strategic pipes' spots, able to communicate directly with the PLC system of the test bench.

A good sensor could be the one commercialized by Keyence, which is already a solutions provider for FCA Group. It can be installed without modifying the hydraulic layout of lubricant system, since it is an "embrace" flow sensor, meaning that it is mounted around the existing pipes. It is able to reveal fluids having a quite high viscosity value, like the one of LI EP 00 grease, and it can be installed on metal pipes too.

By sending directly to the PLC the lack of grease flow information, test bench will immediately give a warning to the operator and stop the machine, by allowing the maintainers to refill the grease tank, restoring optimal lubrication conditions of benches' slides.

Chapter 6

Advanced Kaizen

In the previous Chapter a complete overview of the 7 Quality Control Pillar steps application was given, and at Step 4 two Advanced Kaizen were mentioned: present Chapter will be devoted to the detailed explanation of the two main issues discovered on Thyssen test benches, expounding their origins, the analysis and computations performed to understand them, the suggestions to modify bench's structure in order to solve permanently the issues and enhance the mechanical stiffness of the machine.

All corrective actions implemented have the aim to reduce the *abnormal* noise recorded by the NVH system and so the amount of fake scrap.

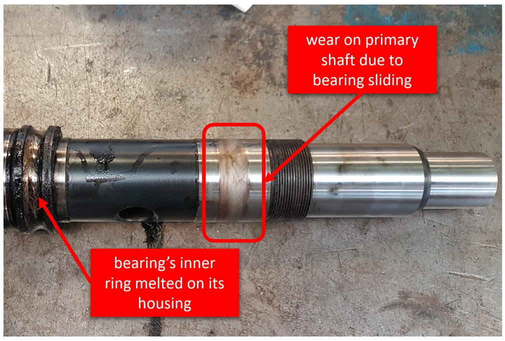
6.1 Group 214: bearing's overheating

During the visual check of *Thyssen5* performed at Step 3, some strange observation gave the start to the present analysis, discovering a design issue related to the subsystem indicated as "PRIMARY SHAFT" (see Table 5.2).

While looking around the test bench, an high temperature was perceived on the primary shaft's case, just by putting an hand on it; not knowing whether the design working temperature should be that high or not, a research among the machine maker documentation was performed, but no information were found regarding the primary shaft's bearings optimal working temperature.

A benchmark between the five test benches in Mirafiori Meccanica has been done: it came up that benches retrofitted first (TH5, TH4 and TH3) had higher temperatures with respect to newer benches, i.e. TH2 and TH7 (see Figure 6.2). To understand if such a rise of temperature could be a problem or not for the correct operating conditions of the bench, a cross research inside the Machine Ledger of *Thyssen5* was performed: reading the list of maintenance interventions carried out over last year, some frequent and apparently strange repairs were discovered about the primary shaft's external bearings: they were replaced twice during the previous 8 months, once with the the primary shaft itself, because of an inordinate wear at bearings' housing level. Moreover, by looking close to the primary shaft's case, some grease spots have been seen around the barb fittings of the lubricant, where seals should prevent the grease leakages. Evidences are shown in Figure 6.1.

(a) Dirt on primary shaft's case due to leaked grease



(b) Primary shaft damaged after bearings overheating

Figure 6.1: Visual evidences of bearings overheating on primary shaft

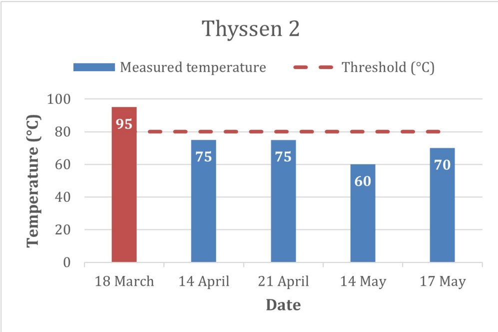
All the evidences collected in the initial phase, have been interpreted as a misoperation of the machine, to be in-depth investigated by studying the sub-system structure and its components' correct operative conditions.

The very first hypothesis done about the issue's cause regarded the bad lubrication conditions: unusual grease stains, overheating and premature bearings damages could be a consequence of an uncorrected lubrication. By questioning the maintainers who performed the interventions, it emerged that the case was full of grease, which was partially deteriorated by the high temperatures, having changed both colour and texture. What if an excessive amount of lubricant is present in the sub-system, compromising correct rotating conditions?

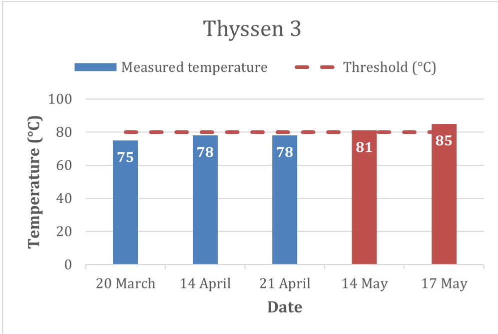
The hypothesis sounds presumable, but the strange fact is that all test benches have the same lubrication system, made of a centralized grease pump that periodically refills the grease inside the primary shaft's case, which is unaltered from the original ZF design. So why the overheating problem and the consequent unusual number of interventions, seem to be only a matter of the last year?

To find a reasonable answer, a monitoring of *Thyssen5* temperature over a month was performed, together with the temperatures of all other test benches to be used as bench-marks.

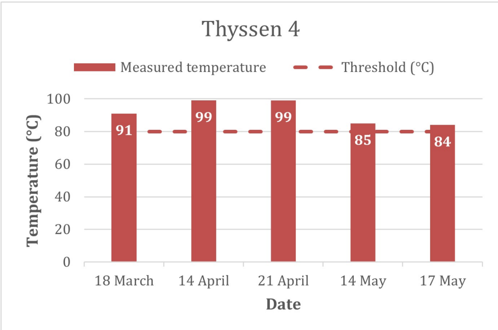
Temperatures were collected through a infrared digital thermometer *Beta IR 1000*, by pointing at two different points on the primary shaft's case and making an average of the values recorded. Not having a clear indication of the design



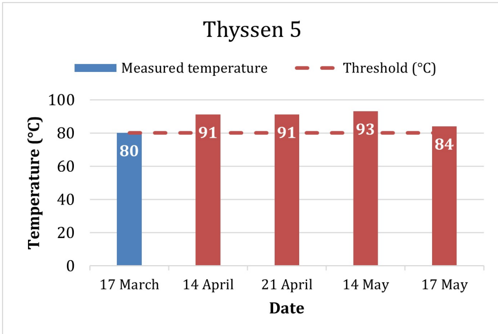
(a) Thyssen2



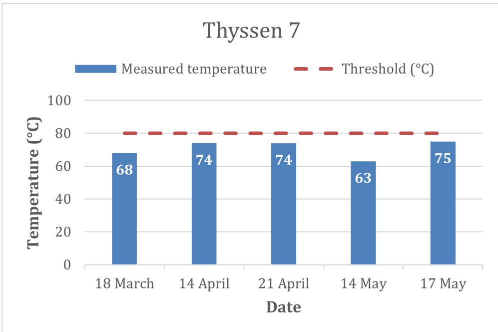
(b) Thyssen3



(c) Thyssen4



(d) Thyssen5



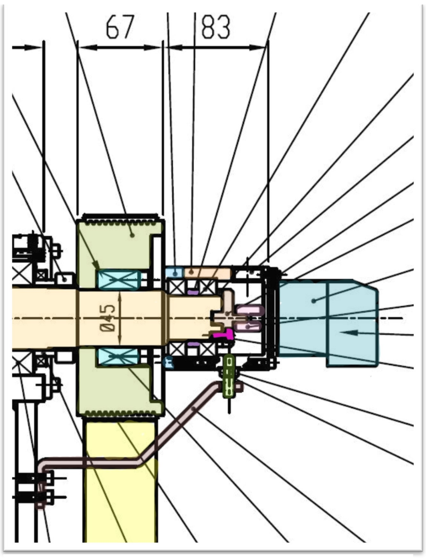
(e) Thyssen7

Figure 6.2: Temperature trend of primary shaft (from March to May 2021)

temperature range, it was assumed that above $80°C$ the test bench is working in critical conditions, which is signaled by the red turrets. It is easy to spot that TH4 and TH5 are the benches having the higher temperatures over the month, while TH3 seems to experience an increasing trend of temperature. TH2 and TH7 are solidly below the critical threshold.

Note that in May an intermediate corrective action was set up, and the Maintenance Department decided to cool down cases of *Thyssen4* and *Thyssen5* using compressed air, which is why their last two turrets show slightly lower values.

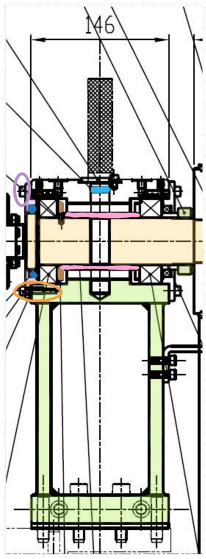
Ref	N°	Quantity	Component
	24	1	pulley
	23	1	cover
	8	1	primary shaft
	22	1	bushing
	21	1	spacing
	210	1	encoder
	13	1	bracket
	209	1	elastic joint
	208	1	pulley clamping unit
	207	1	poly-V belt



Details of drawing *I.01143.214.00.01.0* (Group 213)

Figure 6.3: Detail of Group 213 mechanical drawing and bill of materials

Ref	N°	Quantity	Component
	213	1	locking nutM50
	214	1	o-ring
	8	1	primary shaft
	218	12	screws M6 x 20
	9	1	cover
	204	1	sealing ring
	10	2	ring
	11	1	spacer
	1	1	case



Details of drawing *I.01143.213.00.00.0* (Group 214)

Figure 6.4: Detail of Group 214 mechanical drawing and bill of materials

Supposing that such high temperatures could badly affect the components life of "PRIMARY SHAFT" sub-system, it is necessary to discover which are the mechanical elements inside the overheated case and which of them could be more sensitive or compromised by the excessive temperature levels.

At first the machine maker drawings were analysed: referring to the Thyssen nomenclature (Table 5.1), the sub-system under investigation corresponds to Groups 213 and 214, particularly the overheated case belong to Gr. 214. In Figures 6.3 and 6.4 are highlighted the main components of the two Groups, together with a bill of materials to identify them and their quantity.

To better understand how the main components are placed along the primary shaft and which is their function, it was deemed appropriate to realize a simplified sketch of the sub-system, depicted in Figure 6.5.

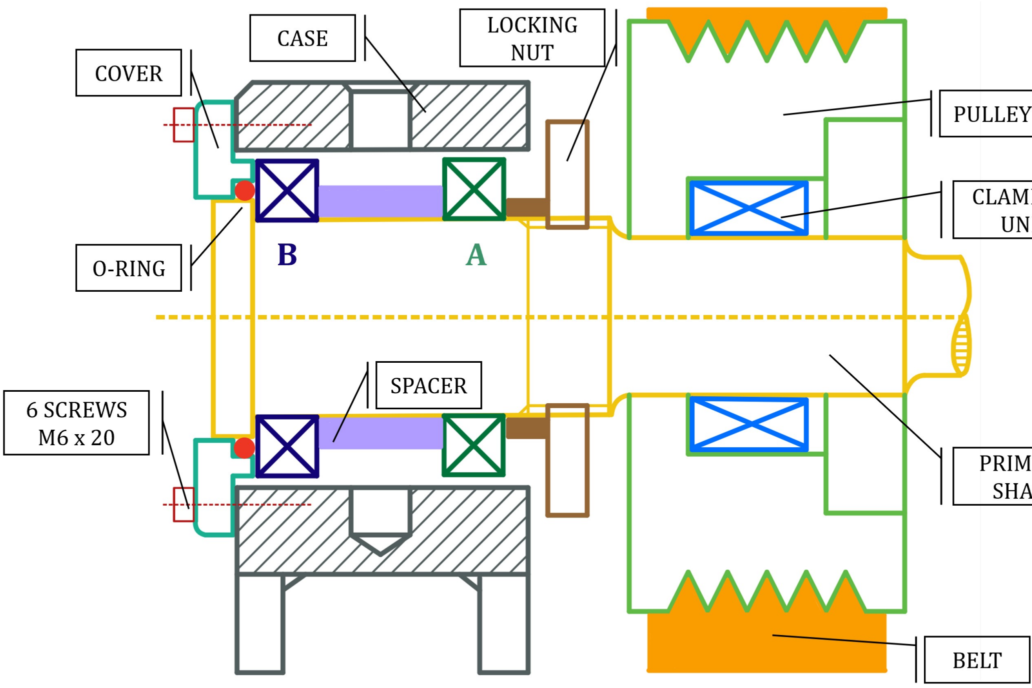


Figure 6.5: Simplified sketch of Group 214 and its motion transmission system

The **primary shaft** is put in rotation thanks to a motion transmission system made of a **V-belt** and **pulley**; the system is supported by two bearings, indicated with letters **A** and **B**, respectively a *tapered roller bearing* and an *angular contact ball bearing*, which are packed by a **locking nut** M50, that ensures the correct preload is applied to the system; finally a **cover** held by 6 **screws M6x20** allows the outer ring of bearing **B** to be kept in position, so that the structure is a typical isostatic one, made of a roller (**A**) and a hinge (**B**) supports. The cover used to fix the outer ring of bearing **A** is not represented in the sketch: it is fixed too, but the roller support type is allowed by the lack of hems around the rolling element (it will be clarified to the reader in the next paragraph, where the arrangement showed in Figure 6.9 is commented). The internal space of the case contains **lubricant grease**, injected through small channels (not represented in Figure 6.5), connected with the grease control unit through a couple of **barb fittings**.

Not having precise indications about optimal working conditions of such elements itemized above, the belt-pulley transmission system is analysed to identify the loads supported by the bearings, and to clarify why such an unusual arrangement was set up by the machine maker designer.

6.1.1 Load case determination

Firstly it has to be identified the type of loads acting on the bearings: the Gr. 214 under investigation is still and the only motion the primary shaft experiences is the rotation determined by the belt-pulley transmission, so that no radial nor axial forces are present, except the ones eventually produced by the motion transmission system.

The belt used is a **poly-V** type from POGGI, an Italian maker whose catalogue [20] has been used to verify the transmission system and to compute the reaction forces. The belt mounted on Gr. 214 is identified as 11L2020-12, meaning that it has a length of 2020 mm and 12 ribs. In Figure 6.6 is reported a sketch of the transmission and in Table 6.1 are collected its main geometrical and physical data.

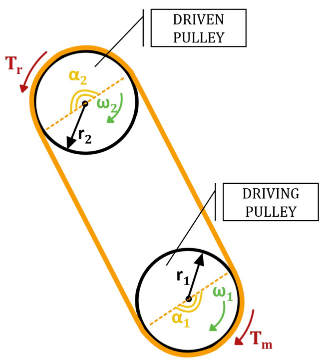


Figure 6.6: Transmission system sketch

Feature		Symbol	Value	Unit
driving pulley	pitch circle diameter	d_1	157	mm
	wrap angle	α_1	180	°
driven pulley	pitch circle diameter	d_2	157	mm
	wrap angle	α_2	180	°
interaxis		c	763	mm
belt length		L	2020	mm
transmission ratio		i	1	/
belt mass per meter of single rib		ml	0.032	kg/m/rib
number of ribs		nn	12	/

Table 6.1: Transmission system geometrical and physical data

Assuming that type and size of the belt chosen by the designer are the correct ones for the application and receiving the confirmation of that from the machine maker, following the POGGI catalogue [20] the belt mounting frequency is checked and consequently the reaction forces are evaluated.

The **mounting frequency** is the frequency of vibration the belt shows while excited by an impulse, usually a small hammer hit on the free portion of the belt between the two pulleys; it can be evaluated through a digital tensiometer, helping the maintainers to impress the right tension to the belt while positioning it. The frequency can be regulated by tightening the bolts holding the driving pulley group (Gr. 204 with respect to Table 5.1).

To verify the correctness of belt tension imposed by the maintainers, which is of **37 Hz**, this value is compared with the theoretical one, related to the maximum power the transmission should be able to deliver. To be on the safety side, the following three powers are computed and the maximum between them is considered for the verification.

$$\begin{cases} M_{t,N} = 60\ Nm \\ n_N = 3000\ Nm \end{cases} \Rightarrow P_N = 18.8\ kW \tag{6.1}$$

$$\begin{cases} M_{t,A} = 84.8\ Nm \\ n_A = 1805\ Nm \end{cases} \Rightarrow P_A = 16.0\ kW \tag{6.2}$$

$$\begin{cases} M_{t,B} = 2.4\ Nm \\ n_B = 4285\ Nm \end{cases} \Rightarrow P_B = 1.1\ kW \tag{6.3}$$

The nominal power (6.1) comes from the electric motor tag of Gr. 204, while the load cases A and B (6.2 and 6.3) are deduced by the cyclogram depicted in Figure 6.7, taking the points at maximum torque and maximum speed respectively. It emerged that actually, the maximum power transmitted by the system is around 16 kW, corresponding to the instant during which the shaft undergoes a maximum torque of 84.8 Nm, but having an electric motor which has a nominal power set on around 19 kW, it is reasonable and safe to verify the belt tension using the highest value of power: $P_{max} = P_N$.

Following the procedure reported in POGGI catalogue [20] step by step, here are the quantities and the corresponding formulas, useful to determine the frequency of the belt and to check if the theoretical one matches with the actual frequency imposed on the test bench *Thyssen5*.

