POLITECNICO DI TORINO

Master's Degree in Mechanical Engineering

Analysis of a bearing production line to improve performance

Thesis supervisor:

Prof. Maurizio Schenone

Graduating student:

Mario Casale

Thesis co-supervisor:

Dr. Paolo Silvestro

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Summary

Abstract

This thesis work was born following an internship experience at the company DMI-Divisione Meccanica Industriale s.r.l. located in Cassino (FR), which works in the field of development and production of industrial machinery, prototyping of components and automated systems for the various SKF plants around the world. The project, subject of this thesis, concerns a complete revamping of an entire production line of deep groove ball bearings (DGBB) destined for the SKF plant in Sopot, Bulgaria.

The revamping process had as its ultimate goal to create an automated production line, which has the following advantages:

- Greater flexibility
- Faster speed
- Increased productivity through less set-up times, downtime and reduced errors
- Higher quality and less waste thanks to sensors that monitor production in real time
- Greater product competitiveness thanks to greater functionality resulting from the interconnection of machinery

The first step towards the realization of the project was the definition of the line layout respecting the bearing production process, from the grinding of the rings to the final controls, and the design of the transfers made by means of motorized conveyors.

Subsequently, a complete revamping of the pneumatic and electronic components was carried out for each of the machines, while each worn mechanical part or in need of improvement was designed by optimizing its characteristics through FEM analysis within the R&D area. As regards the electronic part, importance was given to the possibility of developing a machinery from an industry 4.0 perspective, favouring the interconnection of machinery aimed at centralizing production data and improving the production process which also passes through the implementation of a User-friendly Human Machine Interface (HMI).

For the pneumatic components, on the other hand, the final objective was the optimization of the consumption of compressed air and the improvement of the production and safety standards of each machinery.

Given the large number of machines that made up the line, during the development of the revamping activities, I concentrated on three machines, which the know-how of DMI s.r.l. established to be key machinery for the correct operation of the line in order to maintain a high production performance. The machines in question are:

- MIB OR, measuring machine that checks and measures the outer diameter, taper and taper of the outer ring;
- XHM80, a machine that performs bearing pairing by plastically deforming the OR and inserting the balls between the two rings;
- MVM, a machine that detects and measures the vibrations and noise of the kitchen by rotating the inner ring and holding the OR stationary.

In addition to assisting in the revamping activities, I studied the ISO 12100 and 13849 regulations which allow you to perform an assessment of the risks of the machine and a reduction of the same with consequent management of the residual risk.

For each of the machines analysed, I performed the testing and evaluation tests, in particular I performed statistical evaluation tests of the quality of the measurement systems according to SKF standards, with the help of the Minitab software. At the end of the revamping process of each of the three machines and with the results of the efficiency tests of the machines in hand, I carried out a research activity regarding the improvements that could be made, some then implemented and others not, to each of the three machines in order to improve the operating performance of the line.

The MIB OR machinery, at the end of the revamping process, was analysed in terms of instrument capability and repeatability and reproducibility and it was possible to evaluate the reliability of the measurements of this machinery. My research, however, led to the conclusion that the creation of an automated process control would certainly have increased the operating performance of the line.

The MIB OR, in fact, performs a measurement activity on the outer rings which are ground by the CL machine placed off-line and whose dimensions do not allow a large number of machine stops given the time required to stop the wheels which amounts to more than 5 minutes. Therefore the idea was to detect, thanks to the installation of the GME III owned by SKF, any conditions of out of control of the grinding process and implement the possibility of sending compensation signals of the working parameters to the CL to try to obviate the operating problems of the machine without the need to activate a machine stop every time, leaving this last possibility in the event that the feedback command has no beneficial effect (for example in the case in which the out-of-control conditions derive from an excessive wear of the grinding wheel).

As for the XHM80 machinery, however, the analysis of the efficiency of the operation of the machinery consisted of an assessment of the instrument capability and linearity of the measurement of the machinery. The results of these analyses highlighted the reliability of the machinery. At this point I started a research activity to look for solutions that would allow to increase line performance; none of my proposals, however, was deemed appropriate and I report the reason below.

The first proposal was to use a probe, certainly more precise than the current conical measuring mechanism, to detect the measurements of the IR ring before pairing the bearing as the range of variation of the IR measurements exceeded the micron and the number of rejects made as a result of these measurements was too high. The observation, although correct, was not followed up as the implementation of a probe would have been too expensive. At this point I put forward the idea of using GME III to create an automated process control to correct the raceway lapping machinery of both the outer and inner ring, but in this case it would have been necessary to add two Post- Process immediately after the aforementioned grinding machines as sending a correction signal after the different machining phases that the rings, before reaching the XHM80 had undergone, would have led to the rejection of all the rings on the line between the grinding machines and the XHM80. The second hypothesis of improvement was also discarded due to the costs that its implementation would have led to sustain.

The last machine I analysed was the MVM machine. First of all, unlike the previous machinery, the MVM machinery was subjected to a statistical analysis of quality by attributes rather than by variables as it was sufficient for the machinery to evaluate the ability to recognize a good bearing from a bad one simply by measuring the vibrations of 50 master bearings whose characteristics were known. Having detected the ability of the machinery to perform reliable measurements, I concentrated on carrying out functional tests online by analysing bearings assembled and greased in the company. These tests, thanks to the use of the BVR+ software, capable of performing a frequency analysis of the vibrations generated by the rotating bearing, but above all of recognizing the cause of the bearing discard, have highlighted the presence of numerous dirty bearings. My research activity has therefore concentrated on finding a solution to the dirt accumulated in the bearing; research that led to the need to add demagnetizers and washing machines to the line to help clean the bearing and remove dirt. This solution, as can be seen from the layout presented initially, has been implemented and the number of waste due to dirt has significantly decreased.

In the last days of my internship, I dedicated myself to researching further improvements that can be made to the machinery, but also to possible applications of the line from an industry 4.0 perspective. Therefore, at this stage I have deepened my knowledge about SCADA systems and MES and ERP software that allow production control, but not only. In addition to what has just been said, I have dedicated myself to the study of product traceability using vision devices. The last chapter of this thesis is therefore dedicated to the future developments of the line including further improvements.

1 The Companies: SKF Industries S.p.A. and DMI s.r.l.

This paper comes from an internship experience carried out at the DMI-Divisione Meccanica Industriale S.r.l. which is a company located in Cassino (FR). DMI S.r.l was founded in 2001 and replaced the previous company that had worked in collaboration with SKF since 1960. The company has developed thirty years of experience in the development of machinery, prototyping of components and automation systems, refurbishment of machinery and SKF bearing production lines.

Picture 1 – DMI-Divisione Meccanica Indutriale S.r.l. plant

Thanks to the high degree of competence that the company has developed in the field and through continuous R&D activities, it fits well into the modern production reality, being able to complete important challenges in terms of production quality and delivery times. Currently the company plays a fundamental role in the entire production process of various SKF production plants around the world; in fact, although the market of DMI

S.r.l. has developed at 360° in the world of the closest SKF plant in Cassino with which it shares a Just-in-Time warehouse for most of the line machinery, other collaborations with SKF factories are important like the ones with SSBC or ATC of Shanghai and Tortuguitas in Argentina up to those with the SKF plant in Puebla in Mexico, Pune and Bangalore in India.

The company's know-how is mainly developed around three macro-categories of machinery related to SKF production lines:

- Grinding machinery;
- Bearing assembly machinery;
- Ring (both IR-Internal Ring and OR-Outer Ring) and the complete bearing control machinery.

For each of these machines, the company develops the project in turn-key mode, starting from feasibility and budgeting analyzes up to the production of mechanical components, purchase of electrical and pneumatic sales, assembly and CE certification including technical documentation.

The company carries out two types of work:

- A direct proposal to the customer about prototypes aiming at optimizing both the process and the final product;
- An order, which follows a technical specification sent by the final customer; and it is precisely to this category that the project object of this thesis belongs.

2 The Project

Following a request for a complete revision of a bearing production channel for SKF in Sopot (Bulgaria), DMI evaluated the possibility of a machinery complete revamping. The desire to upgrade the machinery towards an industry 4.0 production perspective comes from the need to provide a qualitatively better product with reduced and optimized production costs. The modernization of the machinery towards a 4.0 perspective is mainly developed with the implementation of new and more performing electronics capable of allowing the on-line data to come from the machinery in the production phase.
The possibility of completely replacing the electronic part of the machines allows you to install the necessary technology such that on each machine it must be possible to obtain through the hardware, in 4.0 industry application:

- Digitization (Computerization): the first step is to digitalize the product, making it capable of providing digital data that can be analyzed in the later stages of the process. This is done through the introduction of electronic boards and sensors which, in addition to acquiring the significant data of the machinery, make the human-machine interface (HMI) more advanced and intuitive. With the introduction of an electronic board of this type on board of each machine, it is possible to obtain several advantages including: greater ergonomics, functionality, flexibility and above all more information for the operator who manages it, ensuring an increase in productivity;
- Connectivity: the second step is to equip the machines with remote connectivity. The initial choice of hardware is always made with this in mind, and wired or wireless connection modules are provided such as Ethernet rather than Wi-Fi or Bluetooth, to name just a few examples. The innovation process in this step consists of the collection of Machine to Machine (M2M) data, from the machines sold all round the world, that are brought together centrally on a remote server in the cloud (Cloud Computing) or on a local server in the customer's company;
- The predictive ability: the next step is to process all this huge amount of data using analysis and forecasting algorithms. Thanks to AI and Machine Learning, it is therefore possible to create alert systems, configure predictive maintenance and

failure prevention processes that have the great advantages of increasing safety and reducing machine downtime. The advantage of this phase lies in the possibility of predicting, on the basis of data from all the machines sold in the world, which piece is about to break and replace it before that more damage is created on the machine, thus avoiding an interruption of work more long and therefore more costly in terms of lost productivity;

- The other great advantage that can be obtained from the digitalization process of its products from an Industry 4.0 perspective is the commercial one: the sale of the machinery can be accompanied by a 4.0 after-sales assistance and maintenance package based on remote monitoring. In this way it is possible to introduce a new strategy from which both the producer and the customer have a benefit: a broader commercial offer for the former, a more advanced and efficient product with better after-sales assistance for the latter.