- **Design Power:** it is the maximum transmitted power the belt-pulley system should ensure to the machine, and it is computed starting from the maximum power previously evaluated, corrected by the coefficient C_c, accounting for the specific operating conditions of test bench:

$$P_c = P \cdot C_c \quad [kW] \tag{6.4}$$

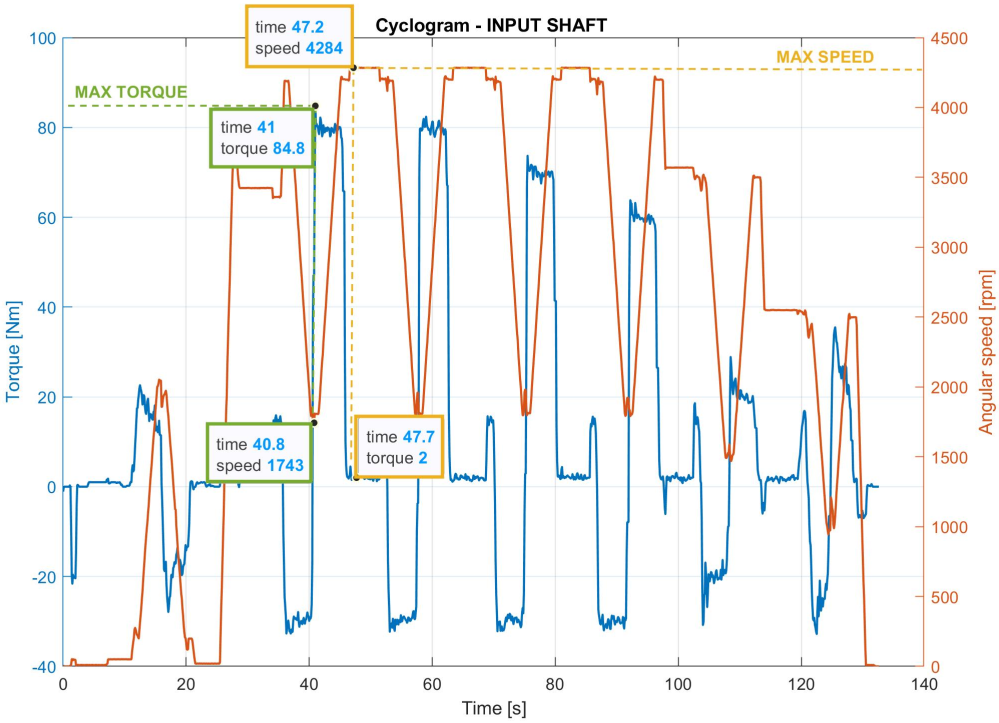


Figure 6.7: Primary shaft excitation from cyclogram

- **Belt Linear Speed:** value obtainable from the rotational speed of the pulley:

$$V = \frac{\pi \cdot d_1 \cdot n}{60000} \quad [m/s] \tag{6.5}$$

- **Static Tension:** it expresses the belt tension deriving from its operating conditions and the specific belt type chosen (mass and number of ribs); also in this case the power value is increased by the corrective factor C_{1y}, depending on the wrap angle:

$$T_{st} = \frac{500 \cdot C_{1y} \cdot P_c}{V} + ml \cdot nn \cdot V^2 \quad [N] \tag{6.6}$$

- **Static Axial Load:** derived from the static tension of the belt, it is strictly related to the belt pull of the system; having in this case a wrap angle of 180°, it is just the double of the static tension value:

$$F_a = 2 \cdot T_{st} \cdot sin\left(\frac{\alpha}{2}\right) \quad [N] \tag{6.7}$$

- **Frequency of Vibration:** it depends on the belt type (mass and number of ribs), to the mounting conditions through the inter-axis c and to the static tension computed before:

$$fr = \frac{1}{2 \cdot c} \cdot \sqrt{\frac{T_{st}}{ml \cdot nn}} \quad [Hz] \tag{6.8}$$

The results of the computations described above are reported in Table 6.2. The actual mounting frequency of 37 Hz slightly differs from the theoretical one, but the two are still comparable: it is reasonable, since real mounting conditions could affect the belt tension, making necessary to perform some adjustments to the system and producing a small difference between real and theoretical mounting parameters.

Table 6.2: Belt excitation from POGGI catalogue

Feature	Symbol	Value	Unit
design power	P_c	24.5	kW
belt linear speed	V	24.66	m/s
static tension	T_{st}	979	N
static axial load	F_a	1958	N
frequency	fr	33	Hz

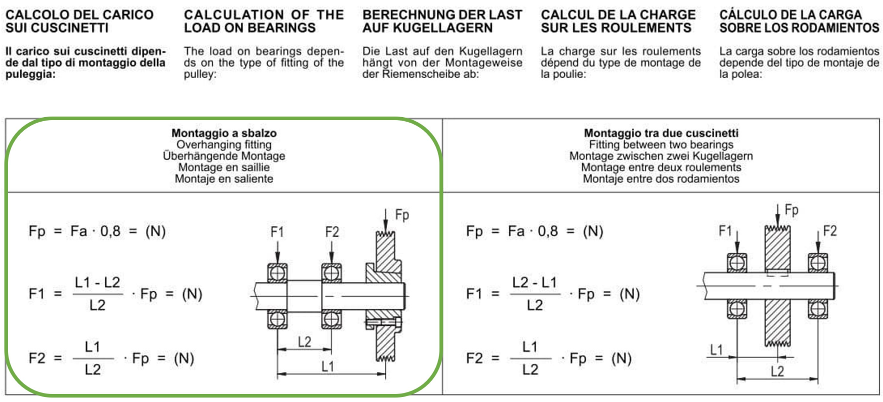


Figure 6.8: Loads on bearings according to POGGI catalogue

Having checked the belt installation tension, POGGI catalogue provides the formulas to compute the loads on the bearings, starting from the belt pull: indications are reported in the catalogue's extract of Figure 6.8.

Note that the primary shaft changes speed and transmitted torque as the checking cycle goes on, thus implying that bearings undergo variable loading conditions:

the formulas circled in Figure 6.8 will be applied in the next paragraphs for all operating conditions, in order to proceed with the bearings verification according to the SKF catalogue [17]. Computational details and results are reported in the next paragraphs.

6.1.2 Actual arrangement

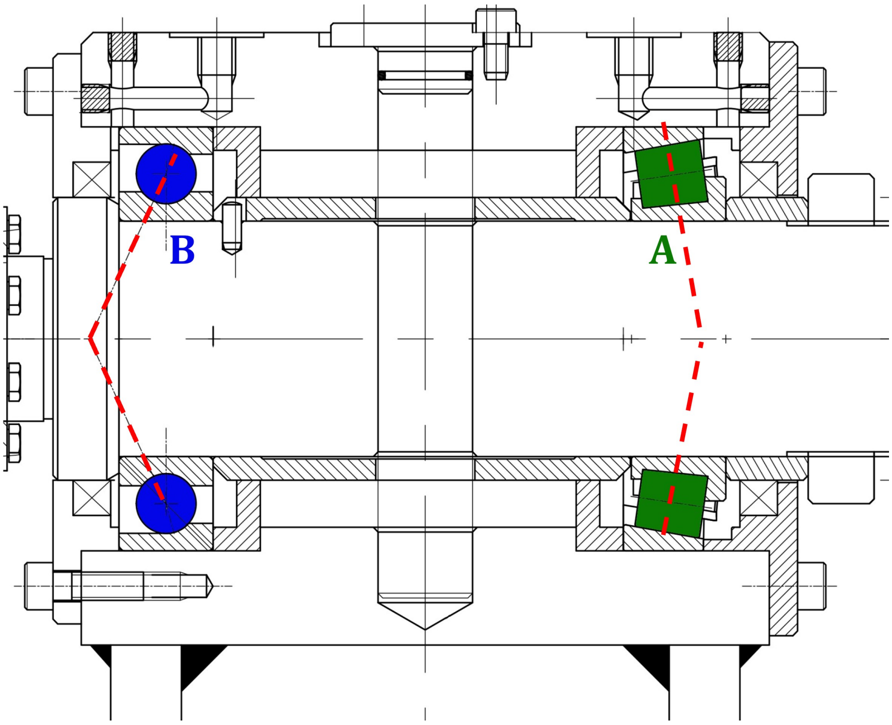
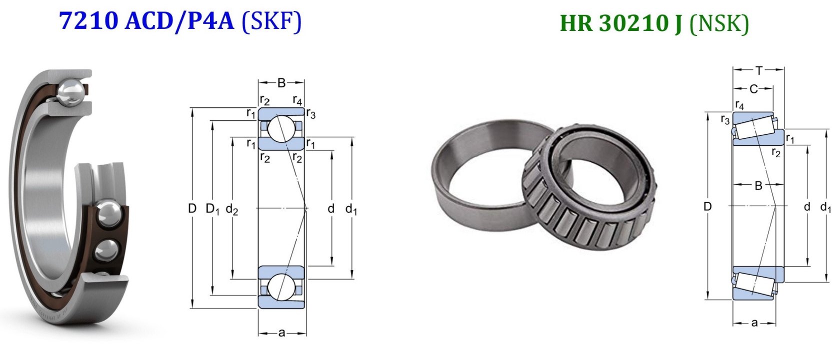


Figure 6.9: AutoCAD scheme of bearings actual arrangement

To verify if the overheating condition of "PRIMARY SHAFT" sub-system badly affects the bearings arrangement on the primary shaft itself, their rating life will be computed according to SKF [17] and NSK [21] methods.

Actual arrangement is depicted in Figure 6.9: it is a "back-to-back" configuration, made of a *tapered roller bearing* on the right (**A**) and an *angular contact ball bearing* on the left (**B**). Both bearings are mounted with interference on the inner ring, which is integral to the rotating shaft; the preload, necessary for a correct mounting of the system, is impressed through two covers, tightened with twelve screws M6x20 (six on the right and six on the left); note that the locking nut M50 visible on the right end of the shaft is not used to adjust the preload, but just to close the system, making easier the mounting and dismounting operations. The space inside the case and all over the bearings is filled with grease *LI EP 00*



(a) Bearing B from SKF catalogue (b) Bearing A from NSK catalogue

Figure 6.10: Extracts from bearings catalogues of the actual arrangement

from Petronas supplier: every 700 cycles (namely every gearbox checked), a small amount of grease is re-filled inside the system through two tiny channels visible in the upper portion of the case, where two barb fittings connect the chamber with grease pipes; o-rings and shaft seals are distributed all over the group to ensure the lubricant sealing.

Note that the present "back-to-back" configuration is quite unusual, since it couples together two bearings of a different type, making harder to evaluate the right preload of the system needed to balance the axial forces developed by the "O" configuration itself. For these reasons the SKF manual does not recommend to use such an arrangement, making even impossible to verify it through their online tool. Nevertheless, bearings **A** and **B** will be verified separately, computing their rating life according to their maker manual.

The two bearings actually mounted on the "PRIMARY SHAFT" sub-system are reported in Figure 6.10 and their data-sheets are reported in Table 6.3.

At first sight, an important thing comes to light: according to *tapered roller bearing*'s maker, the maximum angular speed allowed to it with grease lubrication is 4000 *rpm*, which is quite below the peak values of speed experienced by the bearing during a typical control cycle (see Figure 3.14a).

Keeping in mind the possible under-sizing of bearing **A**, the best way to actually evaluate if the bearing arrangement is theoretically good for the present application is to estimate bearings' life. Even if SKF and NSK manuals have named differently some life parameters, and in some cases they compute them differently, the theory behind the bearings rating life is common and it can be expressed through the

[1] With grease lubrication.

Table 6.3: Bearings data-sheet of actual arrangement

Geometrical Data			**Bearing A** *HR 30210 J*	**Bearing B** *7210 ACD/P4A*
inner diameter	d	mm	50	50
outer diameter	D	mm	90	90
width	B	mm	20	20
number of rolling elements	z	/	18	15
rolling element diameter	D_w	mm	/	12.7
contact angle	α	°	/	25
Calculation Data				
basic dynamic load rating	C	kN	76.0	42.3
basic static load rating	C_0	kN	91.5	32.5
fatigue load limit	P_u	kN	/	1.37
attainable speed [1]	n_{lim}	rpm	4000	14000
Calculation Factors				
corrective factor for axial load	R	/	/	0.57
corrective factor for "O" config.	Y_0	/	0.79	0.76
corrective factor for "O" config.	Y_1	/	1.4	0.92
corrective factor for "O" config.	Y_2	/	/	1.41
corrective factor for "O" config.	X_2	/	/	0.67
factor for equivalent load	e	/	0.42	0.68

formula 6.9:

$$L_{nm} = a_1 \cdot a_2 \cdot \left(\frac{C}{P}\right)^p \quad [millions\ of\ revolutions] \tag{6.9}$$

- a_1: life adjustment factor for reliability, whose values are common for SKF and NSK manuals and here are reported in the SKF table showed in Figure 6.11 (according with ISO 281); in this case a reliability of 90% will be considered, so that the bearings life will be indicated as L_{10m}.
- a_2: life modification factor, depending on bearing size, working conditions and lubricant; in the dedicated paragraph it will be presented as a_{NSK} and a_{SKF} according to the specific manufacturer's procedure applied to compute it.
- P: equivalent dynamic load rating, expressed in [kN] and defined as *«a hypothetical load, constant in magnitude and direction, that acts radially on radial bearings and axially and centrically on thrust bearings»* [17].

- C: basic dynamic load rating, expressed in [kN] and given by the manufacturer catalogue.

- p: exponent of the life equation, which is equal to 3 for ball bearings and to 10/3 for roller bearings.

Reliability	Failure probability	Rating life	Factor
	n	L_n	a_1
%	%	million revolutions	–
90	10	L_{10}	1
95	5	L_5	0,64
96	4	L_4	0,55
97	3	L_3	0,47
98	2	L_2	0,37
99	1	L_1	0,25

Figure 6.11: SKF Table - Values for reliability factor [17]

Knowing the angular speed n of the bearings, it is possible to convert the life value from *millions of cycles* to *hours* using the formula below:

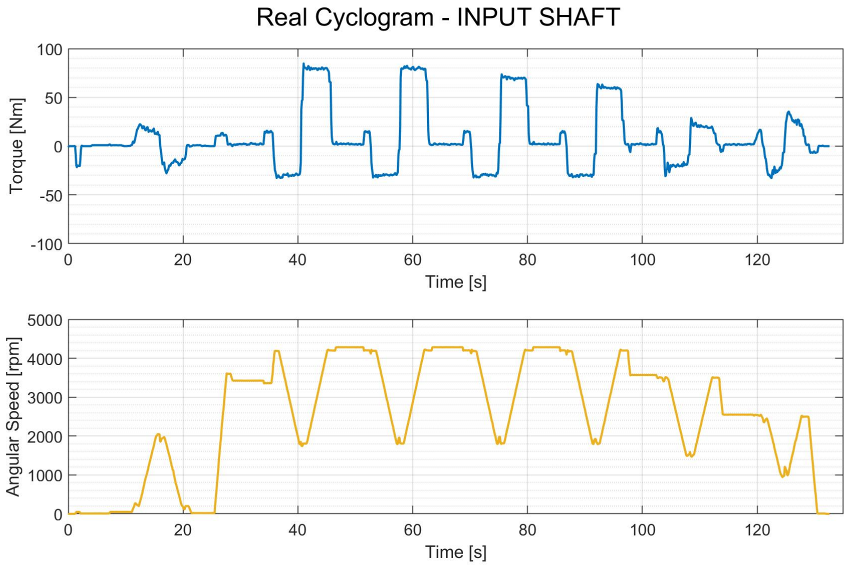
$$L_{10mh} = \frac{10^6}{60 \cdot n} L_{10m} \tag{6.10}$$

Note that the bearings undergo a periodic cycle of excitation and not a single and constant load: following the manual's instructions, formulas 6.9 and 6.10 will be applied for each operating condition obtained from a simplified version of the cyclogram presented in Figure 6.12.

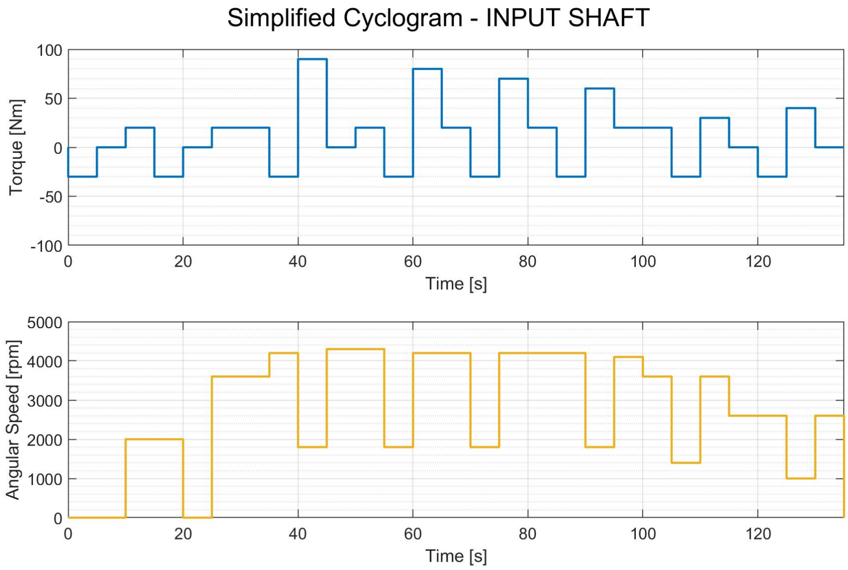
Once the i variable operating conditions have been characterized, it is possible to compute the fraction of life spent under the *i-th* operating condition by evaluating the U_i parameters and then using them to compose the single value of L_{10m} or L_{10mh} to obtain the total life of the bearing:

$$L_{10m} = \frac{1}{\frac{U_1}{L_{10m,1}} + \frac{U_2}{L_{10m,2}} + ... + \frac{U_n}{L_{10m,n}}} \tag{6.11}$$

To understand the U_i parameters meaning, here is proposed an example of calculation for $i = 3$:



(a) Real cyclogram (version till May 2021)



(b) Simplified cyclogram

Figure 6.12: Variable operating conditions obtained from the real cyclogram

$$\begin{cases} \Delta t_3 = 5 \ s \\ M_{t,3} = 90 \ Nm \\ n_3 = 1800 \ rpm \end{cases} \tag{6.12}$$

$$N_3 = n_3 \cdot \Delta t_3 = \left(\frac{1800}{60} \; \frac{rounds}{s} \right) (5 \; s) = 150 \; rounds \tag{6.13}$$

$$N = \sum_i N_i = 6142 \; rounds \tag{6.14}$$

$$U_3 = \frac{N_3}{N} = \frac{150}{6142} = 0.02 \tag{6.15}$$

REACTION FORCES Having define for each i operating condition the characteristic values of torque $M_{t,i}$ and of angular speed n_i, it is possible to compute the reaction forces acting on the bearings.

As far as concern the **radial reaction forces**, the procedure explained by POGGI catalogue [20] will be applied, using the formulas circled in Figure 6.8 and here reported for reading convenience:

$$\begin{cases} F_{rA} = \frac{L_1}{L_2} \cdot F_p \\ F_{rB} = \frac{L_1 - L_2}{L_2} \cdot F_p \end{cases} \tag{6.16}$$

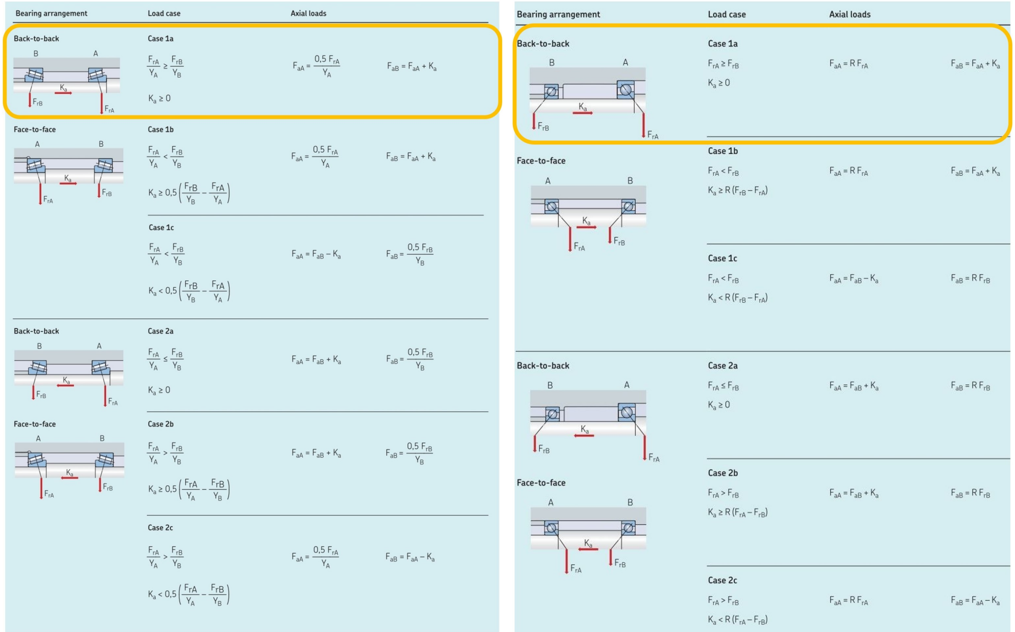
- L_1: distance between bearing **B** and the pulley's axis
- L_2: distance between the two bearings
- F_p: belt pull

About **axial reaction forces**, it is important to point out that no external axial forces act on the system, so that $F_{a,Ai}$ and $F_{a,Bi}$ are only due to the "back-to-back" configuration: their value will be the same but opposite in sign. To evaluate them the procedure reported in SKF catalogue [17] will be applied. In Figure 6.13 are reported the SKF formulas for *tapered roller bearings* and *angular contact ball bearings*.

As it would be clear by looking at the results reported in Table 6.6, bearing **A** hold the greater radial load, so that $F_{r,A} > F_{r,B}$ is always true. Having $K_A = 0$, cases 1a and 2a correspond and the formulas to be used to compute the axial loads are reported below:

$$\begin{cases} F_{aA} = \frac{0.5 \cdot F_{rA}}{Y_A} \\ F_{aB} = F_{aA} \pm K_A = F_{aA} \end{cases} \tag{6.17}$$

Resulting reaction forces for the actual arrangement will be presented in Table 6.6.



Bearing arrangement	Load case	Axial loads	
Back-to-back	Case 1a: $\frac{F_{rA}}{Y_A} \geq \frac{F_{rB}}{Y_B}$, $K_a \geq 0$	$F_{aA} = \frac{0,5\, F_{rA}}{Y_A}$	$F_{aB} = F_{aA} + K_a$
Face-to-face	Case 1b: $\frac{F_{rA}}{Y_A} < \frac{F_{rB}}{Y_B}$, $K_a \geq 0,5\left(\frac{F_{rB}}{Y_B} - \frac{F_{rA}}{Y_A}\right)$	$F_{aA} = \frac{0,5\, F_{rA}}{Y_A}$	$F_{aB} = F_{aA} + K_a$
	Case 1c: $\frac{F_{rA}}{Y_A} < \frac{F_{rB}}{Y_B}$, $K_a < 0,5\left(\frac{F_{rB}}{Y_B} - \frac{F_{rA}}{Y_A}\right)$	$F_{aA} = F_{aB} - K_a$	$F_{aB} = \frac{0,5\, F_{rB}}{Y_B}$
Back-to-back	Case 2a: $\frac{F_{rA}}{Y_A} \leq \frac{F_{rB}}{Y_B}$, $K_a \geq 0$	$F_{aA} = F_{aB} + K_a$	$F_{aB} = \frac{0,5\, F_{rB}}{Y_B}$
Face-to-face	Case 2b: $\frac{F_{rA}}{Y_A} > \frac{F_{rB}}{Y_B}$, $K_a \geq 0,5\left(\frac{F_{rA}}{Y_A} - \frac{F_{rB}}{Y_B}\right)$	$F_{aA} = F_{aB} + K_a$	$F_{aB} = \frac{0,5\, F_{rB}}{Y_B}$
	Case 2c: $\frac{F_{rA}}{Y_A} > \frac{F_{rB}}{Y_B}$, $K_a < 0,5\left(\frac{F_{rA}}{Y_A} - \frac{F_{rB}}{Y_B}\right)$	$F_{aA} = \frac{0,5\, F_{rA}}{Y_A}$	$F_{aB} = F_{aA} - K_a$

(a) Tapered roller bearings

Bearing arrangement	Load case	Axial loads	
Back-to-back	Case 1a: $F_{rA} \geq F_{rB}$, $K_a \geq 0$	$F_{aA} = R\, F_{rA}$	$F_{aB} = F_{aA} + K_a$
Face-to-face	Case 1b: $F_{rA} < F_{rB}$, $K_a \geq R\,(F_{rB} - F_{rA})$	$F_{aA} = R\, F_{rA}$	$F_{aB} = F_{aA} + K_a$
	Case 1c: $F_{rA} < F_{rB}$, $K_a < R\,(F_{rB} - F_{rA})$	$F_{aA} = F_{aB} - K_a$	$F_{aB} = R\, F_{rB}$
Back-to-back	Case 2a: $F_{rA} \leq F_{rB}$, $K_a \geq 0$	$F_{aA} = F_{aB} + K_a$	$F_{aB} = R\, F_{rB}$
Face-to-face	Case 2b: $F_{rA} > F_{rB}$, $K_a \geq R\,(F_{rA} - F_{rB})$	$F_{aA} = F_{aB} + K_a$	$F_{aB} = R\, F_{rB}$
	Case 2c: $F_{rA} > F_{rB}$, $K_a < R\,(F_{rA} - F_{rB})$	$F_{aA} = R\, F_{rA}$	$F_{aB} = F_{aA} - K_a$

(b) Angular contact ball bearing

Figure 6.13: SKF Tables - Axial loads determination [17]

EQUIVALENT DYNAMIC LOAD In order to compute the bearings life, radial and axial loads are made equivalent to a single force, acting radially with respect to the shaft orientation, that -if applied- would produce the same effects of the real reaction forces. In Figure 6.14 is proposed a clarifying scheme, extracted by SKF manual.

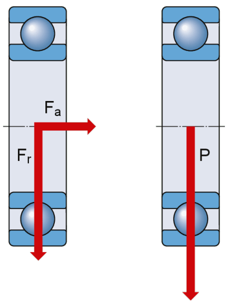


Figure 6.14: Equivalent dynamic load meaning [17]

For both NSK and SKF manufacturer, the value of the equivalent dynamic load P can be obtained by using formula 6.18.

$$P = X \cdot F_r + Y \cdot F_a \tag{6.18}$$

What changes between the two procedures are the coefficients X and Y, which not only depend on the type of bearing, but on the loading conditions too: in some cases the axial load is negligible with respect to the radial one and it is not considered at all, as it happens for bearing **A**. In Tables 6.4 and 6.5 are reported the coefficients, according to NSK and SKF catalogues respectively. For both is highlighted in green the loading condition of the bearing and consequently which X and Y factors should be used to compute the equivalent dynamic load.

Table 6.4: Equivalent dynamic load factors according to NSK catalogue (tapered roller bearings)

	$\frac{F_{aA}}{F_{rA}} <= e$	$\frac{F_{aA}}{F_{rA}} > e$
X	1	0.4
Y	0	Y_1[2]

Table 6.5: Equivalent dynamic load factors according to SKF catalogue (angular contact ball bearings)

	$\frac{F_{aA}}{F_{rA}} <= e$	$\frac{F_{aA}}{F_{rA}} > e$
X	1	X[3]
Y	Y_1[4]	Y_2[5]

Also in this case, for the two bearings there are i values for P, one for each operating condition. Values for the actual arrangement are collected in Table 6.6.

LIFE GAIN FACTOR Similarly to coefficients X and Y presented before, life modification factor a_2 is evaluated differently by NSK and SKF manufacturers, but it is always function of three parameters:

$$a_2 = f_{(P_u,\ \eta_c,\ \kappa)} \tag{6.19}$$

- P_u: fatigue load limit is defined as *«bearing load under which the fatigue stress limit is just reached in the most heavily loaded raceway contact»* in ISO 281:2007 and it is a value provided by the manufacturer; note that in

[2]For NSK bearing *HR 30210 J* it corresponds to 1.4.
[3]For SKF bearing *7210 ACD/P4A* it corresponds to 0.67.
[4]For SKF bearing *7210 ACD/P4A* it corresponds to 0.92.
[5]For SKF bearing *7210 ACD/P4A* it corresponds to 1.41.

Table 6.6: Actual arrangement: reaction forces and equivalent dynamic loads

OPERATING CONDITIONS						*Bearing A*			*Bearing B*		
i	Δt_i	n_i	$M_{t,i}$	$P_{c,i}$	U_i	$F_{r,Ai}$	$F_{a,Ai}$	P_{Ai}	$F_{r,Bi}$	$F_{a,Bi}$	P_{Bi}
[-]	[s]	[rpm]	[Nm]	[kW]	[-]	[N]	[N]	[N]	[N]	[N]	[N]
1	5	1000	40	5.45	0.01	1462	522	1462	625	522	1155
2	5	1400	-30	5.72	0.02	1184	423	1184	507	423	936
3	5	1800	90	22.05	0.02	3361	1200	3361	1438	1200	2656
4	5	1800	60	14.70	0.02	2319	828	2319	992	828	1832
5	10	1800	-30	7.35	0.05	1277	456	1277	546	456	1009
6	5	2000	20	5.45	0.03	985	352	985	421	352	778
7	5	2000	-30	8.17	0.03	1332	476	1332	570	476	1053
8	10	2600	0	0.00	0.07	491	175	491	210	175	388
9	5	2600	-30	10.62	0.04	1532	547	1532	656	547	1211
10	5	3600	30	14.70	0.05	1982	708	1982	848	708	1566
11	15	3600	20	9.80	0.15	1635	584	1635	699	584	1292
12	5	4100	20	11.16	0.06	1914	684	1914	819	684	1513
13	5	4200	80	45.74	0.06	4058	1449	4058	1736	1449	3207
14	5	4200	70	40.02	0.06	3711	1325	3711	1588	1325	2933
15	10	4200	20	11.44	0.11	1975	705	1975	845	705	1560
16	10	4200	-30	17.15	0.11	2322	829	2322	993	829	1835
17	5	4300	20	11.71	0.06	2036	727	2036	871	727	1609
18	5	4300	0	0.00	0.06	1342	479	1342	574	479	1060

NSK catalogue it is not directly reported, but it can be indirectly obtained by the NSK Online Tool [22].

- η_c or a_c: contamination factor, accounting for the cleanliness conditions of the machine; for both computation procedures it will be assumed equal to 0.50, considering normal cleanliness conditions.

- κ: viscosity ratio, related to the lubricant conditions of the bearing, which are compared to the viscosity of the optimal lubricant for that specific bearing.

Tapered Roller Bearing - NSK

NSK manual [21] does not provide directly a way to evaluate factors mentioned in equation 6.19, but their online tool called *NSK Calculation tool* [22] will be used to obtain a_{NSK}.

By imposing the working conditions listed below and inserting the lubricant grease LI EP 00 data (from Petronas data-sheet available online and shown in Figure 6.17a [23]), results reported in Figure 6.15 are obtained.

- Contamination level: NORMAL ($a_c = 0.5$)

- Maximum angular speed: 4300 rpm

- Loading conditions: $F_r = 4058\ N$ and $F_a = 1449\ N$ (for safety reasons, loads used correspond to the maximum equivalent dynamic load experienced by the bearing)

- Average working temperature: 65 $°C$

Bearing Selection

No.	Bearing type	Bearing number	Boundary dimensions (mm)			Basic load ratings (N)		Limiting speed (min^{-1})		Update
			Bore, d	OD, D	Width, B or T***	C_r	C_{0r}	Grease	Oil	
1	Single-Row Tapered Roller Bearings (Metric Design)	HR30210J	50	90	21.75	76 000	91 500	4 000	5 300	Delete

No.	Bearing type	Bearing number	NSK ABLE Forecaster		ISO 281: 2007*****		ISO	
			L_{able} (h)	a_{nsk}	L_{nm} (h)	a_{ISO}	L_{10} (h)	L_{10} ($x10^6$rev)
1	Single-Row Tapered Roller Bearings (Metric Design)	HR30210J	over 200 000	25.01	over 200 000	50.00	27 824	7 012

No.	Bearing type	Bearing number	Average equivalent load P (N)	Average speed N (min^{-1})	Viscosity ratio κ	Actual kinematic viscosity ν (mm^2/s)	Reference kinematic viscosity ν1 (mm^2/s)
1	Single-Row Tapered Roller Bearings (Metric Design)	HR30210J	5 334	4 200	4	75	8.3

The speed exceeds the limiting speed under grease lubrication.
Confirm the operating conditions or select another type of bearing.

Figure 6.15: Screenshot of NSK Calculation Tool results [22]

Using the NSK life theory, the online tool suggests a value of $a_{NSK} = 25.01$. Nevertheless, it is important to pay attention to the blue note at the bottom of the table in Figure 6.15: it is a warning, highlighting what mentioned before, namely that the *tapered roller bearing* HR 30210 J from NSK has a limiting speed which is inferior to the maximum excitation repetitively experienced by the bearing. In such an eventuality, the NSK manual discourages to use a gain factor as a_{NSK} and instead suggests to apply a **unitary value** for it.

<u>*Angular Contact Ball Bearing* - SKF</u>

SKF manual [17] proposes a specific path to obtain a_{SKF} life modification factor value, knowing working and lubrication conditions of the bearing.

- **Reference kinematic viscosity:** it represents the ideal viscosity the bearing's lubricant should have to make it work at the best; it can be obtained through the SKF chart in Figure 6.16a, giving as inputs the average bearing size d_m and the maximum angular speed.

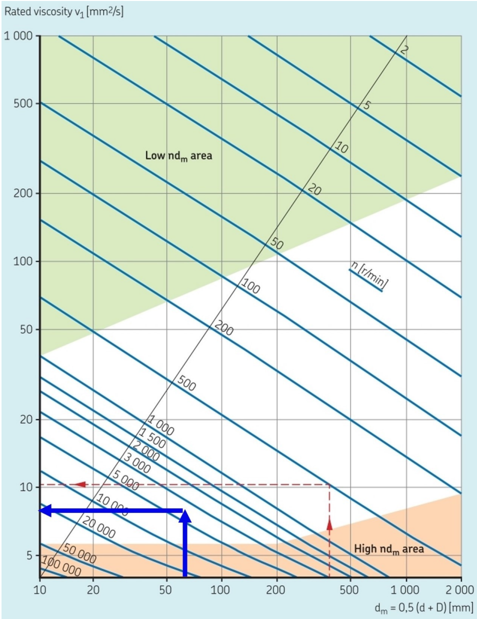
- **Actual kinematic viscosity:** to reproduce as far as possible the ideal lubrication conditions of the bearing, SKF chart in Figure 6.17b can be used, so that according to the reference kinematic viscosity ν_1 found previously and the operating temperature of the system, it is possible to select a lubricant ISO VG by peaking the curve immediately above the point detected.

As clarified by the green and red circles in Figure 6.16b, the expected ISO VG of the ideal bearing's lubricant does not match the ISO VG of the actual grease used, LI EP 00 by Petronas. In Figure 6.17 are showed the lubricant's data-sheet and the corresponding ISO VG according to the SKF table.

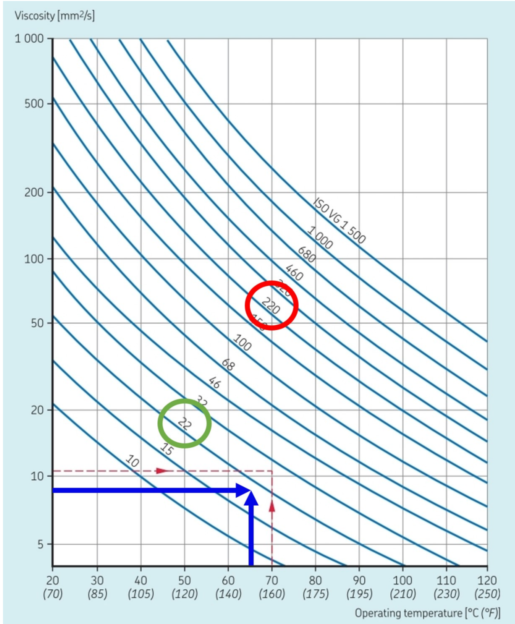
As expected, the huge difference between suggested lubricant and actual grease used, produces a viscosity ratio κ quite high. To accurately read viscosity values from the SKF charts and avoid errors due to the non linear scales, the SKF online tool *SKF Bearing Select* [24] is used to get precise results, depicted in Figure 6.20.