The objectives of the project are:

- Greater flexibility;
- Faster speed;
- Greater productivity through less set-up times, downtime and reduced errors;
- Higher quality and less waste through sensors that monitor production in real time;
- Greater product competitiveness thanks to greater functionality resulting from the interconnection of the machinery.

Thanks to the refurbishment, an integrated system will be created whose benefits are:

- Bidirectionality and proactivity: production scheduling can immediately become executive in the department and the operators in the department and / or the system itself can alert the scheduling office in real-time on any critical issues encountered (broken machine, problems in the order of production which is running, etc.);
- Correlated and aggregated information: the system feeds and pervades the entire company, offering multiple users the ability to operate simultaneously - each according to the assigned skills and responsibilities - by correlating information between factory and business processes. The algorithmic power that for years has been the privilege of a few, is wisely distributed over several people, through simple and immediate use interfaces;

- Visibility: the factory ceases to be a "black box" and becomes "transparent" thanks to a system capable of guaranteeing maximum real-time visibility to each actor involved in Planning and Execution activities (administration, commercial area, technical office , production planning, logistics, warehouse, shipping);

Furthermore, the interconnection of the machines with a MES "Manufacturing Execution System" guarantees:

- Precise calculation of the performance indices of production plants;
- Automation of data collection, interfacing with processes and production progress;
- Real-time reporting of critical events to take corrective actions in time;
- Process traceability;
- Timeliness and accuracy of the data collected;
- Measurement of consumption;
- Real-time production OEE;
- Setup of automatic production lines with considerable time reduction and configuration errors reduced to zero.

2.1 Product and Production Process Analysis

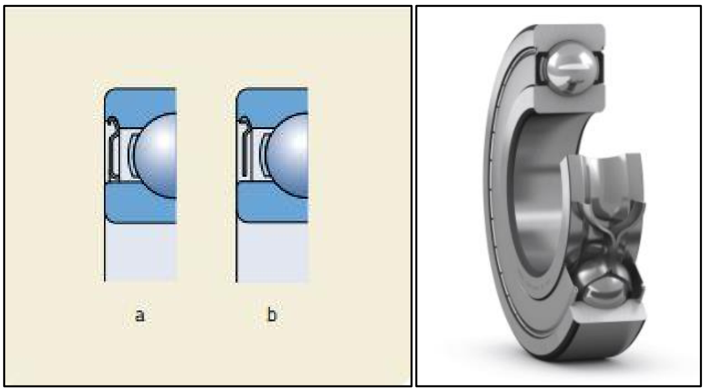
2.1.1 The Product

As already mentioned, the revamped production line is dedicated to the production of rolling bearings. The term rolling bearing is used to describe that class of bearings in which the main load is transferred by means of elements in the presence of rolling contact rather than sliding one [8]. In the particular case of study, the considered production line has to do with radial bearings with a single row of stainless steel balls.

Single row deep groove ball bearings are particularly versatile, suitable for high or even very high speeds, robust and they have minimal maintenance requirements. They can support axial loads in both directions as well as radial loads, even at high speeds. Single row deep groove ball bearings are the most widely used of all bearing types and are available in a wide range of SKF designs and sizes.

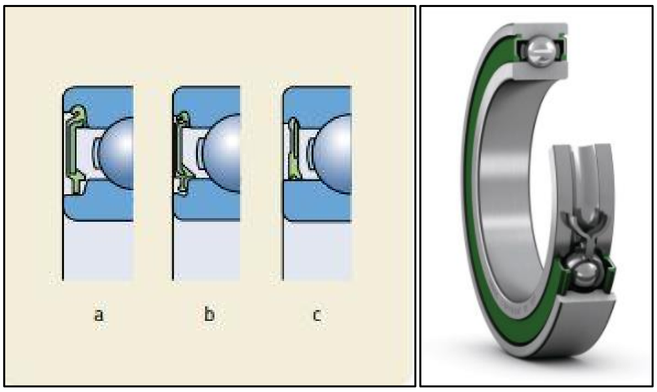
In the particular case analysed we are talking about a bearing 6306 type, which is executed by the production line in the following types:

- 6306-Z/2Z: bearing with a shield in stamped sheet metal on one side of the bearing (Z) or on both sides (2Z). This type of bearings are intended for applications where the inner ring rotates, in fact if the outer ring were to rotate there would be problems with the lubricating grease leaking from the bearing; [9]



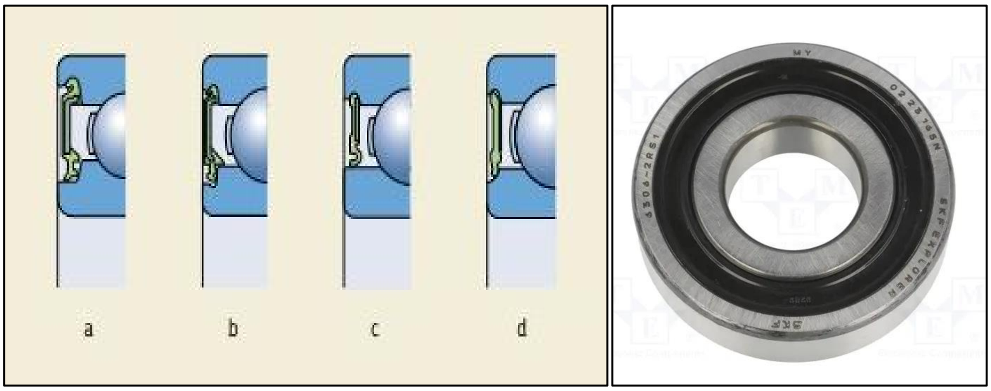
Picture 2 - SKF 6306-Z bearing type

- 6306-RZ/2RZ: bearing with low friction seal in acrylonitrile butadiene rubber (NBR) with a stamped sheet metal reinforcement on one side of the bearing (RZ) or on both sides of the same (2RZ). These bearings allow operation at the same high speeds as bearings with Z shielded bearings, but are more effective in terms of sealing. The choice of gasket material, namely NBR, guarantees good wear resistance and a wide range of operating temperatures (-40 ÷ +100°C for continuous use and up to 120°C for short periods); [9]



Picture 3 - SKF 6306-RZ bearing type

- 6306-RS1/2RS1: bearing with contact seal in acrylonitrile butadiene rubber (NBR) with stamped sheet metal reinforcement on one side of the bearing (RS1) or on both sides (2RS1). The gasket is the same as in the previous case, but, in this case, applications involving high speeds or high temperatures could lead to grease leakages [9].



Picture 4 – SKF 6306-RS1 bearing type

- 6306-TN9: injection moulded cage in polyamide 6,6, of the snap type centred on the balls.

Picture 5 – SKF 6306-TN9 bearing type

2.1.2 The Production Process

The production process of a bearing can be considered essentially composed of three phases:

- Grinding of the rings: at the beginning of the production cycle, the rings are processed separately on two different channels as it can be seen in the next paragraph (see layout diagram). Only at the end of the IR and OR grinding processes, which coincides with the beginning of the assembly phase, the two channels join and the rings will form a pairing to which components will gradually be added;

- Bearing assembly: after the grinding phase, the rings and the balls form a pairing to which cage, grease and shield will be added;
- Dimensions and quality controls along the entire production line.

Let's, now, analyse the production cycle specifically.
The raw material of the considered production process consists in both internal and external rings machined externally to the SKF plant, for which the revamping is analysed, through plastic deformation, turning and heat treatments operations. The raw material is subjected to controls before the production cycle begins, in particular a control of hardness and dimensional characteristics such as hole diameter IR, raceway diameter for both IR and OR and thickness of both rings is carried out. After having passed the inspection phase, the rings are subjected to grinding. Grinding is a machining operation by chip removal in which the cutting tool is the single abrasive grain. Since the single abrasive grain removes only a small amount of material, a large number of grains working together are required to obtain higher removal rates; this is accomplished using bonded abrasives, typically in the form of a grinding wheel. [4]. The machining of the internal-IR and external-OR rings have to be considered separately.

- Inner ring grinding process:
    - Facing Operation: this operation allows to grind both faces of the inner ring;
    - Raceway grinding operation;
    - IR hole grinding;
    - Raceway lapping operation: lapping is a finishing operation suitable for flat or cylindrical surfaces. By means of fine-grained abrasives, it is possible to obtain dimensional tolerances in the order of ±0.4 μm with a surface roughness R_a in the range 0.025-0.1 μm [4].
- Outer ring grinding process:
    - External diameter grinding operation;
    - Raceway grinding operation;

- Raceway lapping operation

After the grinding operations have been completed, the assembling phase begins.
The operations that are carried out in order to assemble the bearing also include controls and are listed below:

- Pairing operation;
- Caging operation;
- Free running inspection;
- Vibration measurement;
- Radial clearance measurement;
- Greasing operation;
- Shield insertion operation;
- Shield control;
- Laser marking operation;
- Addition of the protective film operation;
- Visual inspection.

The production cycle just defined is the starting point for defining the layout. In the specific case study, the SKF production line already had a layout but a new definition of the latter was necessary as can be seen from the next chapter.

2.2 The Machinery

In this paragraph, I want to carry out an analysis, accompanied by a quick description of the operation, of the revamped machinery that will make up the SKF production line. As for the description of the production process, also in this case the grinding machines will be divided according to whether they work on internal or external rings.
For the machining of the inner ring, the machines are the following:

- CD IR - The machine is designed and built for ring hardness control;
- Pre-Process IR – Hole diameter, thickness and raceway diameter measuring machine;
- SPC 62B - Ring face grinding;
- SGB 55 - IR raceway grinding;

- SHG 55 - IR inner diameter hole grinding;
- MIB IR - IR inner diameter and taper measuring machine;
- Demagnetizing and washing machines;
- IRL - IR raceway lapping;
- Demagnetizing and washing machines.