At this point is useless to evaluate a_{SKF} through the dedicated chart in SKF manual, since a note belonging to the same manual and reproduced in Figure 6.18 states that having $k > 4$ makes impossible to assign a gain factor to the rating life equation 6.9.

BEARINGS RATING LIFE At this point all elements needed to compute bearings' life are known, and putting P_i and U_i in equation 6.11 for both **A** and **B** is it possible to obtain the values reported in Table 6.7.



(a) Reference kinematic viscosity from SKF Chart [17]



(b) SKF Chart - Lubricant selection according to the ISO VG

Figure 6.16: SKF Charts to select the lubricant [17]

	Test Method	Unit	Grease Li EP 00
DIN Classification	DIN 51502 DIN 51825		KP00G-30
ISO Classification	ISO 12924		L-XC(F)BIB00
NLGI Grade	ASTM D217		00
Thickener Type			Lithium
Colour	Visual		Light Brown
Penetration, @ 25°C Worked	ASTM D217	0.1 mm	400 - 430
Dropping Point	IP 396	°C	> 150
Base Oil Type			Mineral Oil
Viscosity of Base Oil @ 40°C	ASTM D445	cSt	190
4-Ball Weld Load	DIN 51350:4	N	2200
4-Ball Wear Scar 40kg/1hr	DIN 51350:5	mm	0.5
20,000 Strokes Worked Penetration	ASTM D217	Change 0.1mm	--
SKF Emcor distilled Water SKF Emcor Salt water	ISO 11007		0-0 2-3
Density	IPPM-CS/03	g/ml	0.91
Water Resistance	DIN 51807/1		0-90
Flow Pressure -30°C	DIN 51805	hPa	--

(a) Properties of lubricant grease LI EP 00 (Petronas [23])

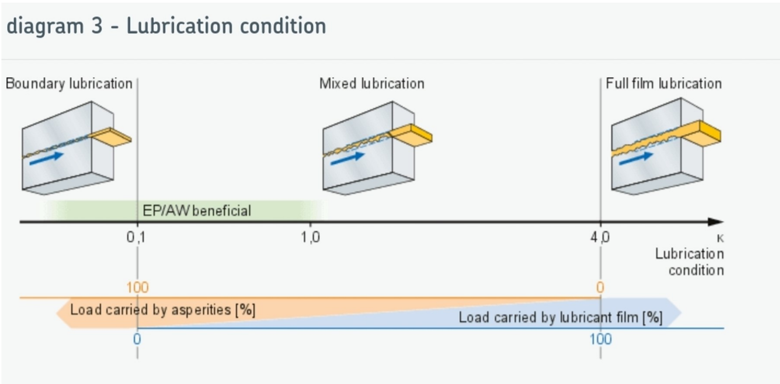
Table 5

Viscosity classification to ISO 3448

Viscosity grade	Kinematic viscosity limits at 40 °C (*105°F*) mean	min.	max.
–	mm²/s		
ISO VG 2	2,2	1,98	2,42
ISO VG 3	3,2	2,88	3,52
ISO VG 5	4,6	4,14	5,06
ISO VG 7	6,8	6,12	7,48
ISO VG 10	10	9,00	11,0
ISO VG 15	15	13,5	16,5
ISO VG 22	22	19,8	24,2
ISO VG 32	32	28,8	35,2
ISO VG 46	46	41,4	50,6
ISO VG 68	68	61,2	74,8
ISO VG 100	100	90,0	110
ISO VG 150	150	135	165
ISO VG 220	220	198	242
ISO VG 320	320	288	352
ISO VG 460	460	414	506
ISO VG 680	680	612	748
ISO VG 1 000	1 000	900	1 100
ISO VG 1 500	1 500	1 350	1 650

(b) SKF Table - Viscosity classification to ISO 3448 [17]

Figure 6.17: Determination of ISO VG curve of grease LI EP 00



Lubrication condition	κ	Size selection
Boundary lubrication Full asperity contact, wear without EP/AW additives, high friction	$\kappa \leq 0{,}1$	static safety factor
Mixed lubrication Reducing asperity contact, wear and surface fatigue without EP/AW additives, friction reduced	$0{,}1 < \kappa \leq 4$	SKF rating life and static safety factor[1)]
Full film lubrication No asperity contact, increasing viscous frictional moment	$\kappa > 4$	SKF rating life (no life gain, possible higher temperatures) and static safety factor[1)]

Figure 6.18: SKF Table - Lubrication conditions [17]

Table 1

Guideline values of specification life for different machine types

Machine type	**Specification life** Operating hours
Household machines, agricultural machines, instruments, technical equipment for medical use	300 ... 3 000
Machines used for short periods or intermittently: electric hand tools, lifting tackle in workshops, construction equipment and machines	3000 ... 8 000
Machines used for short periods or intermittently where high operational reliability is required: lifts (elevators), cranes for packaged goods or slings of drums, etc.	8 000 ... 12 000
Machines for use 8 hours a day, but not always fully utilized: gear drives for general purposes, electric motors for industrial use, rotary crushers	10 000 ... 25 000
Machines for use 8 hours a day and fully utilized: machine tools, woodworking machines, machines for the engineering industry, cranes for bulk materials, ventilator fans, conveyor belts, printing equipment, separators and centrifuges	20 000 ... 30 000
Machines for continuous 24-hour use: rolling mill gear units, medium-sized electrical machinery, compressors, mine hoists, pumps, textile machinery	40 000 ... 50 000
Wind energy machinery, this includes main shaft, yaw, pitching gearbox, generator bearings	30 000 ... 100 000
Water works machinery, rotary furnaces, cable stranding machines, propulsion machinery for ocean-going vessels	60 000 ... 100 000
Large electric machines, power generation plant, mine pumps, mine ventilator fans, tunnel shaft bearings for ocean-going vessels	100 000 ... 200 000

Figure 6.19: SKF Table - Guideline values of specification life for different machine types [17]

Operating viscosity			Lubrication condition
Actual	Rated	Rated at 40 °C	Viscosity ratio
ν	ν 1	ν ref	κ
mm^2/s			
38.3	7.1	21.8	5.39

Figure 6.20: LI EP 00: precise κ value computed through SKF Bearing Selection tool [24]

Table 6.7: Actual arrangement: bearings rating life

	A	**B**
L_{10m} $10^6 cycles$	$1.02 \cdot 10^5$	$1.21 \cdot 10^4$
L_{10hm} $hours$	$4.37 \cdot 10^5$	$5.22 \cdot 10^4$

Operating hours of life should be compared to typical values provided by the bearings maker and related to the machine type they are assemble on. Following SKF indications, for a test bench working on three shifts (so 24/24 h for 6 days a week) performing a defined and periodic cycle, bearings should last between 40000 and 50000 *hours* (see Figure 6.19).

Values obtained for the actual arrangement are barely in the recommended life range, and having such lubrication conditions and under-sizing of one bearing, makes the values of L_{10mh} just estimations of the real life rate, that probably should be decreases to take into account these factors.

6.1.3 New arrangement proposal

As a matter of fact, the analysis proposed in previous paragraph shows the necessity to evaluate a new bearings configuration for "PRIMARY SHAFT" sub-system, mainly for three reasons:

1. *Tapered roller bearing* **A** from NSK results to be under-sized with respect to its attainable angular speed;
2. strange lubrication conditions seems to intensify the overheating phenomenon, creating also dirt and grease leakages over the primary shaft's case;

3. bearings service life is poorly inside the suggested range for such an application, moreover under-sizing and high lubricant viscosity create life diminishing factors which cannot be taken into account by classical life theories, here applied.

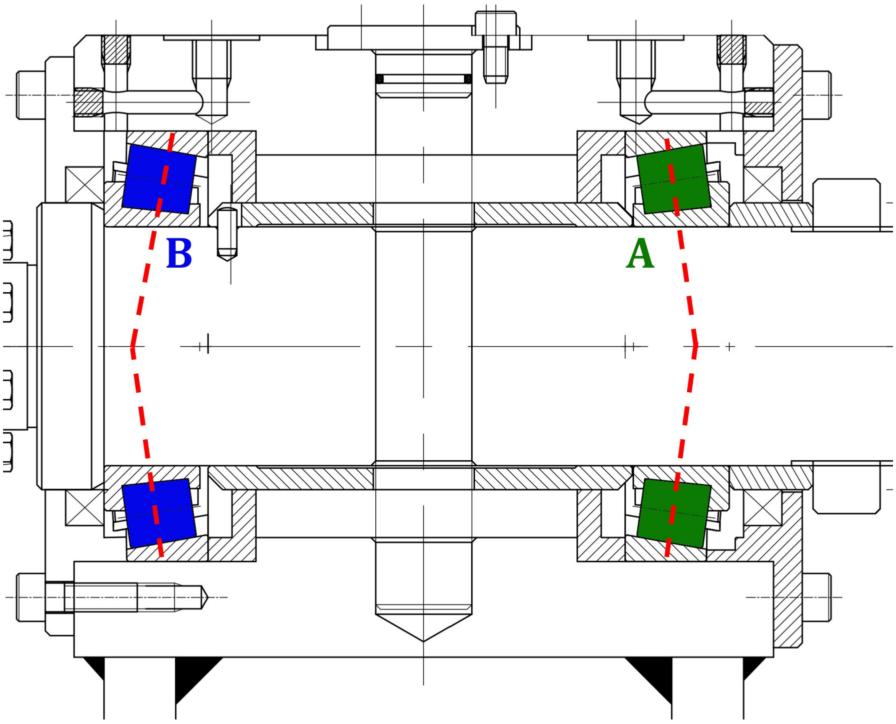


Figure 6.21: AutoCAD scheme of bearings proposed arrangement

Note that being the lubrication system speech complex as well as the new arrangement proposal, it will be treated separately in paragraph 6.1.4.

In the need of determine an alternative bearings arrangement, a natural choice is to preserve the "back-to-back" configuration, which provides a relatively stiff bearings arrangement, can accommodate unforeseen tilting moments and eventually bear axial loads in both directions [17]. To avoid strange bearings coupling, it is preferred to go for a doubling of *angular contact ball bearings* or of *tapered roller bearings*:

- *Ball-Ball Arrangement:* it is preferable for high speed applications, to reduce friction between rolling elements and their tracks, but in this case primary shaft never rotates beyond 4500 *rpm*, which is considered a medium-low angular speed in manuals used till now.

- *Roller-Roller Arrangement:* suitable for medium angular speeds and quite high loads, roller bearings seems to be a better choice for the present application; moreover, despite the under-sizing of bearing **A** and the greater radial load it has to bear, the NSK product still has an higher service life with respect to its mating bearing, thanks to the higher load limits it has.

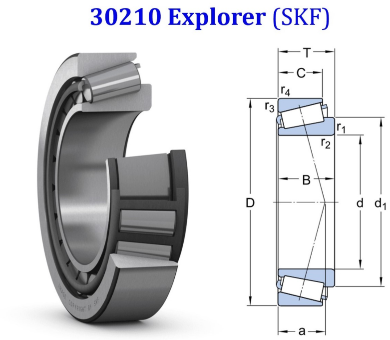


Figure 6.22: Extracts from bearings catalogues of the proposed arrangement

Table 6.8: Bearings data-sheet of proposed arrangement

Geometrical Data			**30210 Explorer**
inner diameter	d	mm	50
outer diameter	D	mm	90
width	B	mm	20
number of rolling elements	z	/	20
rolling element diameter	D_w	mm	/
Calculation Data			
basic dynamic load rating	C	kN	93.1
basic static load rating	C_0	kN	91.5
fatigue load limit	P_u	kN	10.4
attainable speed	n_{lim}	rpm	7500
Calculation Factors			
corrective factor for "O" config.	Y_0	/	0.8
corrective factor for "O" config.	Y_1	/	1.4
factor for equivalent load	e	/	0.43

Following this idea, together with Thyssen designer a new *tapered roller bearing* from SKF is selected, having higher load and speed capabilities: in Figure 6.22 is shown an extract from SKF catalogue [17] and in Table 6.8 are summarized its main features, to be compared to the ones of the actual bearings in Table 6.3. New arrangement is proposed in Figure 6.21: its features are almost the same, but this time there aren't located bearings, since both rollers can slip on the external ring.

Computational steps to obtain service life values of the two bearings, follow the same SKF procedure depicted in paragraph 6.1.2, so here only the results will be proposed. In Table 6.10 are reported reaction forces and equivalent dynamic loads, to be compared with the ones of Table 6.6; in Table 6.9 are shown the new service life values, directly compared with actual arrangement values.

Table 6.9: Actual arrangement VS Proposed arrangement: bearings rating life

	A		**B**	
	"actual"	"proposed"	"actual"	"proposed"
L_{10m} $10^6 cycles$	$1.02 \cdot 10^5$	$9.43 \cdot 10^6$	$1.21 \cdot 10^4$	$3.77 \cdot 10^7$
L_{10hm} $hours$	$4.37 \cdot 10^5$	$4.06 \cdot 10^7$	$5.22 \cdot 10^4$	$1.62 \cdot 10^8$

It is immediately clear that the new arrangement has much more service hours at the test bench's disposal, and even with uncertainties deriving from environmental conditions which cannot be taken into account from the rating life theory expressed by formula 6.9, new *tapered roller bearings* **30210 EXPLORER** from SKF should ensure a reduction of maintenance interventions over the group and higher stiffness to the sub-system, decreasing the noise levels due to abnormal elements' wear which reverberates on the transmission tested. Furthermore, dealing with a couple of equal bearings improves the stability of the arrangement (as said before, *Ball-Roller* arrangements are not typical nor suggested by bearings makers) and makes easier and less expensive to provide spare parts and to manage them inside the plant's warehouse.

6.1.4 Lubrication system modifications

Besides the arrangement modification proposed in previous paragraph, it results to be of key importance to accurately analyse the lubrication system, making effective changes to it and to the type of grease used.

First benefit can be recognized in the life modification factor a_{SKF}: according to SKF manual [17], having a viscosity ratio κ higher then 4, does not allow the designer to assign any gain to the life estimation. To address the issue, an

Table 6.10: Proposed arrangement: reaction forces and equivalent dynamic loads

OPERATING CONDITIONS						*Bearing A*			*Bearing B*		
i	Δt_i	n_i	$M_{t,i}$	$P_{c,i}$	U_i	$F_{r,Ai}$	$F_{a,Ai}$	P_{Ai}	$F_{r,Bi}$	$F_{a,Bi}$	P_{Bi}
[-]	[s]	[rpm]	[Nm]	[kW]	[-]	[N]	[N]	[N]	[N]	[N]	[N]
1	5	1000	40	5.45	0.01	1462	522	1316	625	522	981
2	5	1400	-30	5.72	0.02	1184	423	1066	507	423	795
3	5	1800	90	22.05	0.02	3361	1200	3025	1438	1200	2256
4	5	1800	60	14.70	0.02	2319	828	2087	992	828	1556
5	10	1800	-30	7.35	0.05	1277	456	1149	546	456	857
6	5	2000	20	5.45	0.03	985	352	886	421	352	661
7	5	2000	-30	8.17	0.03	1332	476	1199	570	476	894
8	10	2600	0	0.00	0.07	491	175	441	210	175	329
9	5	2600	-30	10.62	0.04	1532	547	1379	656	547	1028
10	5	3600	30	14.70	0.05	1982	708	1784	848	708	1330
11	15	3600	20	9.80	0.15	1635	584	1472	699	584	1097
12	5	4100	20	11.16	0.06	1914	684	1723	819	684	1285
13	5	4200	80	45.74	0.06	4058	1449	3653	1736	1449	2724
14	5	4200	70	40.02	0.06	3711	1325	3340	1588	1325	2491
15	10	4200	20	11.44	0.11	1975	705	1777	845	705	1325
16	10	4200	-30	17.15	0.11	2322	829	2090	993	829	1558
17	5	4300	20	11.71	0.06	2036	727	1833	871	727	1367
18	5	4300	0	0.00	0.06	1342	479	1207	574	479	900

alternative lubricant grease was selected with Thyssen help: remembering what is shown in Figure 6.16b, the new grease was picked to have a viscosity as close as possible to the suggested one, so that the choice fell over **ISOFLEX NCA 15**, a Kluber grease having a viscosity of 24.5 mm^2/s at 40 $°C$, differently from LI EP 00 grease, which instead has a value of 190 mm^2/s at 40 $°C$. With the help of *SKF Bearing Select* tool [24] to get an accurate κ estimation, in Figure 6.23 are shown the viscosity values related to the new lubricant grease for the actual working conditions.

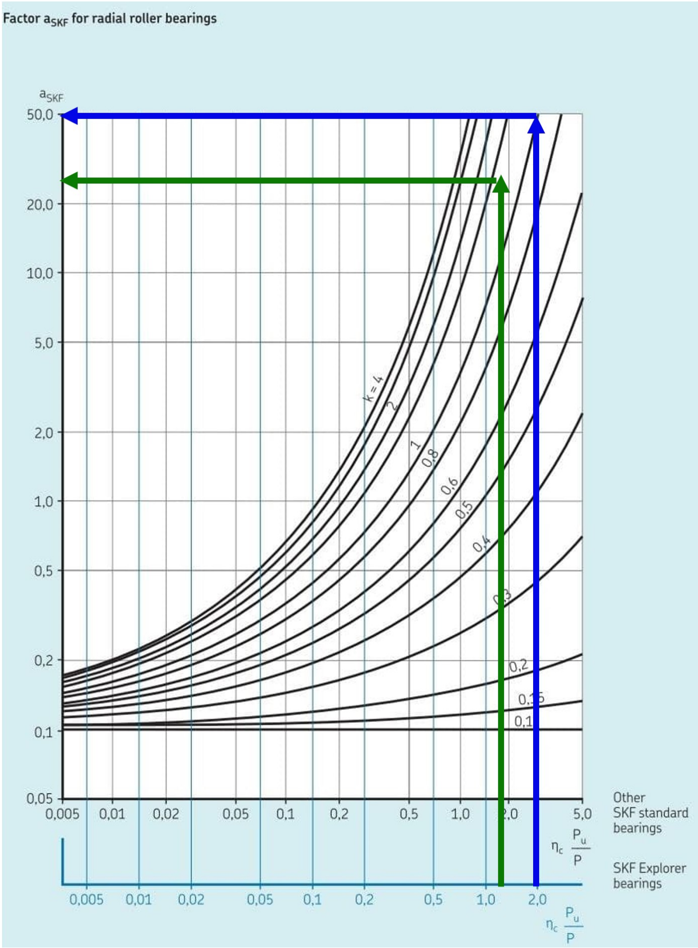
Designation		Operating viscosity			Lubrication condition
		Actual	Rated	Rated at 40 °C	Viscosity ratio
		ν	ν_1	ν_{ref}	κ
		mm^2/s			
Left	☆ ■ **30210**	9.31	7.14	18.7	1.3
Right	☆ ■ **30210**	9.31	7.14	18.7	1.3

Figure 6.23: ISOFLEX NCA 15: precise κ value computed through SKF Bearing Selection tool [24]

Being now $\kappa < 4$, it is possible to use the SKF chart reproduced in Figure 6.24a to evaluate the life modification factor for both bearings. Note that even though **A** and **B** have the same size and features, the same working temperature, angular speed and contamination conditions, the two bears different loads, in particular bearing **A** holds a greater radial load: this is why the a_{SKF} value associated to it is lower then the one for bearing **B**. The x-axis of a_{SKF} chart shows a dependency from the equivalent dynamic load P, which changes according to the specific *i-th* operating condition considered; to be on the safety side, a_{SKF} was determined using the highest value among P_i, and so putting the system in the worst condition possible to estimate the life gain. Being $P_{A,max} > P_{B,max}$ as a consequence it results $a_{SKF,A} < a_{SKF,B}$. Once again precise numerical data are obtained through the *SKF Bearing Select* tool [24], of which a screenshot is reported in Figure 6.24b.

A further enhancement was deployed over the lubrication system. In the actual configuration, test benches are equipped with two hydraulic circuits, one for lubricant oil and one for lubricant grease. The latter one, depicted in Figure 6.25, delivers grease to the drive shafts' slide-ways (Gr. 216) and to the internal (Gr. 213) and external (Gr. 214) bearings on the primary shaft. The greasing happens every 700 gearboxes tested, which corresponds more or less to a re-lubrication once a day.

Commonly bearings lubricated with grease are lubed *for life*, meaning that the time at which the grease is consistently consumed matches with the bearing's end



(a) SKF Chart - Factor a_{SKF} for radial roller bearings [17]

Designation	SKF life modification factor	Contamination factor
	a_{skf}	η_c
	h	*h*
Left ☆ ■ **30210**	34.27	0.5
Right ☆ ■ **30210**	50	0.5

(b) SKF Life modification factor computed through SKF Bearing Selection tool [24]

Figure 6.24: Determination of a_{SKF} values

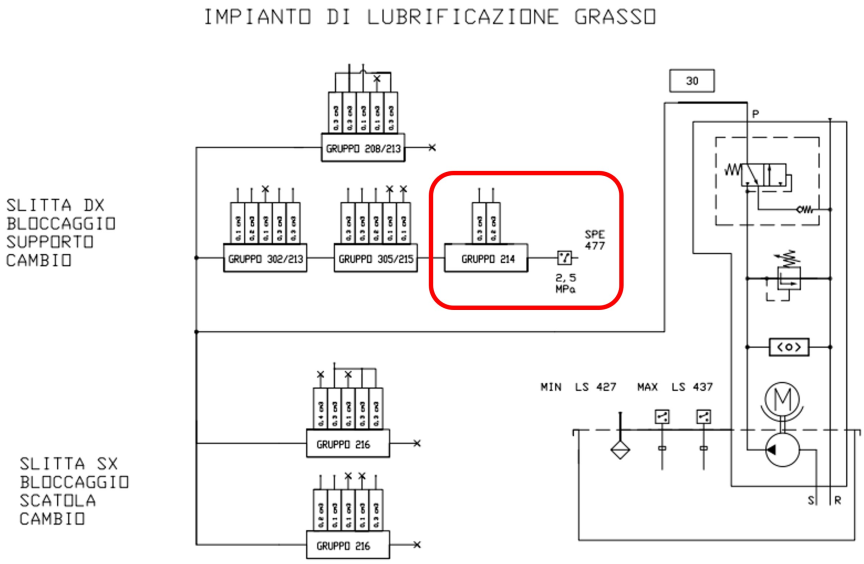


Figure 6.25: Hydraulic scheme of grease lubrication system

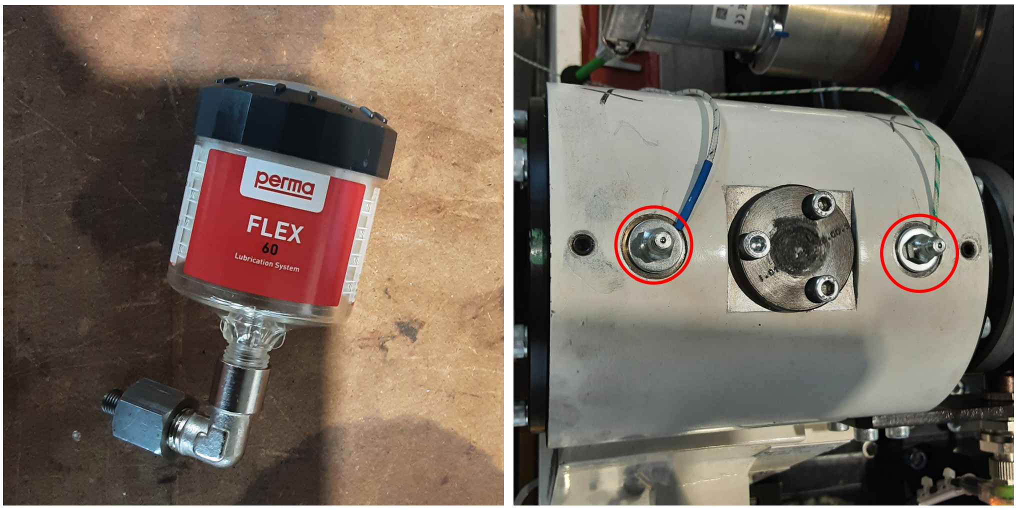
of life, so a constant and huge greasing is suspicious and could largely contribute to the overheating of the system, mostly when considering that the hydraulic circuit does not incorporate a drain for exhausted grease.

Very viscous grease paired with an excessive lubricant amount inside the primary shaft's case, is suspected to produce the following two phenomena:

1. without frequent checks over the grease amount and its chemical condition, the primary shaft's case risks to get full of lubricant, which is driven toward the case's sides by the centrifugal effect induced by the system rotation, and eventually causes the leakage of grease from the seals, spreading dirt all over the system;

2. when the grease loses its lubricity, it gets a heavy mass rotating alongside the shaft, producing high levels of friction and contributing to the case's temperature increase; having triggered a vicious cycle, the higher temperatures damage more and more the grease chemical structure, making it a solid and burned paste.

To get rid of this condition without modifying the hydraulic circuit described above, the test benches maker together with a lubrication specialist, have found the automatic grease guns depicted in Figure 6.26a: properly setting their timer and putting inside them the right amount of lubricant, the grease guns provide a continuous, but minimum greasing to the system. They can be easily attached to



(a) Automatic grease guns (b) Barb fittings on primary shaft case

Figure 6.26: New lubrication system for primary shaft bearings

the system through the barb fittings already present (Figure 6.26b) and there is no need to check periodically the grease to avoid unforeseen leakages, the case will be cleaned at the same time of the scheduled bearings replacement. Phenomena described above will be erased and vibration induced by high temperatures will be largely mitigated.

6.1.5 Corrective actions analysis

All improvements described till now are the outcome of a deep analysis of the "PRIMARY SHAFT" sub-system mechanical structure, performed as a Team made by the author of the present work, the mechanical specialist of Mirafiori's Maintenance Department and the test benches' managers at Thyssenkrupp Italia.

Since the Advanced Kaizen was developed simultaneously with the building of the newest test bench *Thyssen1*, the machine already got the upgrades depicted here and was installed in Mirafiori Meccanica with new bearings and new lubrication system.

Being *Thyssen1* a new machine, it would have unlikely displayed in the short period the same issues of TH5 here faced, making it impossible to evaluate the real enhancement of the sub-system. For this reason, the plant gave the permission to implement the improvements over an "older" test bench, to be used for benchmarking in the next months, and once the benefits deriving from the interventions would have been confirmed, the improvements would be extended to other test benches. Due to production schedules, interventions were performed not on TH5, but on TH3 on the 12 of June 2021.

Obviously, real results would be appreciate only in 2 or 3 years from now, checking the bearings conditions and periodically monitoring the sub-system's temperature. This is one of the greatest limits of present Thesis, but to somehow overcome it, it is here proposed a double check of "PRIMARY SHAFT" sub-system, to get immediately aware of the goodness of the corrective actions:

- Primary shaft's case **temperature monitoring** during the days following the intervention;
- **Vibration analysis "Do-It-Yourself"** to evaluate the background noise produced by the system, before and after the intervention.

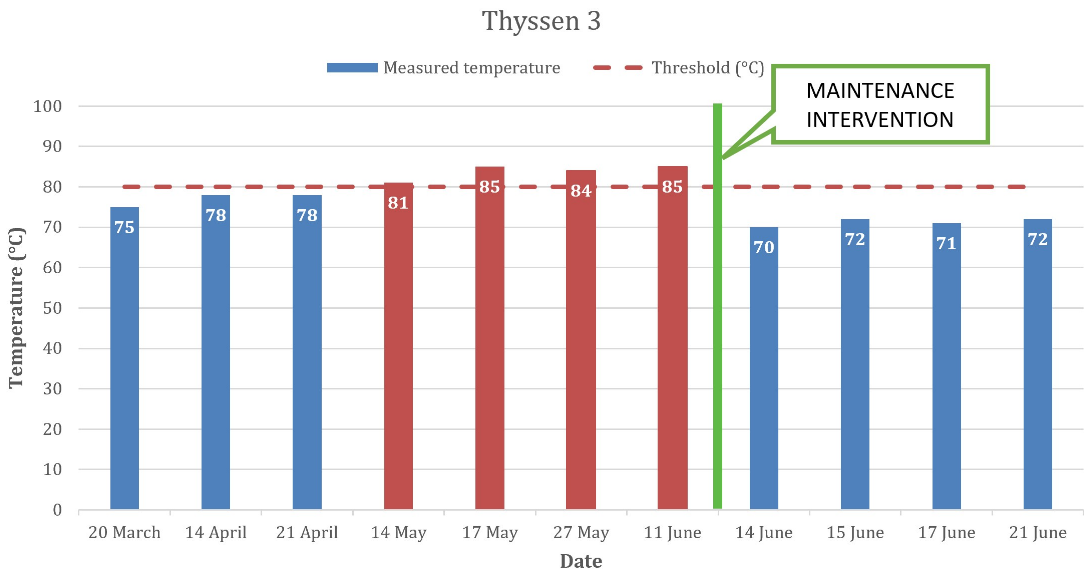
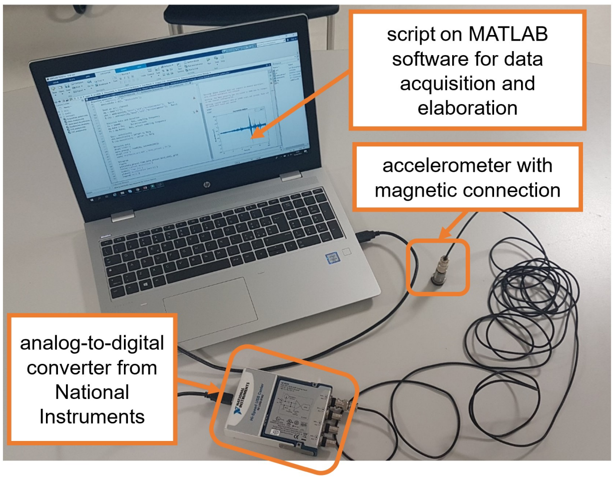


Figure 6.27: TH3 temperature trend post maintenance intervention

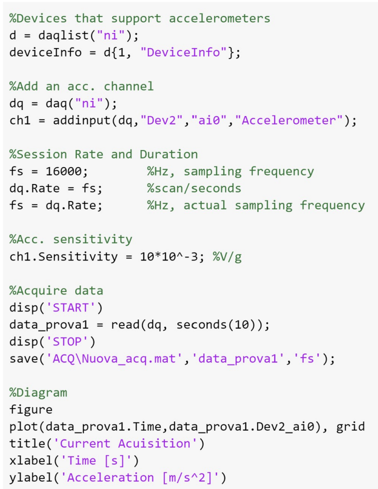
Temperatures are collected a few days before the intervention and then during the two weeks after it. Measurements are proposed in Figure 6.27. It is immediately clear that the working temperature range is reduced, going from an increasing trend between $80 \div 90\ °C$ to a stable value in $70 \div 75\ °C$ range. Precisely the fact that the temperature seems to keep constant once the test bench is at its steady-state, shall be interpreted as a step towards the issue resolution: the grease seems to properly work in the system, lubricating the bearings and preserving its chemical stability during operations.

For this reason, after a week from the first intervention, it is decided to change lubricant to all test benches and once again it is recorded a sensible change in their temperature trend, meaning that probably the main triggering factor of the overheating was the wrong lubrication system. As a further improvement, bearings arrangement will be changed in the near future, if the TH3 will keep to show good and stable performances.

Being the temperature under control, the system should have significantly reduced its vibration, thus decreasing the abnormal background noise recorded by the NVH sensor on the test bench. To roughly evaluate it, a DIY vibration acquisition system is built up.



(a) Acquisition system



```
%Devices that support accelerometers
d = daqlist("ni");
deviceInfo = d{1, "DeviceInfo"};

%Add an acc. channel
dq = daq("ni");
ch1 = addinput(dq,"Dev2","ai0","Accelerometer");

%Session Rate and Duration
fs = 16000;        %Hz, sampling frequency
dq.Rate = fs;      %scan/seconds
fs = dq.Rate;      %Hz, actual sampling frequency

%Acc. sensitivity
ch1.Sensitivity = 10*10^-3; %V/g

%Acquire data
disp('START')
data_prova1 = read(dq, seconds(10));
disp('STOP')
save('ACQ\Nuova_acq.mat','data_prova1','fs');

%Diagram
figure
plot(data_prova1.Time,data_prova1.Dev2_ai0), grid
title('Current Acuisition')
xlabel('Time [s]')
ylabel('Acceleration [m/s^2]')
```

(b) MATLAB script

Figure 6.28: DIY vibration acquisition and elaboration system

As is evident from Figure 6.28, the system is made of a PC featuring MATLAB software with *Data Acquisition Toolbox*, an analog-to-digital converter, an accelerometer with a magnetic connection and its cable.

Vibrations are measured before and after the intervention on primary shaft's bearings, keeping constant the angular speed of the shaft and positioning the accelerometer on 6 different spots over the case, named from A to F, which is fundamental to avoid the structure's nodes and actually do not record anything of meaningful. Having just a single sensor, the test have been repeated six times, once for the test at 2000 rpm and once for the one at 4000 rpm. During the two tests, speed engaged (5^{th} speed) and torque transmitted (20 Nm) are kept constant. Records last 10 s and "old" and "new" signals are plotted together, respectively in blue and orange.

In Figure 6.29 are depicted the signals acquired in the time domain, together with an indication of the 6 spots in which the accelerometer was placed. A first and simple observation consists in appreciate the different amplitudes of vibration:

increasing the angular speed means to increase the structure output. Moreover, it is possible to see that not all points vibrate in the same way, especially points A and D, corresponding more or less to the middle of the case, they seem to have the lowest output of all, probably because the vibrations produced by the bearings reverberate along the case and cancelled themselves in the middle of it. In any case, it is not possible to assess if the system noise decreased after the intervention by simply looking at the acceleration records given in time domain.

To give a faithful interpretation of the tests, the Fast Fourier Transform of the signal is computed through the MATLAB command *fft* and resulting spectra are shown in Figure 6.30. A sharp decreasing of the orange peaks can be detected in each test and in every point of the case, which is interpreted as a reduction of the background noise level.

Results analysed till now seems to give the positive evidence of a resolutive intervention over Thyssen Gr. 214. Nevertheless, the final check will be available only in a few months, comparing a consistent number of NVH curves recorded before and after the maintenance intervention: if a considerable decrease in the curves off-set would be detected, the amount of test bench's noise affecting the NVH records would have been downed for real, bringing the level of fake scrap produced by the test bench closer to zero.