For the machining of the outer ring, the machines are the following:

- CD OR - Ring hardness controlling machine;
- Pre-Process OR - Thickness and raceway diameter measuring machine;
- CL 660 - OR outer ring grinding machine;
- MIB OR - OR outer ring and taper measuring machine;
- SSB 80 - OR raceway grinding;
- FSF - OR raceway lapping machine
- Demagnetizing and washing machine.

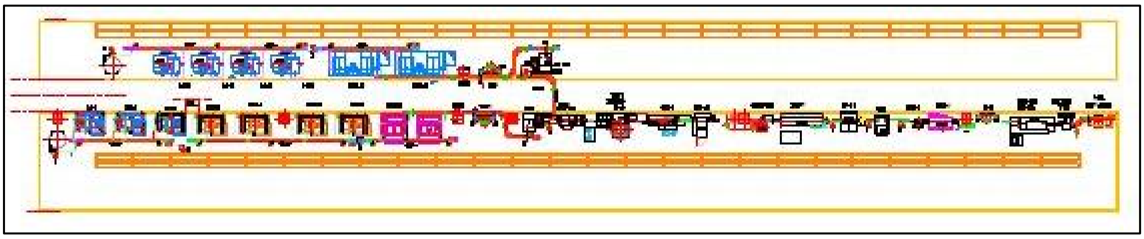
For the side of the line, concerning pairing and controlling machines, the machines are:

- XHM 80 - Matching rings and insertion of balls;
- HWA - Riveted/Clamped Cage Assembly;
- TN9 - Plastic cage insertion;
- Demagnetizing and washing machines;
- MYD – Smoothness of the motion control;
- MVM - Measurement of bearing noise and vibrations;
- MGI - Radial clearance measurement of DGBB bearings;
- HHM - Weighing and subsequent greasing of the bearing;
- LBM - RS/Z bearing shield insertion;
- MXI - Shield controlling machine;
- Component control scale;
- Laser marking machine;
- Spray Running - Addition of protective film;
- Visual inspection;
- Manual Packing.

2.3 Layout Analysis

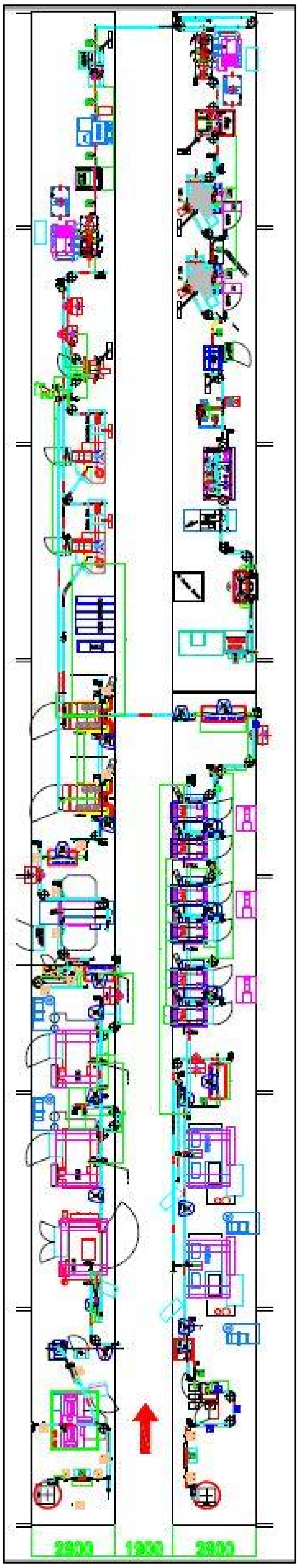
2.3.1 Layout definition

The first step of the revamping process covered by this thesis was the definition of the layout. The study of plant layout has become one of the most important sectors of industrial engineering; in general, a study of the plan layout is carried out when there is a need to change the arrangement of the machines within the available area or when improvements are made in correspondence with one or more production processes [5] (both of them are characteristics of the problem of study).
The production line to be reconditioned had a linear layout for a total length of 58m and is reported in the following picture 6.



Picture 6 – SKF production line initial Layout configuration

The first request for the work commissioned to the DMI-Divisione Meccanica Industriale S.r.l. was the evaluation of a possible reduction in the length of the line. For this purpose, the several layout possibilities were analysed until some were proposed to SKF and the one in the following Picture 7 was approved with a reduced total length of 50.5 m.
At first, it was verified that the type of layout was suitable to meet the production requirements. The layout configuration has been kept linear considering to create an automated production line.

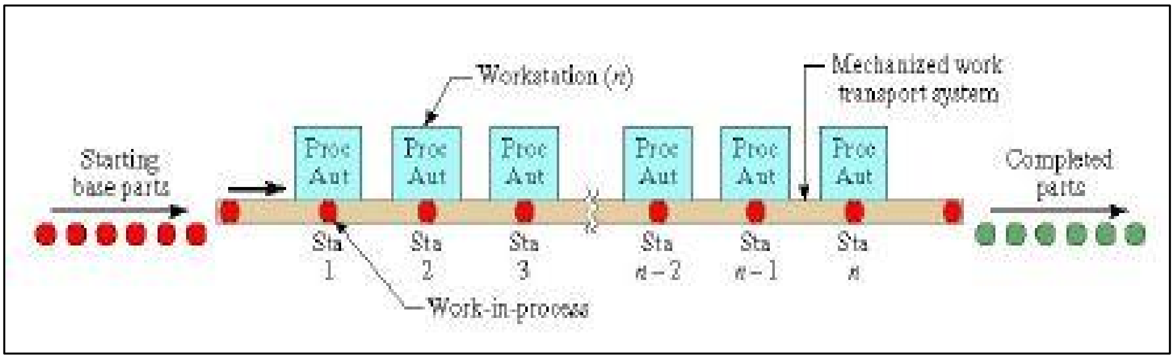


Picture 7 – Layout SKF production line

The use of an automated production line is justified because different products (4 bearing types) are produced in batches by the system, since changeovers are required. Other considerations carried out for the choice of this kind of production system are:

- High demand, requiring high production quantities;
- Stable product design, because frequent design changes are difficult to accommodate on an automated production line since the sequence of the processing operations could change requiring a change in the order of the machines in the line;
- Long product life, at least some years;
- Multiple operations performed on the product during its manufacture.

It is important to highlight that the machines are installed linearly in a well-defined order, strictly correspondent to the product production cycle. In a more deep analysis the layout is segmented in-line, this means that it is composed by three line segments perpendicular to each other, resulting to be, specifically, a U-shaped layout.
Looking at the layout Picture 7 and at the Picture 8, a raw work part enters one end of the line, and the progressing steps are performed sequentially as the part progresses forward. The line include inspection stations to perform intermediate quality checks.



Picture 8 – Automated production line scheme

Each station performs a different operation, so all operations must be performed to complete each work unit. Multiple parts are processed simultaneously on the line, one part at each station. The line is balanced, the processing times of the machines are equal so that no buffer are strictly needed. Although the line is balanced, the need for intermediate buffers, in the event of a machine breakdown, has been evaluated taking into account the possibility of accumulating the workpieces on the belt upstream of the machine subject to failure.

The advantages of the application of an automated production line will be:

- Low amount of direct labour;
- Low product cost, because the cost of the fixed equipment is spread over many units;
- High production rate;
- Minimal work-in-process (WIP) and manufacturing lead time;
- Minimal use of manufacturing floor space.

2.3.2 Material Handling System

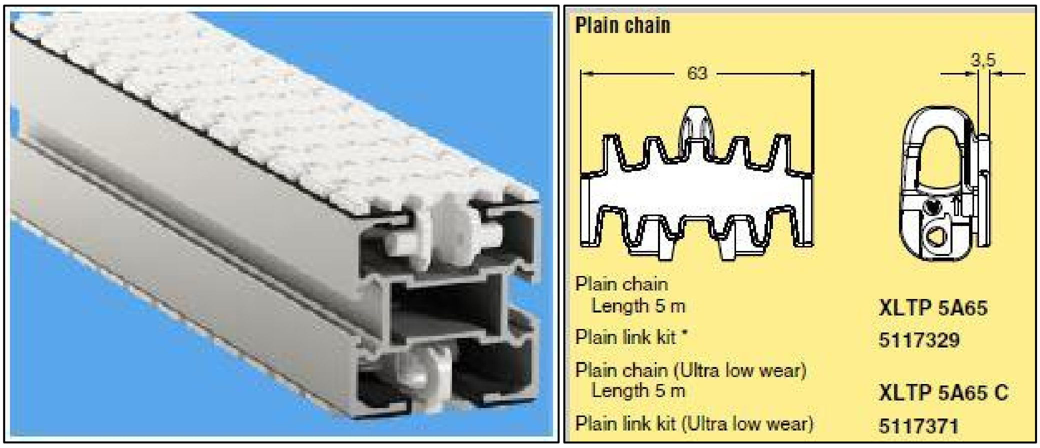
Material handling system means the transport and management of materials along the production line. From the times when transport was carried out using almost exclusively the effort of man, the technique of transport has developed in the direction of a lower use of human energy: the most varied devices suitable for transforming new energy sources into useful work, have in fact replaced the effort of man.

The study of internal transport can allow the achievement of the following objectives:

- Limit costs thanks to:
  - A smaller number of material handling and recovery;
  - Fewer routes;
  - Better use of space;
  - Increased productivity;
- Reduce waste and losses;
- Improve working conditions in the sense that
  - Ensuring greater safety;
  - Requiring less effort;
- Increase the efficiency of the company [5].