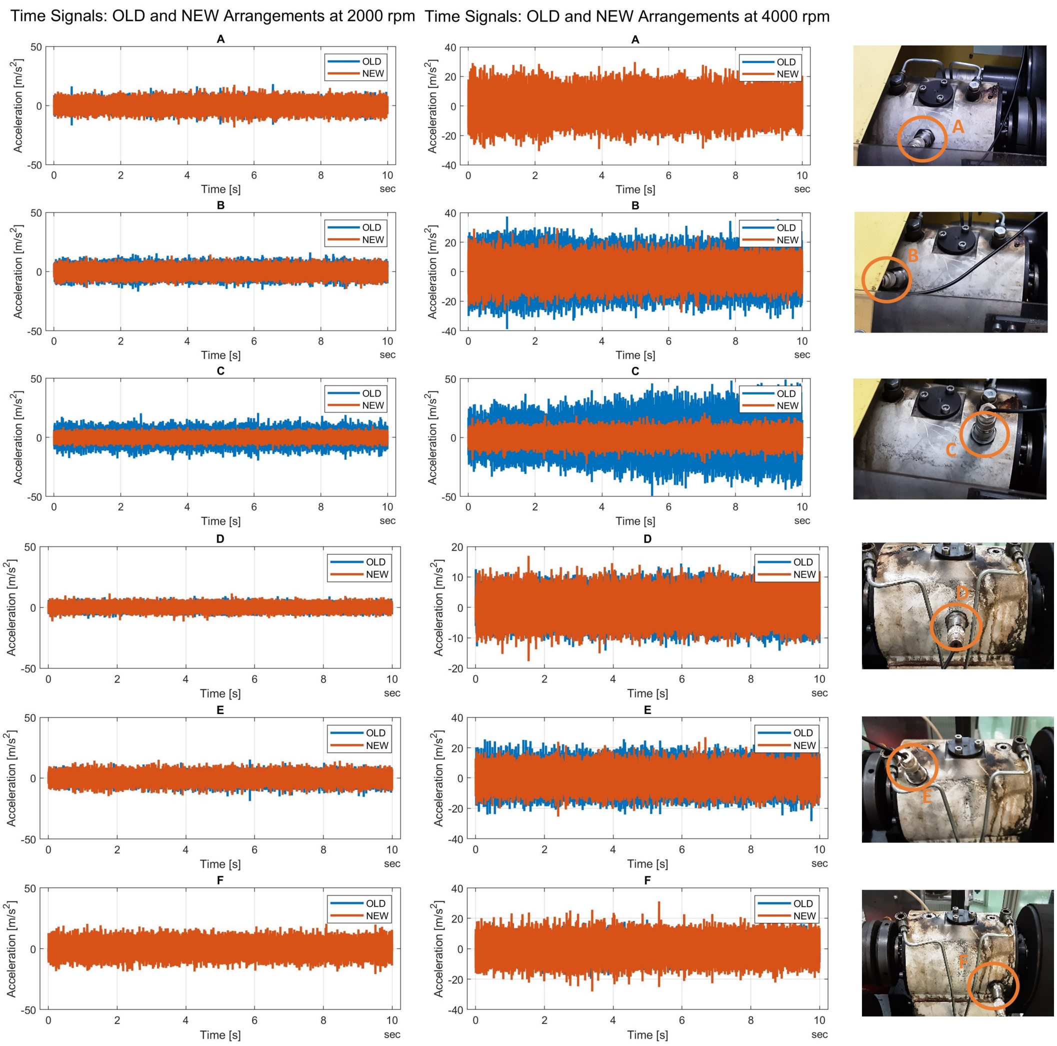


Figure 6.29: Time domain signals acquired through DIY system

Figure 6.30: Spectrum obtained through Fast Fourier Transform function

6.2 Secondary shafts: joints breakage

As introduced in paragraph 5.2, on "SECONDARY SHAFTS" sub-system were discovered two main issues:

(a) Tripods joint unscrewing, and eventually screws breakage;

(b) Frequent breakage of elastic joint.

Trying to solve both problems, it will be necessary to partially re-design the secondary shaft itself, which is actually made of three different portions, clearly identified in Figure 6.31.

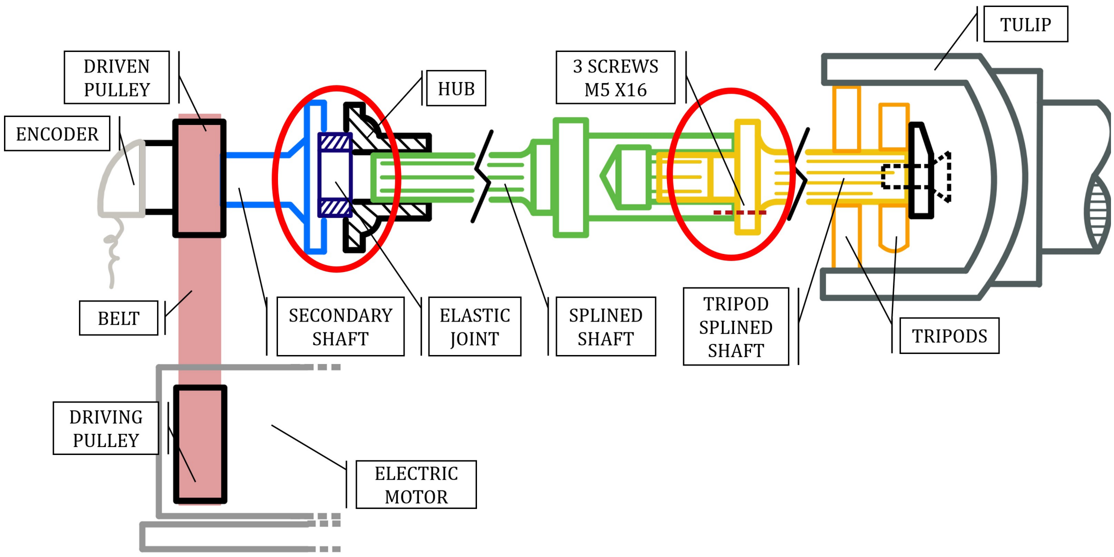


Figure 6.31: Sketch of "SECONDARY SHAFTS" sub-system

With respect to the test bench's sketch proposed in Figure 3.1, in Figure 6.31 is detailed the left drive shaft of the bench, which is actually equal to the right drive shaft and so not doubled here.

Similarly to the primary shaft, there is a belt-pulley system, which transmits the motion from an electric motor to the first portion of secondary shaft, which in turn is linked through a lamellar elastic joint to a longer shaft with a splined end; between this longer shaft and the gearbox, there is another shorter shaft, splined too, shaped to engage the tulips of C5.14. For the sake of notation, the three portions will be called respectively:

- *Secondary Shaft*: receives directly motion and torque from the belt-pulley system;

- *Splined Shaft*: longer portion, on which are mounted and/or inserted most part of other sub-system components;
- *Tripods Splined Shaft*: shorter portion with two splined ends, the first one needed to engage internally the *Splined Shaft*, the second one to accommodate the tripods joint and subsequently the tulips. Note that there are tripods of two different sizes, in order to couple with large and small tulips, according to the C5.14 model.

Red circles in the sketch are meant to highlight the critical spots of the system:

(a) Once a shift, two maintainers stop the test bench in order to tight up the three screw M5x16 used to reinforce the splined connection between *Splined Shaft* and *Tripods Splined Shaft*.

(b) Periodically (almost every 6 or 8 months, according to the Machine Ledger), the "SECONDARY SHAFTS" sub-system suddenly stops and maintainers who perform the repair found out the lamellar joint is seriously damaged or even broken, making the secondary shaft's electric motor not able to transmit the motion any more. Moreover, it frequently happens that broken reed petals are spread all over the shield, causing malfunctions of other nearby components too.

Starting the inspection in June 2021, it came out the issues are common to all test benches and they show up periodically:

(a) Constantly after about 1.5 years from the test bench installation;

(b) After 6 months or not later then 1 year after the elastic joint replacement.

By dedicating a paragraph to each issue, present work will try to find a reliable solution to the problems, giving some hints about the possible corrective actions implementation.

6.2.1 Tripods joint unscrewing

To face the issue, the very first thing to do is to find the potential root cause of the abnormal vibration developed at the tripods joint level, between *Splined Shaft* and *Tripods Splined Shaft*. Such vibration makes necessary the tighten of six screws M5x16 (three for each drive shaft), at least three times a day.

After a confrontation with the mechanical specialist of Maintenance Department, most probable cause is recognized in the wear of the internal splined connection, which cannot be properly hold by three small screws like the ones adopted by the machine maker: they probably selected M5 screws because of space constrains, but such small sized threaded elements could be not sufficiently strong to hold the system, so that when the mechanical clearance between splined connection's teeth increases, vibration dumping on the screws intensify, thus starting the screws unscrewing, and eventually the rise of shear stress.

Present diagnosis is consistent with the issue occurrence: new shafts do not show such a behaviour, while components mounted on test benches for 1 or at least 2 years, start to exhibit the M5 screws breakage, sign of an abnormal shear stress bore by them.

The internal splined teeth wear shows up even though their surface is mechanically treated to be strengthen up. Unfortunately, pictures of the worn splined connection are not available, as it would have required the dismounting of the complete sub-system, not compatible with production schedules.

Waiting for more accurate diagnosis, in following paragraphs there will be the description of three possible alternative solutions, to strengthen the connection or to change its shape, in order to stop the abnormal vibration source coming from the joint. The three solutions will be presented in order of "invasivity" and will be shortly commented in final paragraph 6.2.3

BOLT SECURING WASHERS A first and simple solution initially proposed by Thyssenkrupp designer, consists in the insertion of bolt securing washer on the three screw M5x16. The item used is from Nord Lock maker and can be seen in Figure 6.32.

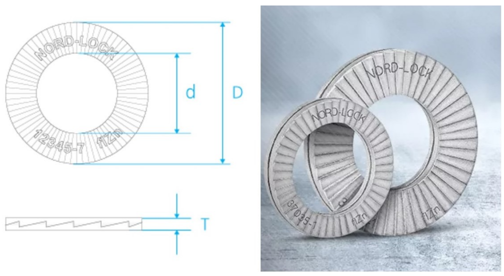
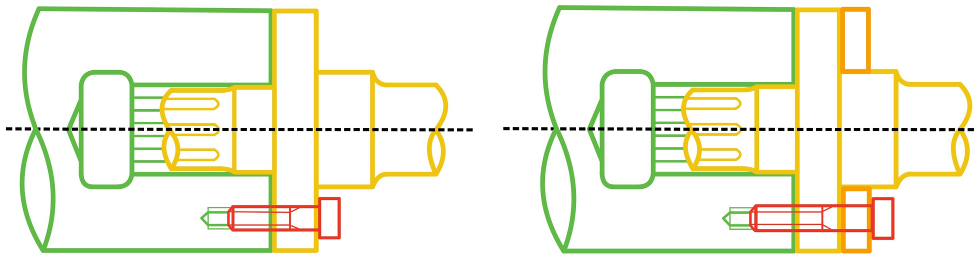


Figure 6.32: Locking washers from Nord Lock

The solution was initially tempted at the beginning of 2020, and the joint looked like the sketch depicted in Figure 6.33a. However, tests run in Thyssenkrupp plant showed an ineffective action of the washers placed on the *Tripods Splined Shaft*: being the shaft thermally treated to strengthen the splined connection, washers cannot actually grasp the metal surface on which their are placed, thus making the application useless.

Under Mirafiori Meccanica's request, Thyssenkrupp proposed a second layout, testing it on *Thyssen1* before its delivery to the plant. This time the locking washers are placed on an intermediate spacer, made in mild steel, on which the anti un-screwing components seems to work properly.



(a) First design attempt (b) Second design attempt

Figure 6.33: Bolt securing washers possible solutions

In any case the solution is not believed to be the resolutive one: washers work perfectly on TH1, but as mentioned before, issue will show up later on, along the newest test bench's life, so that positive results assessed by Thyssen could be not so relevant in the end. Moreover, bolt securing washers might help the screws to stay in place without undergoing shear stress, but if the splined connection suffers of excessive or asymmetric wear, washers would be just a temporary answer to the problem.

SPLINED PROFILE MODIFICATION Actually the used splined profile corresponds to standard DIN 5472 (6x23x28), with straight teeth (Figure 6.34). As mentioned right above, it should be important to evaluate the type of wear the splined connection shows after 1 or 2 years of operation, so that with respect to the peculiar damage discovered, it would be necessary to apply different corrective actions:

1. **uniform wear** on both tooth sides: it is just the normal splined connection's life course, that eventually brings to an increase of mechanical clearance of the connection, due to the natural material wear.

   In this case the only thing to do -without changing the connection design- is to replace the two shafts.

2. **asymmetrical** tooth **wear**, concentrated at its tip: in this case is probable a misalignment of the shafts, producing an abnormal wear of the splined connection.

A smart solution here, could be the splined profile modification, it would result particularly suitable a convex toothing choice.

Unfortunately, not having images or data relate to the teeth wear, it is not possible to asses which case is the present one.

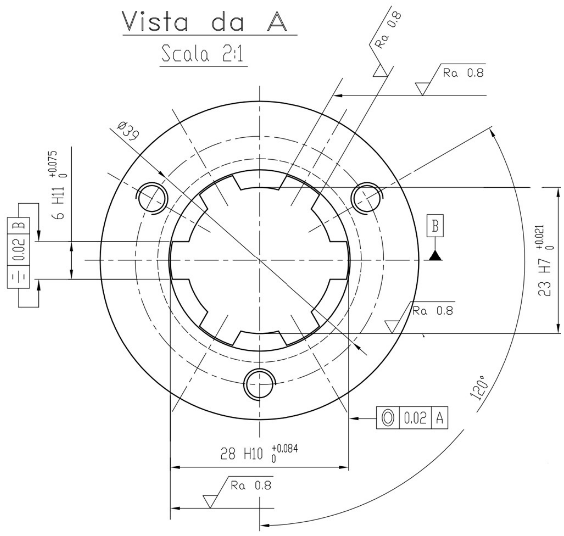
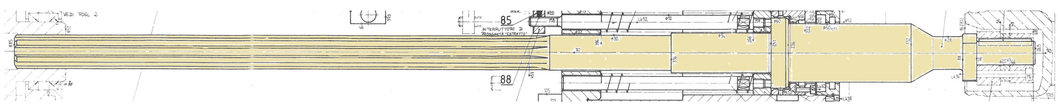
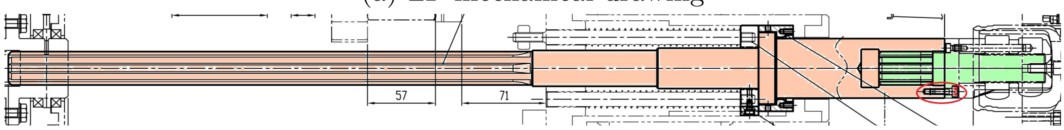


Figure 6.34: Actual splined shape (on *Splined Shaft* side)

SPLINED SHAFT IN SINGLE PIECE A far more radical solution is the final one proposed and requires the elimination of the internal splined connection, by designing a splined shaft in a single piece. The idea is suggested by previous test benches version, depicted in old ZF drawings in Figure 6.35a: before being retrofitted, benches had a drive shaft made of only two components, the so-called *Secondary Shaft* and a (longer) *Splined Shaft*.



(a) ZF mechanical drawing



(b) Thyssen mechanical drawing

Figure 6.35: Comparison of *Splined Shafts* designs

Thyssenkrupp designers thought to a different solution, reported for comparisons purposes in Figure 6.35b: while asked the reason for such a split of the shaft, different from the original version, designer replied it is a common *best practice* of the group, used to ease maintenance activities on the system.

Nevertheless, present situation shows how the picked solution of splitting the shaft was not correctly evaluated or designed, since the abnormal vibration developed here is sign of a lack of good boundary conditions' evaluation or of an incorrect splined profile selection.

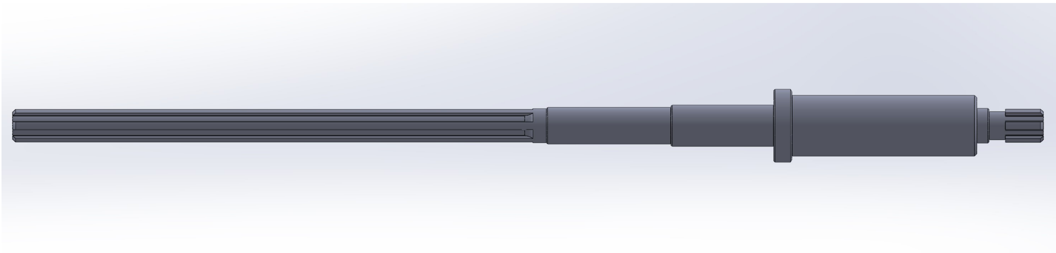


Figure 6.36: *Splined Shaft* realized in a single piece (Solidworks)

Opting for a return to the beginning, the alternative layout of a single *Splined Shaft* is proposed in Figure 6.36. It has been also considered possible mounting and dismounting issues that could follow the layout modification: according with Machine Ledger of all test benches, interventions over that test bench spot are almost zero, excluding the frequent screw tightening or replacement; moreover, it seems that to maintain one of the two shafts, it is still necessary to remove all shield around the "SECONDARY SHAFTS" sub-system, making the shaft's splitting foresight almost useless.

6.2.2 Elastic joint breakage

Second critical issue related to "SECONDARY SHAFTS" sub-system is the breakage of the elatic joint: periodically, joint highlighted in blue in Figure 6.37 breaks, determining the secondary shaft's blockage, and so the machine breakdown.

Its root cause has been detected in a wrong management of stuck gearboxes, especially on TH2 and TH7 where the test is run by cobots. As explained in paragraph 3.2.1, the only way to detect a stuck gearbox is to start the testing cycle and to record abnormal torque peaks, on INPUT or OUTPUT SHAFTS, which is symptom of an excessive resistant torque produced by the C5.14's gears as the test bench tries to move them.

Every time a stuck gearbox is produced and approached to a test bench, torque peaks repeat themselves. Usually a single faulty gearbox determines more than one torque peak over the test bench, since before the operator decrees the defect,

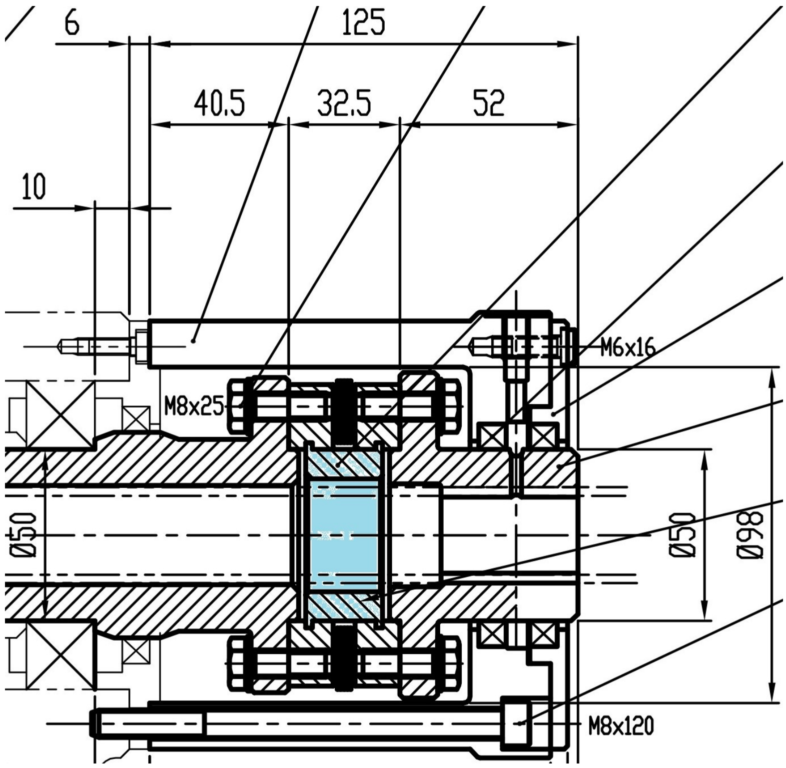


Figure 6.37: Detail from Gr. 216 drawing: elastic lamellar joint

he or she tries to start the cycle twice or three times; cobots are programmed to try three times before marking as non compliant the C5.14. Repeated attempts cause micro damages to the lamellar joint, which sooner or later will bring to the connection breakage.

It is precisely the elastic joint the point in which the peak torque is dumped, since it is the only "pliant" component between the motion transmission system on one side, and the stuck gearbox on the other side. It is like applying a high torsional moment to the structure schematised in Figure 6.38, which has an hinge and a fixed constrains.

Figure 6.38: Scheme of actual constrains while testing a stuck gearbox

It is important to note that even if a similar excitation appears on the primary shaft, almost in the same shape, its elastic joint breakages are quite rare: it is because differently from the secondary shafts, the primary one has an additional joint along its axis, the *EAS 496.714.0* from Mayr, which is a safety clutch meant to disconnect the primary shaft from the motion transmission system every time the transmitted torque exceeds 200 Nm.

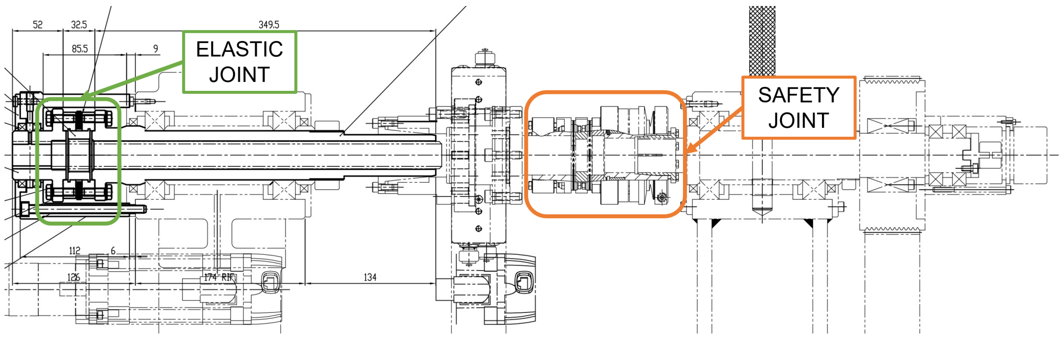


Figure 6.39: Comparison with joints placed on "PRIMARY SHAFT" sub-system

Taking a cue from the primary shaft solution, the Advanced Kaizen Teams proposes the introduction of a maximum torque safety system. In Figure 6.40 is shown the OUTPUT SHAFT cyclogram, in which is highlighted a possible torque threshold to dimension the safety joint.

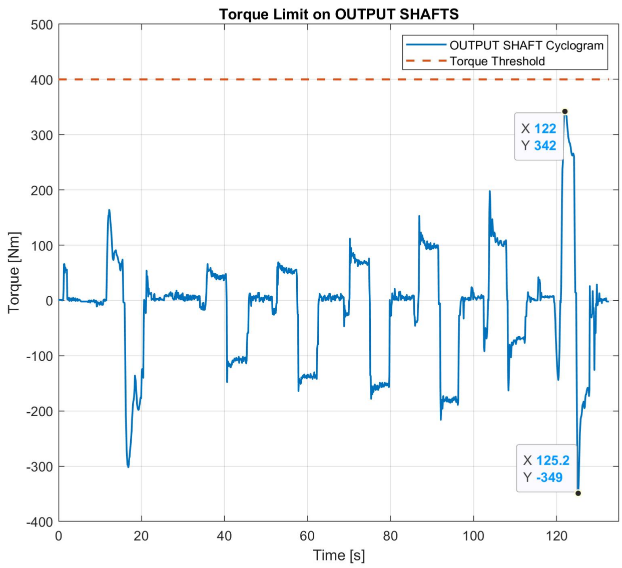


Figure 6.40: Torque thresholds base on OUTPUT SHAFTS cyclogram

Having defined a maximum torque of 400 Nm, there is still a major problem to solve: how is it possible to insert a safety joint without radically change the "SECONDARY SHAFTS" sub-system? In particular, it would be preferable to avoid a lengthening of the shafts to place a safety clutch in it, since it means change also the shields and cases size and probably to enlarge the test bench's covered area, thus reducing the passageways width (which is a plant's security requirement).

A less intrusive, yet smart solution, could be the insertion of a **safety pin** in the free space between the bearings, as shown in Figure 6.41. The *Secondary Shaft* length would be unaltered, but it would be split into two portions, the yellow one simulating the hub and the light blue one being the inner shaft of the connection. At this point it would be sufficient to correctly dimension the pin, in order to make it break at around 400 Nm. The fusible element would break inside the *Secondary Shaft*'s case, not damaging surrounding elements and eventually a proper opening could be designed over the case, in order to easily replace the broken pin. In any case, the repairing interventions would require a shorter time and the replacement cost for spare parts (pins instead of elastic joints) would sharply decrease.

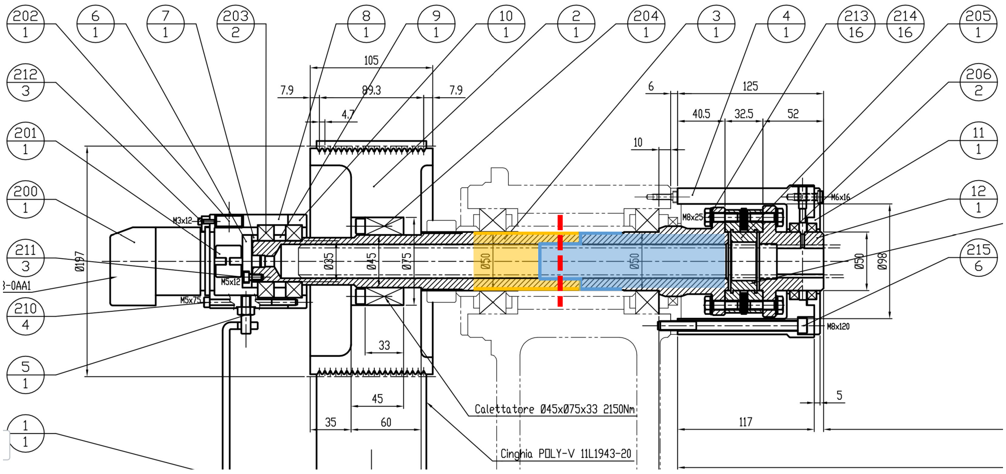


Figure 6.41: Ideas to insert a safety pin in the existing *Secondary Shaft*

To dimension the safety pin, the procedure of Niemann's *Machine Design* [18] is followed. With respect to the sketch proposed in Figure 6.42, quantities involved in the computation are linked by relationships in equation 6.20, and their meaning is explained right after them.

$$\begin{cases} F_s = \frac{T}{D} \quad [N] \\ A_s = \frac{\pi}{4} d^2 \quad [mm^2] \\ \tau_s = \frac{F_s}{A_s} \le \tau_{s,zul} \quad [MPa] \end{cases} \tag{6.20}$$

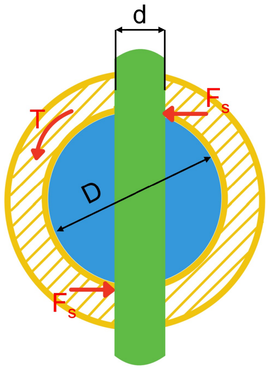


Figure 6.42: Sketch of pin joint

- d: diameter of cylindrical pin $[mm]$
- D: shaft's diameter $[mm]$
- A_s: pin's area to compute stresses $[mm^2]$
- T: torque to be transmitted from hub to shaft $[Nm]$
- F_s: shear force $[N]$
- τ_s: shear stress acting on the pin $[MPa]$
- $\tau_{s,zul}$: admissible sher stress $[MPa]$

Note that while sizing the pin to be able to transmit a certain torque, the designer must ensure that maximum shear stress imposed to the pin is $\tau_s \leq \tau_{s,zul}$. Since in this case it is necessary that the shaft does not transmit a torque higher than the maximum one, fixed at $T_{max} = 400\ Nm$, the designer will impose that:

$$\tau_{s\ (T_{max}=400\ Nm)} \geq \tau_{s,zul} \tag{6.21}$$

In particular, the selected pin should have an admissible shear stress $\tau_{s,zul}$ which is as close as possible to $\tau_{s\ (T_{max}=400\ Nm)}$ (during the present computations it will be considered the range $\tau_{s,zul} - 5\ MPa \leq \tau_{s\ (T_{max}=400\ Nm)} \leq \tau_{s,zul} + 5\ MPa$).

Definition of admissible shear stress is performed according to Niemann by applying equation 6.22:

$$\tau_{s,zul} = \tau_{s,zul\ r} \cdot C_d \cdot C_k \tag{6.22}$$

- $\tau_{s,zul\ r}$: reference admissible superficial stress, depending on the mechanical properties of the pin's material; it is obtained by linear interpolation of values reported in Table 6.43, knowing the tensile strengths R_m of the material

- C_d: dynamic factor, here selected equal to 0.7 accounting for "cyclical load starting from zero"
- C_k: reduction factor, here selected equal to 0.7 for "plain pins working under shear stress"

	Materiale dei componenti					
	GJL	GS	S235	E295	E335	E360
$p_{zul,r}$ [1)]	70	84	91	126	140	154
	Materiale delle spine e dei perni con R_m =					
	400	490	590	690		
	p. es. 9520	E295	E335	E360		
$\sigma_{bzul,r}$ [1)]	77	112	133	147		
$\tau_{szul,r}$ [1)]	56	70	84	98		
	Accoppiamenti precisi di scorrimento lubrificati (snodi), perni/spine in acciaio					
	Materiale dei componenti					
	GJL	GS	Bronzo	Acciaio[2)]		
p_{zul}	5	8	10	15		

[1)] Per spine piene con carico permanente e valore massimo di uno spettro di carico: fattore dinamico $C_d = 1$; per carico variabile: $C_d = 0{,}5$; per carico a ciclo dallo zero $C_d = 0{,}7$.
Fattori di riduzione per spine piene, flessione e taglio; pressione superficiale in spine intagliate: $C_k = 0{,}7$; $C_{kp} = 0{,}8$.
Per i valori di p_{zul} con l'impiego di gusci di cuscinetto cfr. capitolo 15.
[2)] Accoppiamento di materiali acciaio temprato/acciaio temprato.

Figura 11.17 – Materiali e sollecitazioni ammissibili in N/mm² per collegamenti a spina con spine piene e collegamenti a perno, per le sollecitazioni cfr. figure 11.15, 11.16.

Figure 6.43: Niemann Table - Admissible shear stress determination [18]

Looking for a quite strong pin, which is able to transmit high torque levels, the choice fell on quenched cylindrical pins DIN 6235 from Gandini Fasteners catalogue [25] (see also ISO 8734 or UNI 6364 A). Such pins have diameters ranging from 1 mm to 20 mm and are made in *100Cr6* steel, whose mechanical properties are depicted in Figure 6.44. It will probably be necessary to perform proper studies on material's tensile strengths, but for the purpose of the present analysis, it will be assumed the value $R_m = 1470\ MPa$.

Mechanical Properties (For reference only)				
Steel Name (Steel Number)	Tensile Strength (MPa)	Yield Strength (MPa), ≥	Elongation (%, ≥)	Diameter (mm)
100Cr6 (1.3505)	1080-1470	835	9	10
	830-1130	590	10	30

Figure 6.44: Mechanical properties of *100Cr6*

Having now defined $\tau_{s,zul}$, for a series of diameters d it is computed $\tau_{s\ (T_{max}=400\ Nm)}$, looking for the closest value to the admissible one. It comes out that a pin with a diameter of $d = 14.5\ mm$, undergoes a shear stress of 81 MPa, which respects the relationship:

$$\tau_{s\ (T_{max}=400\ Nm)} \geq \tau_{s,zul} = 80.6\ MPa \tag{6.23}$$

Actual commercial diameters nearby the ideal one, produce the following characteristics:

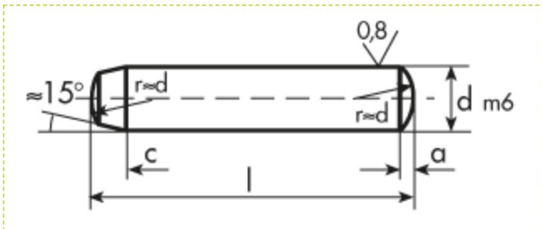
$$d = 14\ mm \Rightarrow \tau_s = 87\ MPa \Rightarrow T = 372\ Nm \tag{6.24}$$

$$d = 16\ mm \Rightarrow \tau_s = 66\ MPa \Rightarrow T = 486\ Nm \tag{6.25}$$

Since the pin with $d = 14\ mm$ is the one producing the pin's break at the torque level closer to the fixed threshold, this is the size selected for the safety joint. Pin features are reported in Figure 6.45.

MATERIALE:
100 Cr 6 (1.3505)
Durezza 58 ÷ 62 HRC
Resistenza > 600 N/mm2

Rettificata
A richiesta (h6)



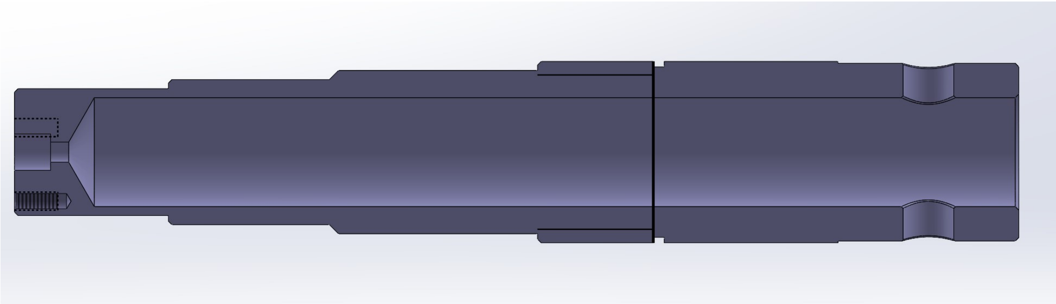
SPINE
CILINDRICHE
DIN 6325
temprate (m6)

ISO 8734
UNI 6364 A

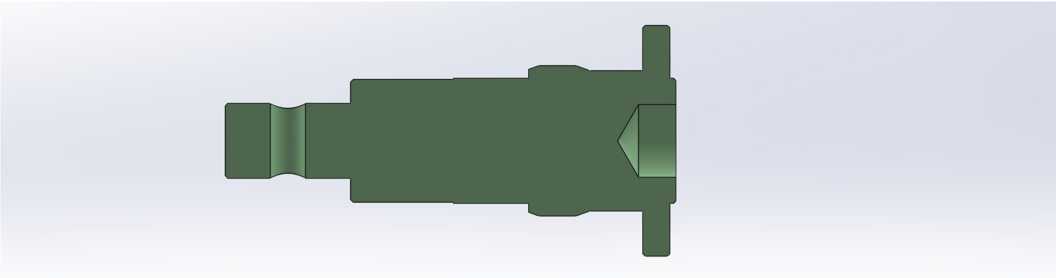
L	tolleranza	d (m6)	descrizione	Prezzo IVA escl. Euro/100	Variazione Prezzo % 1	Variazione Prezzo % 2	Confezione	a ≈	c
55.00	± 0,75	14.0	**14 (m6) X 55**	**160,00**	10,00%	-	50	2,0	4,0

Figure 6.45: Selected safety pin

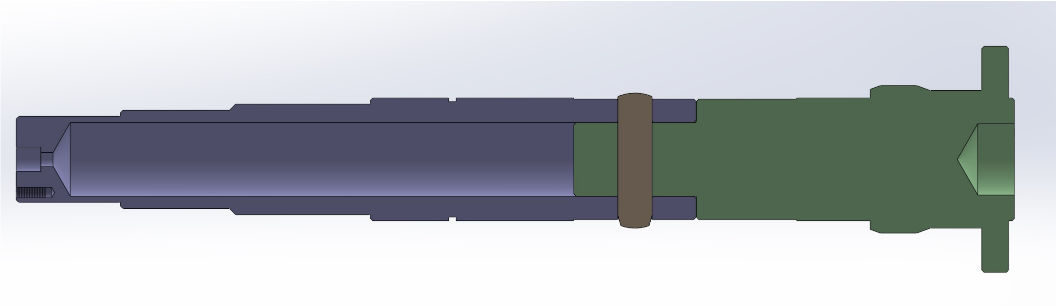
To prove the feasibility of the solution, the joint is model on software Solidworks and results are shown in Figure 6.46.



(a) *Secondary Shaft* - first part



(b) *Secondary Shaft* - second part



(c) *Secondary Shaft* - assembly

Figure 6.46: *Secondary Shaft* with safety pin joint (Solidworks)

6.2.3 Corrective actions analysis

To solve the two chronic loss factors affecting "SECONDARY SHAFTS" subsystem, it will be necessary to change the main structure of the three shafts, core elements of the system.

To reduce vibrations at tripods joint level, it will be required the joint modification, but not in an invasive way. Three possible proposals are recalled here:

- Bolt securing washers: it is necessary to add a spacer in mild steel, to make the washers be able to grip the surface and so locking the screws in their place;
- Modify splined profile: it will need the re-design of just a portion of *Tripods Splined Shaft* and *Splined Shaft*;
- Re-design of *Splined Shaft*: obtained through the design in a single piece of the element, which will require the replacement of both *Splined Shaft* and *Tripods Spline Shaft*.

All the three solutions, put here in order of invasivity, won't actually determine high modification costs, since the three machining operations required could be easily performed by the plant itself, in its tool-room.