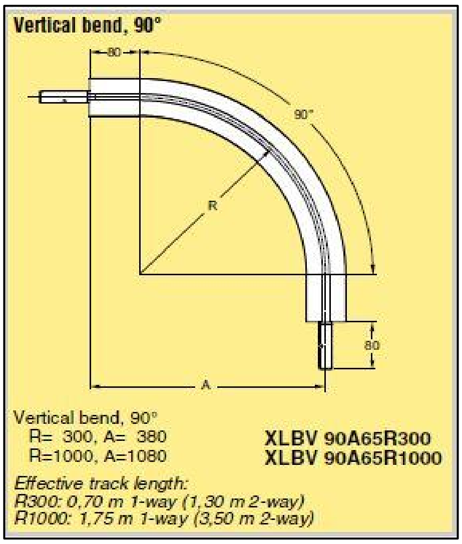
In the case study, the handling of materials along the line was designed using a Flexlink conveyor based on aluminium with low friction slide rails guiding a plastic multi-flexing chain. By using this Material handling system it is possible to make the product to be conveyed travel directly on the conveyor. The particular conveyor system used in the

X65-Flexlink (see Picture 9) which is suitable for a wide range of applications, such as ball bearing or gear wheels transport, and preferable in high speed applications.
The chain used has a plain configuration characterised by a ultra-low wear and a width of 63 mm (see Picture 9).



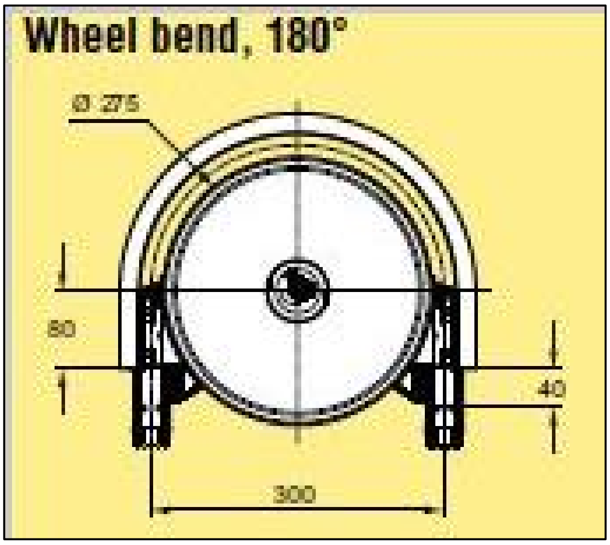
Picture 9 - Flexlink X65

It is important to underline, from the layout, how height increases were necessary both to load some machinery such as grinding machines and to allow the crossing of the internal region of the production line. This crossing is necessary both for the re-joining of the two channels IR and OR and to allow the line to close on itself in correspondence with the machines that carry out the controls on the bearing at the end of the line. Therefore, if the basic height of the conveyor along the line is 900 mm, with this height increase it reaches 2500 mm.
In the stretch of re-joining the IR and OR channels, the height increase is obtained using vertical bend 90 ° as in Picture 10, which works like an elevator.



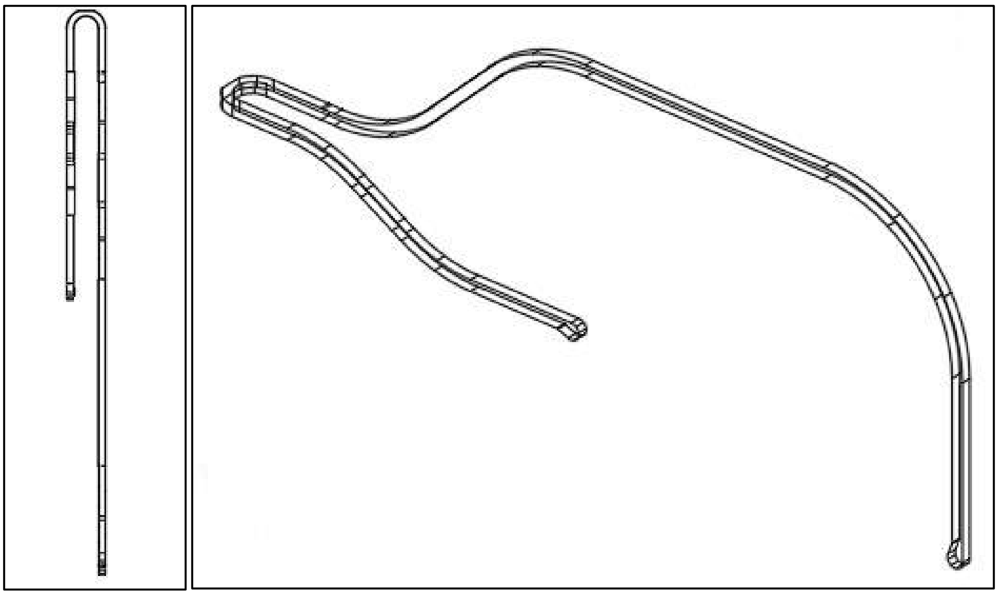
Picture 10 - Vertical bend 90°

On the other hand, the section of line which follows the MVM machine and crosses the internal region of the channel is made by using the same elevator previously presented for the raising phase, while the descent one is made by using a 180 ° curve with the presence of the suitable wheel (see Picture 11) and two inclined sections.



Picture 11 - Wheel bend 180°

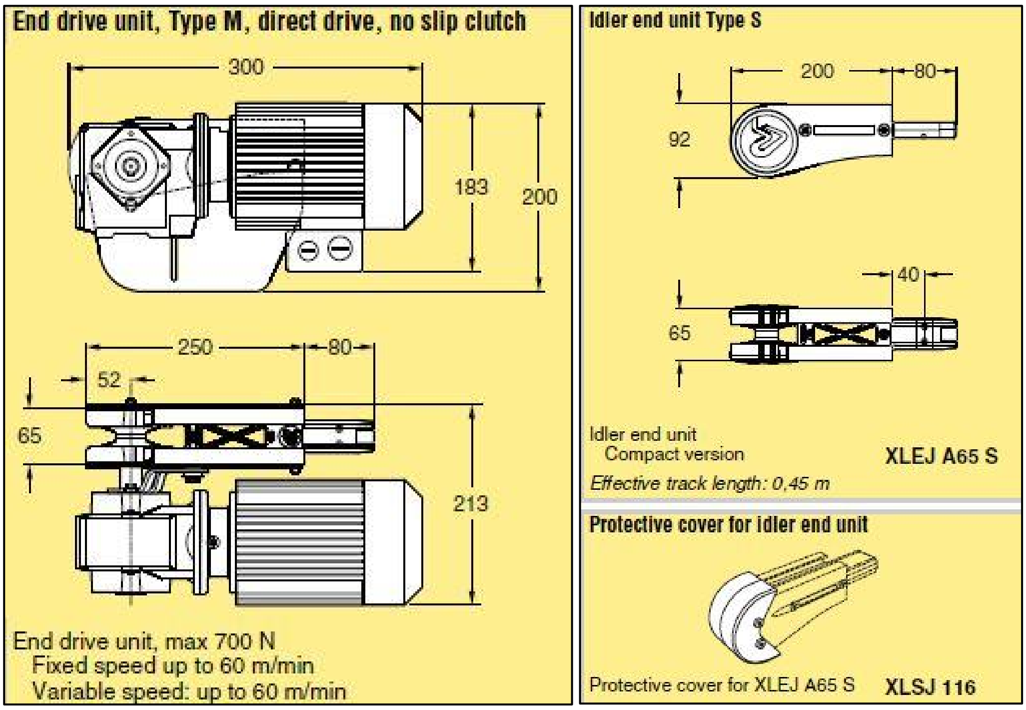
The drawing of the path just presented is reported in the following Picture 12.



Picture 12 - Bearing path after MVM machine

Another important feature of the material handling system designed is the presence of selectors along the line. These selectors allow the alternating feeding of the same machines, as in the case of the grinding machines on the IR and OR channels, or they allow the feeding of different machines depending on the processing operation required by the processed bearing, as in the case of HWA or TN9, which respectively insert the steel or plastic cage.

X65 conveyor system includes end drive unit and idler unit necessary to assure the movement of the material handling mechanism. These components have been chosen from a wide range depending on the speed and transmission required. The required movement is a continuous movement at a medium speed, therefore the chosen components are shown in the following Picture 13.



Picture 13 - End drive unit and Idler end unit

2.4 The Revamping process

Revamping is a term born in the railway sector to indicate general restructuring interventions involving all the systems of a locomotive or passenger carriage. First of all, the components are disassembled and checked, carrying out extraordinary maintenance on them to bring them to a level of performance that is as similar as possible to the new product. In current language, the term revamping often has multiple meanings even if they are nuances of the same concept, therefore it is necessary to define it in the context in which it must be considered to avoid confusion.

In the context in question, revamping means the replacement of parts and/or integration of the original project, with mechanical and electrical solutions in order to reduce production costs, the size of the machines, to increase the reliability of the control system with consequent savings on installation and maintenance activities [3].

A very important aspect of the revamping is that this modernization action leads to a higher degree of machinery safety. This is not always true, but only applies under certain conditions, as in most cases new hazards are introduced due to new functions of the revamped machine, which must be adequately reduced with the interventions identified by the risk assessment [1].

A brief note should be made about the difference between these three words, often used indistinctly without knowledge of the facts: revamping, retrofitting and restyling. Revamping is a process intended to extend the life of a machine/plant, also in relation to any regulatory updates on safety; retrofitting, on the other hand, is a process intended for both the replacement of worn and obsolete components and the implementation of new functions and systems that were previously absent.

Finally, the restyling is a process related mainly to the aesthetic aspect and can be better interpreted as a restructuring but without actions to improve functionalities. To be precise, it can be stated that what would actually be called retrofitting is often understood as revamping, as it would not make sense, in most cases, to perform a pure replacement of worn components with others of the same characteristics (otherwise would be necessary a provision for a further replacement in a relatively short time) [1].