Instead, the second issue faced by the present work will require a more invasive intervention, which has to be validated and approved first by the CRF (*Centro Ricerche Fiat)*: the design is not present in previous test benches' versions nor was proposed by the machine maker, so the approval will follow a more strict path. Moreover, it will be necessary to perform punctual tests about the pin's material, by contacting the supplier or by running the test in FCA Group. In both cases, an extra time to validate the solution will be required.

Chapter 7

Conclusions

The test benches' *know-how* acquisition took 6 months of work and study to be accomplished, together with the collaboration of two key plant institutions, namely Quality and Maintenance Departments, and the machine maker company, Thyssenkrupp Italia.

Main steps towards machine knowledge acquisition are represented by the following actions and documents produced:

- a complete and detailed **test bench guide** to its sub-systems and main components, in the form of a document called *Scomposizione Banchi di Delibera Thyssen*;
- detection of benches' **control parameter** and their optimal working ranges, listed in the X Matrix document;
- solid basis to build **AM and PM cycles** of the machine, using the QM Matrix tool; by punctually apply them, the *Zero Defects Conditions* of test benches will be ensured.

Note that the standardised method of Quality Control Pillar steps followed, results to be fundamental for this Thesis' goal achievement: the author was guided stage by stage, investigating on test benches' nature and reasoning to find reliable solutions to main issues discovered.

In particular the application of the Advanced Kaizen tool allowed the kaizen Team to verify and practically use the mechanical data and information acquired during the preliminary study of test bench *Thyssen5*, especially consolidating the knowledge acquired over "PRIMARY SHAFT" and "SECONDARY SHAFTS" subsystems. Moreover, it made possible the resolution of several issues aroused over previously mentioned groups, getting the bench rid of two impacting *abnormal* *noise sources*, i.e. the primary shaft's bearings and the unscrewing of the splined connection between *splined shaft* and *tripods splined shaft*.

So that being the Thesis targets achieved, herein is proposed an impact analysis of the applied solutions' and an overview of future works to be implemented on Thyssen test benches.

7.1 Impact of implemented corrective actions

As the reader who has been through the study till this point will know, of three corrective actions proposed by the present work, only one of them is effectively applied: it is the new bearings arrangement and grease to solve overheating problem of "PRIMARY SHAFT" sub-system. About secondary shafts re-design ideas to fix their issues, deployment time will be longer, since it is needed the approval of Manufacturing Engineering Department.

Even dough some corrective actions are still in a preliminary stage, studies carried out allowed Mirafiori Meccanica's specialists to acquire two important skills:

1. to intervene on test benches' issues and breakdowns independently from the machine maker company;
2. to understand how the machine works, in order to improve its structure and reliability, bringing test benches in the *Zero Defects Conditions* status, thus saving both time and money related to maintenance activities.

It is remarkably relevant to underline how important is the ability to act autonomously on benches' chronic loss factors: as said many times, fall within this meaning all machine's issue causing *abnormal noise* levels, which may badly affect NVH records, thus increasing the fake scrap declared by the test bench.

Since fake scrap has a direct impact on Quality KPI called DRR (see paragraph 4.3), beneficial effects of Advanced Kaizen I should be pictured by the indicator's trend. In Figure 7.1 it is proposed the *Direct Run Rate* evolution in terms of relative increase or decrease on the monthly value.

To recall to the reader how the indicator should be interpreted, note that having a DRR of 100% means that all items tested at the End Of Line (i.e. the test wenches) are compliant and ready to be delivered to the costumer, so that the plant's target is typically as close as possible to the maximum value. That is why having continuous DRR increases can be seen as a positive sign.

Nevertheless, a fair data interpretation makes impossible to charge all DRR beneficial effects upon the bearings overheating resolution: every week the plant employees and managers carry on kaizen and corrective actions to improve the

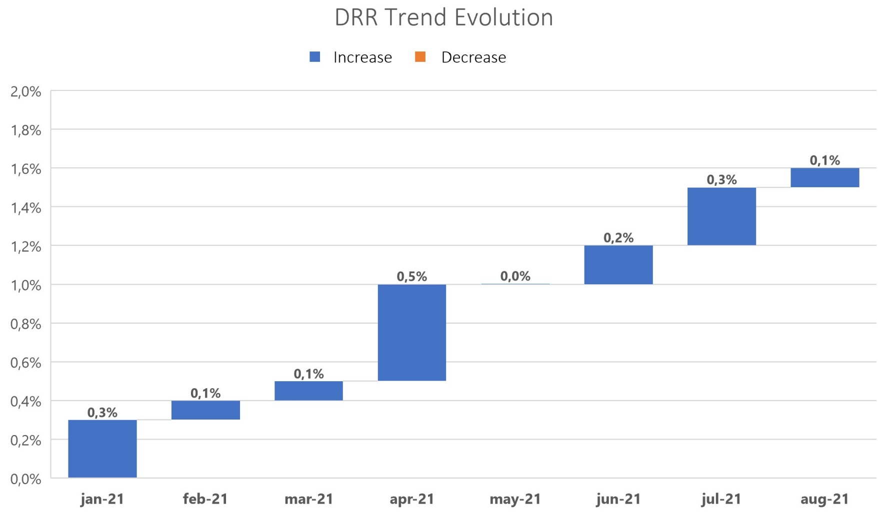


Figure 7.1: DRR trend from January to August 2021

plant scorecard, so that inside the DRR value converge also other corrective actions' effects.

To be unequivocally sure that the smoothing of primary shaft's *abnormal noise source* had had a positive impact over test benches, let's analyse TH5 scrap causes as they are recorded by the UPS software. In Figure 7.2 is proposed a picture of test benches scraps month by month. For confidentiality reasons all generic C5.14 defects causing the scarp are grouped under the voice «REAL SCRAP», while all gearboxes which didn't pass straight the control cycle, but were declared compliant after further checks, are named «FAKE SCRAP».

After the maintenance intervention on primary shaft's bearings in June 2021, the level of fake scrap on TH5 considerably decreased. It is considered a positive sign, highlighting the beneficial effect determined by the bearings and grease replacement. It can be pictured in an alternative way by thinking about the NVH curves: with respect to fixed thresholds, common to all benches, *Thyssen5* showed an higher "test bench noise", which pulled higher the gearboxes curves and caused an inevitable fake scrap increase, as now more and more gearboxes are closer to the thresholds. The maintenance operation brought back test bench's noise level to original conditions, which are now comparable and in accordance with the established thresholds.

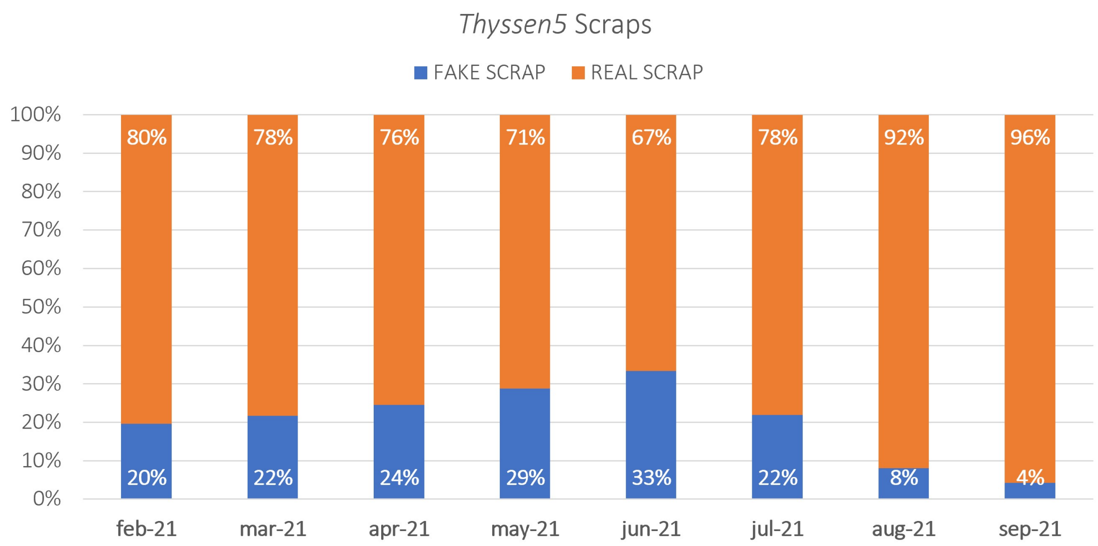


Figure 7.2: Decreasing of fake scraps levels over test bench TH5

7.2 Future development

Even dough results presented right above are symptom of a good work developed on Thyssen test benches, their enhancement has just begun. Because of temporal limits, the study could not face and solve many other smaller issues detected on TH5, that once fixed will further improve benches' efficiency.

Just to mention a few examples, regarding mainly minor problems related to the bigger issues addressed in Chapter 6, here is proposed a list of what to do next:

a. collect precise information about splined connection wear, in order to pick and implement one of the three solutions proposed in paragraph 6.2.1;

b. extend the new lubricant grease used in Group 214 also to Group 213 (see Table 5.1 for references), so that the lubricant LI EP 00 at high viscosity will be used only for slide-ways and not for bearings;

c. since intervention over primary shaft's bearings, and eventually on point *b*, requires the modification of the hydraulic system's layout with respect to the grease circuit, it has to be re-evaluated the pressure of the system (actually set to 2.5 *bar*) and the pressure transducer position, finding the new farthest position from the grease tank, which will be no more Gr. 214.

d. intervene on all test benches to align them, so that they will have the same elements, spare parts and structure's layout.

These are only few ideas of how is possible to enhance test benches, all deriving from improvements already set up on *Thyssen5*, but now nothing stands between the maintainers knowledge and other bench's sub-systems that could be improved. Having now a solid *know-how* of them, knowing in which way the machine is build on and what are its critical and sensitive components, the plant has the key to finally manage properly and autonomously Thyssen test benches. In particular, test benches knowledge and efficiency will be completed as the QM Matrix will be filled in, so that AM and PM cycles will be regularly applied.

Hoping that the study will go on, with all tools and skills available to do it, present Thesis work for Mirafiori Meccanica plant ends here.

RINGRAZIAMENTI

Queste pagine rappresentano per me il termine della carriera universitaria, e il lavoro che ho svolto presso Mirafiori Meccanica è stato un primo assaggio di ciò che vorrei fare *da grande*. Sono tante le persone che mi hanno accompagnato durante i cinque anni al Politecnico, sia da vicino che da lontano, ma tutte indifferentemente hanno saputo trasmettermi tanta passione e forza per concludere al meglio delle mie capacità il percorso di studi.

Ringrazio la mia professoressa e relatrice Francesca Maria Curà, che con pazienza e gentilezza mi ha guidato non solo durante lo sviluppo della presente tesi, ma anche durante la tesi triennale e il tirocinio: a lei mi sono rivolta per questi passaggi chiave dei miei studi, perché in lei non ho trovato una docente attenta e preparata, una persona gentile e umana. Grazie prof, perché ha saputo essere per me l'esempio brillante di *Ingegnere* che vorrei arrivare ad essere in futuro: sicura, professionale, umana.

Ringrazio le altrettanto importanti figure professionali che hanno addolcito e reso naturale il passaggio dai banchi del Poli alle scrivanie degli uffici di una grande azienda come Stellantis. Grazie al mio tutor Alessandro Giazzi e ai suoi collaboratori Riccardo Stigliani, Gino Martelloni, Andrea Rovera, Marco Parola, Gerardo Rosata ed Eduardo Nicolella. Grazie al mio specialista meccanico preferito Enrico Sinigaglia e al suo superiore Riccardo Zanni.

E Paolo: a te va il ringraziamento più grande, per avermi insegnato tutto, ma davvero tutto quello che era possibile nei 6 mesi in cui abbiamo condiviso la scrivania. Grazie per avermi insegnato cosa vuol dire essere un Ingegnere di Qualità e soprattutto cosa vuol dire *Lavoro*: grazie per avermelo insegnato con pazienza, disponibilità e allegria.

Ringrazio i miei compagni Ludovica, Francesco e Antonio: i vostri sorrisi e le vostre parole sono state il tassello fondamentale per costruire un'esperienza universitaria piena e bella e unica. Siete stati la mia casa lontano da casa e avete saputo portare gioia e un pizzico di follia anche qui. Grazie per essere i miei *Amici*.

Ringrazio Debora, che invece mi sopporta da molto più tempo, ma a cui voglio un bene immenso. Grazie per l'infinita pazienza che hai nell'ascoltarmi e consigliarmi, sempre.

Ringrazio il mio *Amore*, Alessandro. Non potevo chiedere una compagnia migliore per questi due anni passati così inseparabilmente insieme e non potrei desiderarne altra per tutti gli anni che verranno. Grazie per aver reso interminati gli spazi che abbiamo condiviso e aver costruito attorno a me una casa dolce e sicura. Grazie per come sei, per come mi fai sorridere, per come mi fai sentire. Grazie.

Ed infine, l'ultimo e più importante ringraziamento va alla mia *Famiglia*. A mio zio e ai miei nonni, per la dolcezza con cui mi state accanto sempre, nelle piccole cose come nelle grandi sfide che intraprendo: grazie. E alla mia mamma, per aver sacrificato tanto e avermi trasmesso un senso infinito del dovere: è per te che non ho smesso di impegnarmi un attimo in questi anni ed è per noi che continuerò ad impegnarmi, sempre di più, sempre più avanti. Grazie per aver sofferto con me durante i giorni brutti e per aver gioito con me durante quelli belli.

Grazie mamma.

Grazie a tutte le persone che ho incontrato in questi anni, amici, colleghi, professori: tutti in un modo o nell'altro avete contribuito a questo traguardo, anche sena saperlo. Grazie perché con l'aiuto e il sostegno di chi ti sta accanto, tutto è possibile davvero.

Grazie.

Bibliography

[1] Edoardo Frittoli. "Lo stabilimento FIAT Mirafiori compie 80 anni: storia e foto". In: *Panorama* (2019). DOI: https://www.panorama.it/economia/lo-stabilimento-fiat-mirafiori-compie-80-anni-storia-foto (cit. on p. 4).

[2] FCA Italy Spa. "Mirafiori PWT Presentation". In: (2021) (cit. on pp. 4, 5, 8).

[3] AAVV. *Gruppo Fiat*. URL: https://it.wikipedia.org/wiki/Gruppo_Fiat#Storia (cit. on p. 4).

[4] AAVV. *Fiat Chrysler Automobiles*. URL: https://en.wikipedia.org/wiki/Fiat_Chrysler_Automobiles (cit. on p. 4).

[5] AAVV. *Fiat Mirafiori*. URL: https://it.wikipedia.org/wiki/Fiat_Mirafiori#La_nascita (cit. on p. 4).

[6] Alessandro Fasana and Stefano Marchesiello. *Meccanica delle vibrazioni*. CLUT, 2006 (cit. on p. 30).

[7] AAVV. *World Class Manufacturing*. URL: https://it.wikipedia.org/wiki/World_Class_Manufacturing (cit. on p. 33).

[8] AAVV. *Total Productive Maintenance*. URL: https://it.wikipedia.org/wiki/Total_Productive_Maintenance (cit. on p. 33).

[9] AAVV. *Lean Manufacturing*. URL: https://en.wikipedia.org/wiki/Lean_manufacturing#Key_principles_and_waste (cit. on p. 33).

[10] Marica Nardiello. *Miglioramento indice FTQ nell'ambito del pilastro Quality Control in FCA*. Master Thesis Politecnico di Torino, 2019 (cit. on pp. 34, 39).

[11] Luigi Cuffaro. *Creazione di un sistema di manutenzione dei calibri di delibera finali linee ingranaggi secondo le linee guida del WCM in FCA*. Master Thesis Politecnico di Torino, 2020 (cit. on p. 34).

[12] Quality Engineering Team. "Quality Control Pillar Presentation". In: (2019) (cit. on pp. 39, 42).

[13] AAVV. *Kaizen*. URL: `https://en.wikipedia.org/wiki/Kaizen` (cit. on p. 43).

[14] Lean Manufacturing. *Chapter 5. Autonomous Maintenance. Part 1*. URL: `https://leanmanufacturing.online/chapter-5-autonomous-maintenance-part-1/` (cit. on p. 51).

[15] Lean Manufacturing. *World Class Manufacturing PM – Machine Ledger and PM Calendar*. URL: `https://leanmanufacturing.online/world-class-manufacturing-pm-machine-ledger-and-pm-calendar/` (cit. on p. 51).

[16] Lean Manufacturing. *Chapter 8. Quality Maintenance. Part 1*. URL: `https://leanmanufacturing.online/chapter-8-quality-maintenance-part-1/` (cit. on p. 51).

[17] SKF Group. *Rolling Bearings*. SKF, 2018 (cit. on pp. 72, 90, 92, 93, 95, 96, 100–102, 104, 106, 109).

[18] Bernd-Robert Hohn Gustav Niemann Hans Winter. *Manuale degli Organi delle Macchine*. Tecniche Nuove, 2006 (cit. on pp. 73, 125, 127).

[19] KEYENCE ITALIA spa. *Sensori di flusso ad abbraccio*. KEYENCE ITALIA, 2021 (cit. on p. 79).

[20] POGGI Spa. *Trasmissioni Meccaniche - Cinghie e Pulegge Poly-V*. POGGI, 2017 (cit. on pp. 86, 87, 95).

[21] NSK Motion and Control. *Rolling Bearings*. Gruppo Bianchi, 2018 (cit. on pp. 90, 99).

[22] NSK Motion and Control. *NSK Calculation Tool*. URL: `https://www.jp.nsk.com/app02/BearingGuide/html/bearing78983.htm` (cit. on p. 99).

[23] Petronas. *PETRONAS Grease Li EP 00 and Li EP 0* (cit. on pp. 99, 101).

[24] SKF Group. *SKF Bearing Select Tool*. URL: `https://www.skfbearingselect.com/#/one-or-two` (cit. on pp. 100, 103, 108, 109).

[25] Gandini Fasteners srl. *SPINE CILINDRICHE, CONICHE E AD INTAGLI*. URL: `https://www.gandini.it/www/spine/index.cfm?languageid=it&fuseaction=lst&idcat_articoli=4&idsottocat_articoli=I050` (cit. on p. 127).