Picture 14 - Clear example of revamping: the original components were replaced with new components with similar characteristics, while only the control system was completely replaced

Picture 15 - Clear example of retrofitting: the new car has nothing to do with the original, as almost all components have been removed and replaced with equipment with additional functions

Picture 16 - Clear example of restyling: the components have been cleaned, replaced or fixed, but no functions have been added

2.4.1 Advantages and disadvantages

The choice of whether or not to carry out a revamping must be well thought out and has both advantages and disadvantages. The first advantage is, without any doubt, the adoption of recently built command and/or control systems and this implies the automatic presence of interfaces ready for the 4.0 industry revolution, as well as with the new computerized systems the average repair time decrease, since the machine directly indicates the problem to be solved and the procedure to follow.

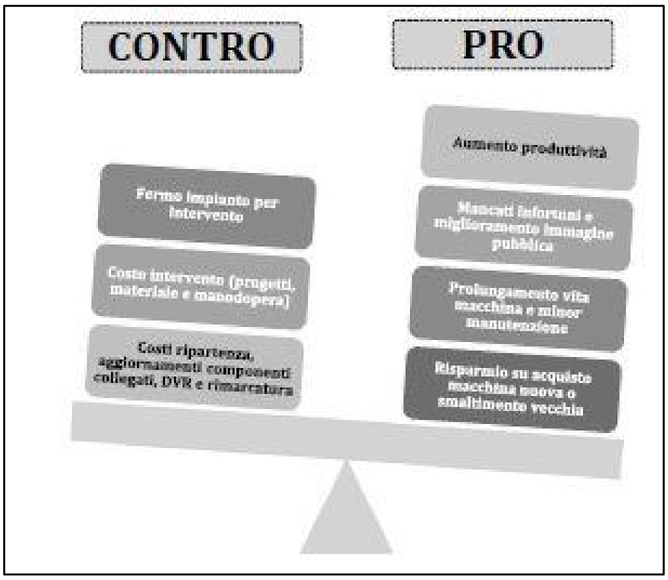
Another important aspect is the guarantee of compatibility: by replacing all or part of the original components with new parts, the availability of spare parts is guaranteed for an almost unlimited time. It can often happen that, in the event of a broken component of an old machine, the owner is faced with the problem of finding a spare, if not original at least compatible; in this case, the alternatives are custom-made manufacturing or the adoption of additive manufacturing technologies, applicable only on condition that you have the original design or at least the possibility of reproducing it with low cost technologies.

Last, but not least, is the advantage that comes from economic savings. Thanks to its experience in the field, the DMI S.r.l. estimates that, for ordinary and non-special machines, with a correctly designed and executed revamping it is possible to save from one third to two thirds of the cost of a new machine with the same characteristics but more recent than the one subjected to revamping.

Among the disadvantages of performing a revamping, for the company owning the machinery/plant, the most relevant is certainly the need to temporarily block the operation of the machine/plant to be modernized for the time necessary for maintenance interventions. This block, which is especially necessary when complete disassembly, sending the machinery to external companies and subsequent reassembly are needed, can be particularly long [1].

The experience of DMI S.r.l. suggests a duration of 3-4 months for a revamping intervention on a single machine. In the case-study, a complete revamping of a production line, the time necessary to carry out all the operations was 6 months, but, for the line another 1-2 months will be required to be operational again. This time is needed for installation and setting up of the machinery.

As regards the aspects just noted, which can be considered the most important in the choice of whether or not to execute a revamping, it seems quite obvious that performing a revamping is always the best choice that the company that owns the machinery / plant can make (this is highlighted in the following figure 17).



Picture 17 - Convenience of revamping execution

To weigh the choice carefully, however, it is also necessary to take into account other aspects that have not been considered so far and which can be listed as follows and they can be divided among advantages and disadvantages.
We can therefore definitively say that the positive aspects that characterize the execution of a revamping intervention are:

- Higher revenue due to the increased productivity;
- Lack of cost due to the accidents avoided following the safety measures;
- Greater revenue that possibly derives from the improvement of the company's image;
- Savings on any PPE (Personal Protective Equipment) no longer necessary after the intervention;
- Savings on frequent maintenance due to sudden breakages with consequent, but frequent, downtime;
- Savings deriving from the use of easily available components for future maintenance and on any repairs under warranty;
- Savings on the purchase of a new machine and on the disposal of the old one.

The negative factors to be analysed before choosing to perform a revamping intervention are the following:

- Loss of money due to the stoppage of machinery for a time necessary to carry out the intervention;
- Cost of repairs, materials and labour used;
- Costs due to the restarting of the machines/plant;
- Costs due to the CE marking at the end of the intervention and the updating of the risk assessment document (DVR);
- Costs for the operators training;
- The loss of revenue resulting from a possible resale of the old machine, as functioning;
- Cost of any software or hardware updates also for other company equipment and/or adjustments to existing systems [1].

2.4.2 Revamping procedure followed by DMI s.r.l.

The procedure that allows the execution of a revamping, according to the company know-how of DMI S.r.l. consists of the following passages:

- Dismantling of mechanical, pneumatic and electrical parts;
- Machinery Cleaning;
- Painting;
- Assembly of mechanical parts with completion of missing parts;
- Assembly of electrical panel according to machine directive 2006/42/CE;
- Assembly of the pneumatic system according to the 2006/42/CE machine directive;
- Construction of safety guards according to ISO 14120;
- Machinery analysis of risks according to ISO 12100;
- Machinery testing and validation;

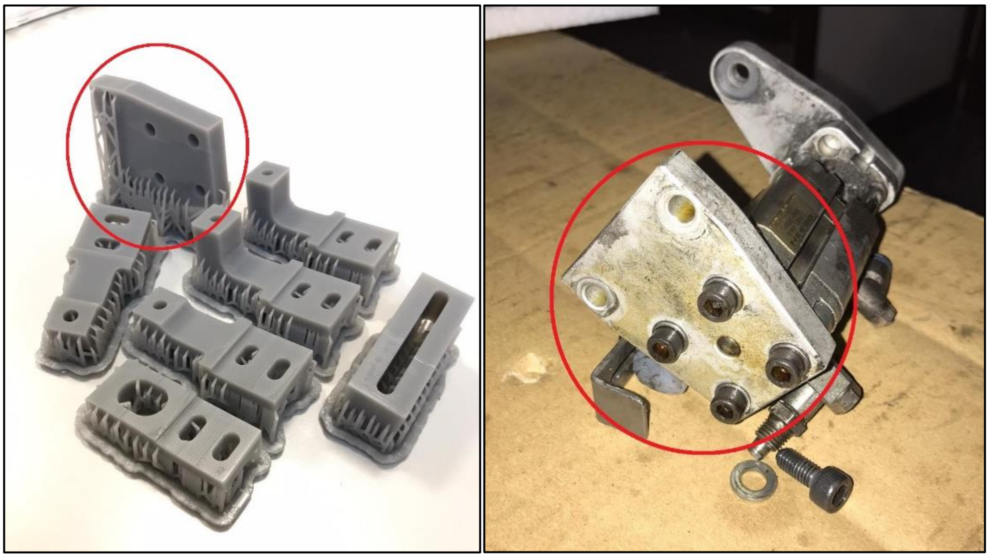
2.4.2.1 Revamping of mechanical components

Therefore the first step involves the complete dismantling of the machinery, and the assessment of the state of the mechanical components of the latter. The company know-how foresees that the quality of the screws and their size are evaluated in order to reorder the corresponding commercial products, the bearings are replaced as well as the springs. The springs will be of a stabilized type as the stabilization treatment allows the product to be guaranteed the acquisition of specific mechanical properties, as well as the subsequent maintenance of the elastic memory typical of springs over time. The degree of wear of the motion transmission components, from the slideways to joints and clutches, is then immediately detected; when the degree of wear compromises the mechanical functioning of the component, the latter will be redesigned. An example of completely damaged transmission components is shown in the Picture 18, here are represented two tooth clutches of a gearbox whose toothing is, for the one on the left, completely damaged while for the other the breakage of four teeth has occurred.

Picture 18 - Damaged tooth clutches of a gearbox

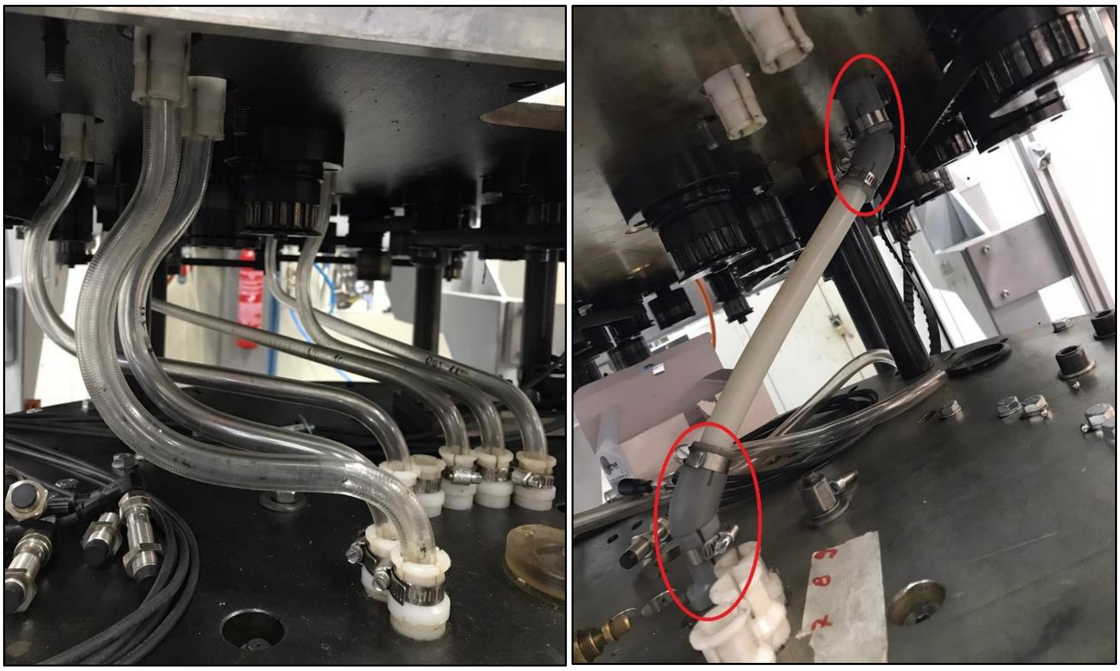
2.4.2.1.1 The use of 3D printing

An important aspect of the company know-how is the use of 3D printing for the realization of components to be replaced during the revamping phase, in particular this technology is used for connection and fastening components. The material used for 3D printing is photosensitive epoxy resin, specifically from the Tough and Durable family of resins produced by Formlabs which includes more robust, functional and dynamic materials, which can withstand compression, elongation, flexion and impact without breaking. These resins are to be taken into consideration in cases where bending at limited stress levels is preferable rather than breaking, and therefore it is ideal for designing connectors and fastening elements. An example is shown in the figure 19, where the 3D printed components are used to connect the pneumatic cylinder to the machine structure. The components are shown on the left, while the application of the highlighted one is reported on the right.



Picture 19 - Application of 3D printing on the pneumatic cylinder connection

3D printing technology also finds application in the production of components that improve the working conditions of others. In the Picture 20 we find the use of 3D printing to make the fixing components of the tube installed on the XHM80 machine that brings the balls from the respective drawer, selected by the machine after the measurement of the raceways of the rings, up to the bearing in assembly phase. In this case it was necessary to replace the tubes necessary for the descent of the spheres and to optimize the path of these avoiding excessive bending, the highlighted components have solved the further problem of the orientability of the tubes.



Picture 20 – Application of 3D printing on the fixing of pipes on XHM80 machine

2.4.2.2 Revamping of pneumatic circuit

2.4.2.2.1 Pneumatic cylinders choice and air consumption evaluation

After the mechanical revamping is completed, the pneumatic one starts.

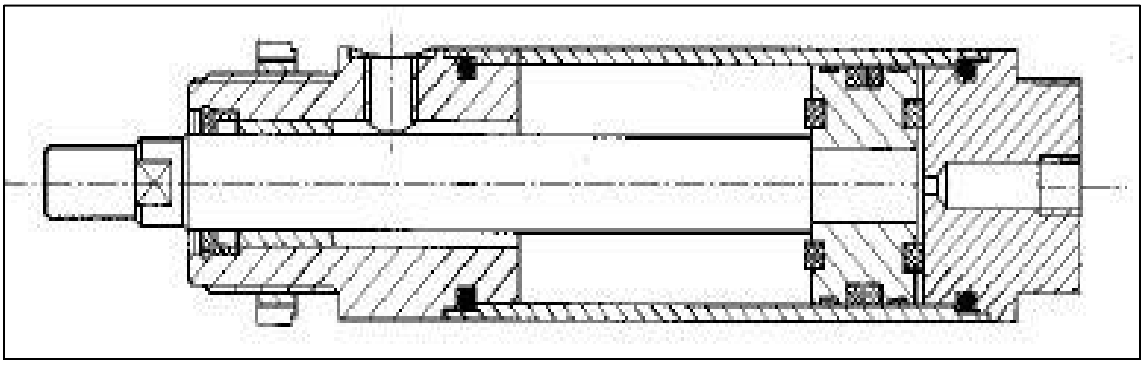
The revamping of the pneumatic component of the machinery begins with the dismantling of the pneumatic circuit previously installed on the machine, and replacing all the pipes that make up the compressed air distribution circuit to the actuators and with the evaluation of the status of the pneumatic cylinders. When the pneumatic cylinders are to be replaced (due to air loss and a decrease of the efficiency), they are purchased from the same supplier as the cylinders to be replaced; when this is not possible, a compatible ones are ordered and adapted. The cylinders installed on the machine must obviously satisfy the request to minimize the consumption of compressed air.

The actuators are the final organs of an automatic system: their function is to perform the operations controlled by the system; pneumatic cylinders, used in a normal revamping process by DMI S.r.l., are the most common actuators in compressed air systems.

They represent the main means by which to push sleds, lift weights, block workpieces, remove pieces, operate levers, etc. Pneumatic cylinders transform compressed air energy

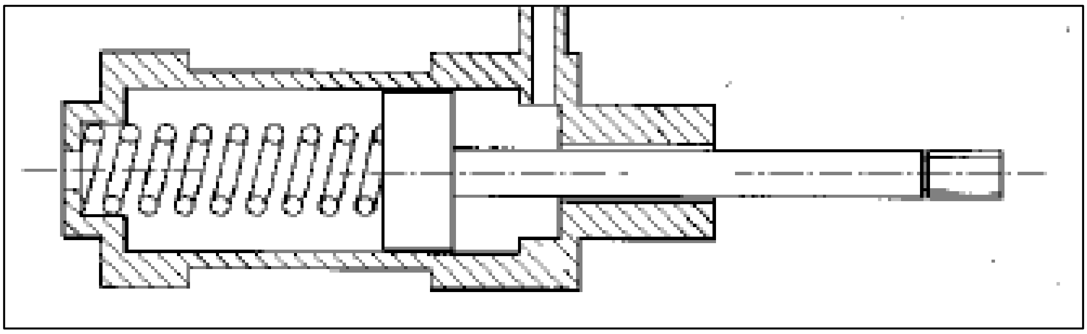
into mechanical work, producing forces that are proportional to the supply pressure used; it is therefore possible to obtain different performances with the same cylinder.
The cylinders are linear motors, as they produce a force which translates over a limited stroke. By means of mechanical adaptations (hinges, gear systems, etc.) it is also possible to obtain alternative angular rotations. The cylinders are divided into two groups, and are chosen by DMI S.r.l. depending on the applications required by the machinery for which the revamping is being carried out. The two categories are:

- Double-acting pneumatic cylinders: the cylinder can perform work both in the rod exit phase and in the re-entry phase. Obviously the two forces are different because, at the same pressure, the two surfaces of the piston on which the compressed fluid acts are different: in the rear chamber a part of the piston surface is occupied by the rod [3] (Picture 21). Double-acting cylinders are recommended, in any case, for large diameters and long strokes [2].



Picture 21 - Double-acting pneumatic cylinder

- Single acting cylinder: the return of the piston is given by a spring placed in the rear chamber. In this case the rear chamber does not have the air supply inlet and the cylinder performs the work only in the outlet phase [3]. These cylinders usually have a short stroke, between 20-50 mm, and are suitable for locking mechanical parts during certain processes. The possibility of compensating, by carrying out a more or less long stroke, any differences in size between different pieces make them suitable for both series and single piece machining [2] (Picture 22).



Picture 22 - Single acting cylinder

The air consumption, having chosen the cylinders that will make up the pneumatic system on the machine, for the machine is equal to the sum of the air consumptions calculated for each actuator, both in the push and in the traction phase; It has been evaluated being in the order of 1000 l/min.

For the thrust phase, the rod comes out, the following relationship applies:

$$Q_s\left[\frac{l}{min}\right] = \frac{\pi D[mm]^2}{4} \cdot c \cdot \left(p_{rel,esercizio}[bar] + 1\right) \cdot n\ [\frac{stroke}{min}] \cdot 10^{-6}$$

In case we consider the traction phase, the air consumption during the retraction of the rod is equal to:

$$Q_t\left[\frac{l}{min}\right] = \frac{\pi(\ D[mm]^2 - d[mm]^2\ )}{4} \cdot c \cdot \left(p_{rel,esercizio}[bar] + 1\right) \cdot n\ [\frac{stroke}{min}] \cdot 10^{-6}$$

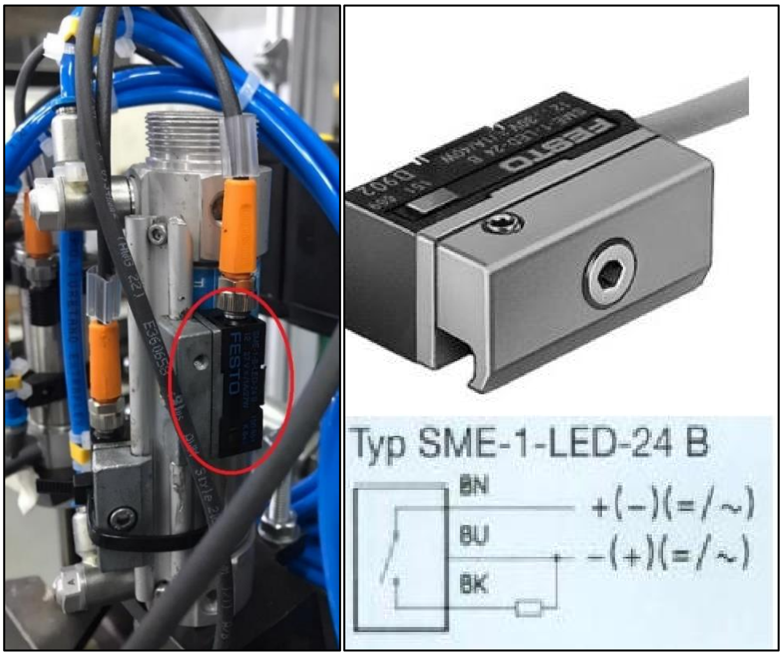
where:

- D[mm] is the bore diameter of the cylinder;
- d[mm] is the rod diameter of the cylinder;
- c[mm] is the stroke of the piston;
- $p_{rel,esercizio}$ = 4 bar is the working pressure (relative) of the machine;
- t [s] is the cycle time;
- $n[\frac{stroke}{min}] = \frac{60s}{t}$ is the number of strokes per minute of the piston.

2.4.2.2.2 Limit switches choice

The problem subsequently addressed by DMI s.r.l. in the revamping phase of the pneumatic circuit placed on the machine was the choice of the limit switches to be

implemented on the circuit itself; the choice, in particular, fell on the use of magnetic limit switches with Reed contact. Magnetic sensors, also called magnetic limit switches, are used to detect the position of the piston of a cylinder without placing limit switch elements in the movement area of the rod and to obtain a signal that can be used directly in electrical circuits. The use of magnetic limit switches requires to apply permanent magnets to the piston that produce a moving field with the piston itself (in this case DMI srl will use cylinders from Festo which in the identification code report -A which stands for adaptation for proximity sensor). The magnetic field is transmitted outside the barrel if the barrel itself is made of diamagnetic material (aluminium, brass, stainless steel).
Reed sensors are then placed on the outside of the barrel, with sheets in insulated phials, so that when the magnet is far away the contact is open and when the plunger is in correspondence with the Reed switch it closes [2]. The sensor used by DMI s.r.l. is a sensor from Festo, model SME-1-LED-24-B shown in Picture 23. Using these sensors, the examination of the status of the signals of a circuit is simpler as the latter are equipped with LEDs that indicate the presence of the electrical output signal. The sensors are fixed by directly using the tie rods of the cylinders (where they exist), or by introducing special external guides on which the Reed contacts can be inserted. Position adjustment is made easily with screw locking systems [2].



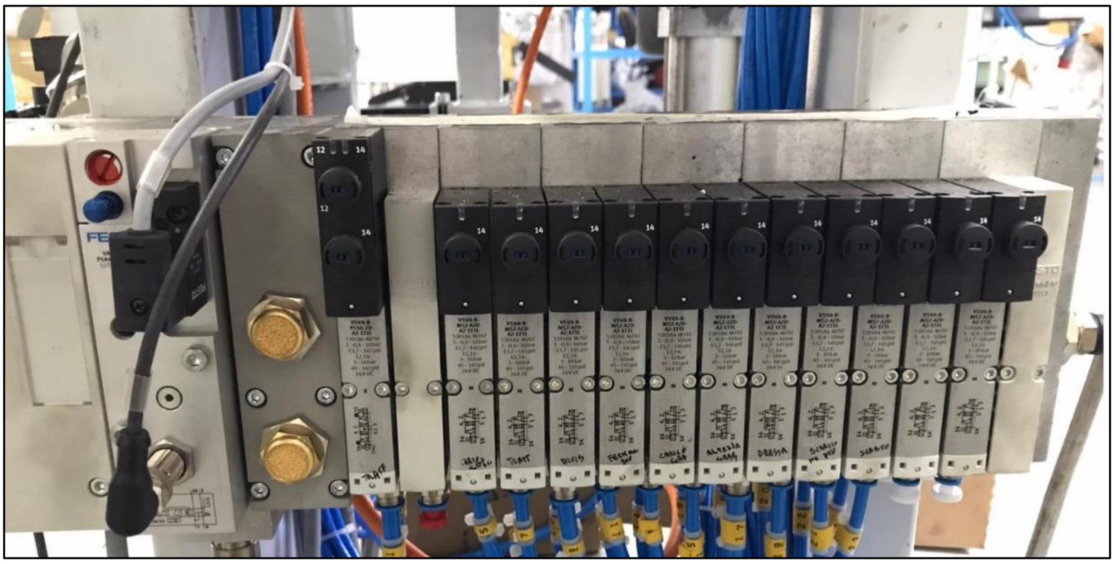
Picture 23 - Festo SME-1-LED-24-B, application and circuit

2.4.2.2.3 Distribution valves choice

In order to complete the process of defining the pneumatic circuit, it is necessary to identify the type of direction control valves (distribution valves) that perform the function of controlling the cylinders. These valves have the task of reversing the direction of the motion of the piston by reversing the air supply to the two chambers of the cylinder and can be controlled manually, pneumatically or electrically. The valves commonly installed in the pneumatic circuits on the machine by DMI s.r.l. belong to the last type and are called solenoid valves. In this case, the solenoid valves are used since a connection between the electronic control unit and the pneumatic actuation unit is required since DMI s.r.l. established that the control of the system will be entrusted to a PLC.
The solenoid valves installed on the machine are directly operated, this means that the coil solenoid acts directly on the control valve, determining its position without passing through a small pneumatic valve (in this case it would be indirect operation), and they are powered at 24 V in direct current (DC). Depending on the application, the valves used in the on-board system can be of two types: monostable and bistable. They are distinguished as follows:

- monostable valves: they switch when the coil is powered and therefore there is a command signal, but when the latter fails, they automatically return to the rest position; they are equipped with a single control coil and are provided with a return spring;
- bistable valves: they have two equilibrium positions, and to change position an electrical impulse is required which feeds the coil and when this disappears the valves belonging to this category maintain the last position reached; they are equipped with two control coils each of which is entrusted with the switching of the valves in one direction.

The on-board installation of the solenoid valves is performed by DMI s.r.l. taking advantage of the possibility of creating valve blocks via Festo valve terminals. The valve block can also be customized, leaving the possibility of integrating both monostable and bistable valves in the same block. An example of a valve block is shown in the Picture 24, where the VTSA valve terminal installed on the TN9 machine is shown.



Picture 24 - Valve terminal by Festo installed on TN9 machine containing both monostable and bistable valves

2.4.2.2.4 LFR unit installation

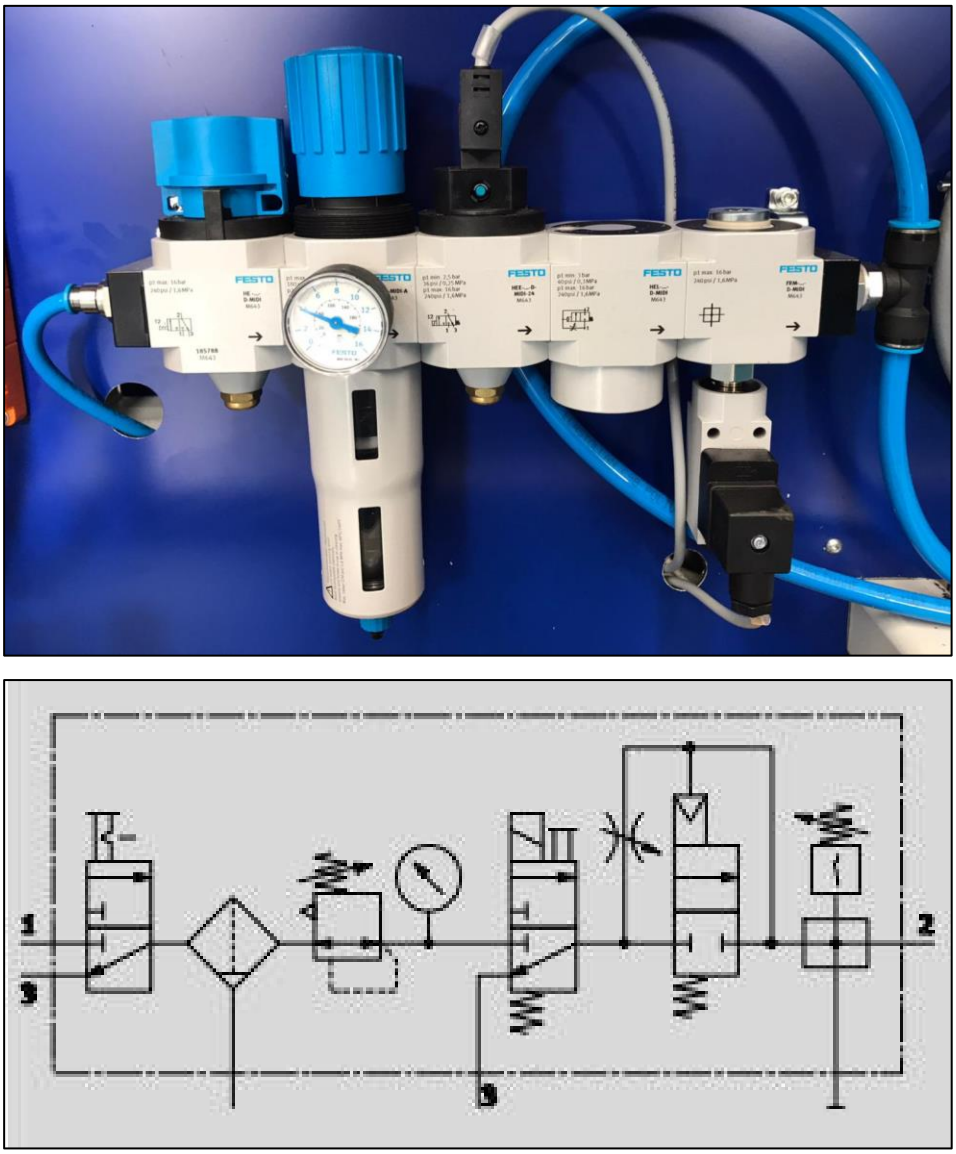
The last aspect, of fundamental importance, to be kept in mind when completing the revamping of the pneumatic component of the machinery is the need to treat the compressed air entering the machinery. Compressed air treatment is necessary to achieve the requirements of pneumatic equipment. The treatment operations consist either in a more or less strong filtration, in the reduction and stabilization of the pressure, and in the possible addition of suitable substances. In the general organization of the plant, the air treatment groups are placed in the places of use, upstream of the pneumatic equipment.
Filtration is an essential treatment of compressed air and has the purpose of cleaning the latter and eliminating the various impurities present. This protects the equipment and prevents breakdowns due to a mixture of dust, water and oil. In fact, the impurities present in the compressed air accelerate the wear of the pneumatic components, forming deposits that damage above all the seals, with consequent leakage and pressure losses.
Pollutants are contained in the form of solid particles, oil, water. Each of these pollutants is present in the air for specific reasons and requires a certain type of filter. Solid particles can be extremely dangerous both for an abrasion action and for an occlusion effect of small passage holes and are present because they are sucked in with atmospheric air. Traces of oil are present in the compressed air because vapours or oil drops are added to the compressor.

Compressed air treatment filters normally perform a double action, carrying out both mechanical filtration for solid particles and a condensate separation action by means of a centrifugation device. The condensate can be discharged automatically, semi-automatically or manually [2].

In the LFR group shown in Picture 25 by way of example there is a filter with automatic drainage which is equipped with a float that rises under the pressure of condensation causing the opening of a valve followed by the expulsion of the condensate which occurs thanks to the air pressure itself. The condensate level then drops, the valve closes and the expulsion cycle can continue automatically.

Pressure reducers are used to solve the problem of pressure changes that take place in the distribution lines of pneumatic systems; they reduce a high inlet pressure to a reduced and stabilized outlet pressure [2] (the pressure reducer in the LFR group in Picture 25 lowers the pressure to a value of 4 bar at the outlet) .

Lubricators are used in compressed air treatment units for equipment that requires the air to contain traces of oil for the correct lubrication of the sliding seals. Their function is therefore to add a certain quantity of oil, in the form of small droplets, in order to produce an aerosol that is carried away by the compressed air. Depending on how the oil atomization is produced, there are mist lubricators and micro mist lubricators [2]. In the LFR group shown as an example, the lubricator is absent.



Picture 25 - LFR compressed air treatment group installed on the MVM machine

The LFR unit shown above and implemented for the treatment of the air entering the MVM machine, is an integrated unit produced by Festo, model Service units LFR-K / LFRS-K, D series. In particular, we are speaking about the LFR-1/2-D-MIDI-KG-A model and is composed by:

- On-off valve HE manually actuated;
- LFR filter regulator;
- On-off valve HEE solenoid actuated, 24 V DC;
- Soft-start valve HEL pneumatically actuated;
- Branching module FRM with pressure switch.

As easily understood, the LFR group adopted by DMI s.r.l., on board the machines being revamped, is equipped with an extra valve in addition to the common two on / off valves: this is the soft-start valve. This valve is installed for system safety reasons.

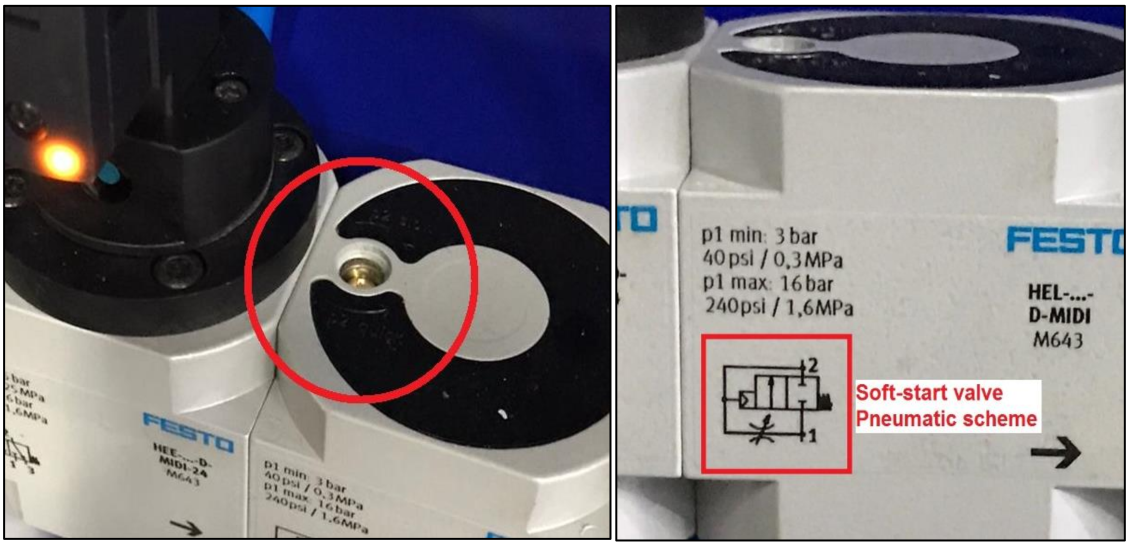
A problem that arises many times in pneumatic circuits is that related to the correct start-up of the equipment itself. In particular, it must be taken into account that the operating conditions of valves and cylinders depend on the values of the supply pressure and the applied signals.

When an equipment is connected to the compressed air network and begins to be supplied, a convulsive intake of air occurs which fills the various pipes with variations over time that depend on the characteristics of the circuit and which differ from case to case. During these rapid transients, the pressure values on the valve controls and in the cylinder chambers are not those of steady state; then irregular situations may occur, which cause unwanted motions of the actuators. The phenomenon is very important for those circuits whose pressure value is rather critical.

To avoid these operating irregularities, which can compromise the safety of the systems causing interference of the mechanical parts and damage, special soft-start valves can be used. For the management of complete circuits, these valves are inserted on the supply line of the circuits themselves and in fact constitute one of the functional blocks of the air treatment and supply units together with the filter, the pressure reducer, the lubricator and the on-off valves (this is the application of the soft-start valve preferred by DMI s.r.l.).

The function of the soft-start valves is to achieve a slow and progressive introduction of compressed air in the initial phase of filling the circuits. In this way, the air can fill all the points with the same progression, avoiding those pressure imbalances that occur in a rapid transient and that can cause uncontrolled movements. When the pressure has reached a sufficiently high level, to avoid problems, the entry is completed quickly [2].

The soft-start valve used by DMI s.r.l. during the revamping phase of the pneumatic systems on the machine, it is a two-port, two-position valve with a calibrated spring, controlled by the downstream pressure with an adjustable screw resistance placed in parallel. In Picture 26 the detail of the adjustment mechanism of the valve belonging to the LFR group presented previously and its pneumatic scheme are shown.



Picture 26 – Soft-start valve adjustement mechanism and pneumatic scheme

2.4.2.3 Revamping of electrical components

2.4.2.3.1 Electrical panel composition and installation

As regards the electrical components, DMI s.r.l. performed a 100% revamping for all the machines of the SKF production line under study. The first step of the revamping was the composition of the electrical panel starting from the choice of the box.

The electrical panel on the machine is the part of the electrical equipment that is normally used by the machine operator. In fact, it contains all the power equipment (switches for operation, contactors, automatic switches, drives, etc.) and control equipment (relays, programmable controllers, measurement and regulation devices, etc.) essential for the automatic operation of the machine.

Externally then, on the access door to the panel or on the other surfaces, for example the side ones, there are the various command organs (selectors, buttons), signalling (pilot lights), control (measuring instruments) that are normally used by the operator to operate the machine.

Hence the fundamental importance of the machine control panel which must be designed and built with very high standards of functionality, safety and reliability both in terms of use and maintenance.

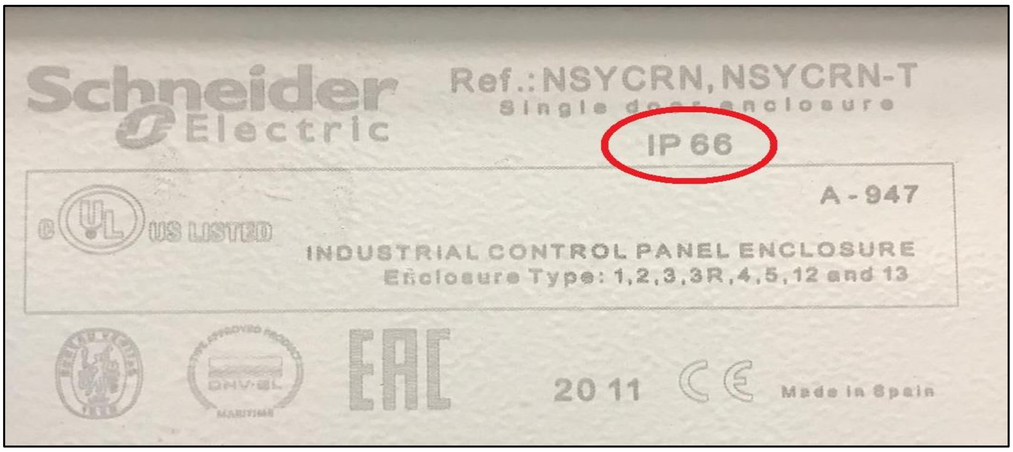
The Machinery Directive 2006/42/EC relating to machinery establishes the essential requirements for the purposes of safety and health protection and, although it does not establish the design criteria for electrical panels and electric motors (regulated by Directive 2006/95 / EC) however, it should be remembered that these must be made in such a way as to allow the satisfaction of the safety requirements applicable to the machine as they are an integral part of it.

A fundamental aspect to consider in the construction of an electric panel is the degree of protection provided by the external box of it, a degree of protection that concerns both protection against mechanical impact IK and protection against contacts with parts under a certain voltage and the entrance of solid or liquid bodies.

As an example regarding the choice of the protection of the electrical panel, the box installed on the Pre-process IR machine is shown, which, after checking the hardness, measures the hole diameter, ring thickness and raceway diameter of the inner ring (Picture 27). In particular, it is a steel box produced by Schneider Electric, belonging to the Spacial CRN class, and consisting of a door with lock and side panels made of a single piece welded on the back with double profile to form a protected sealed area.

Picture 27 – Schneider Electric steel box, class Spacial CRN installed on Pre-process IR machine

As far as the IP protection degree is concerned, with the installation of this protective box, an IP66 degree and an IK10 degree, certified by the manufacturer (Picture 28).

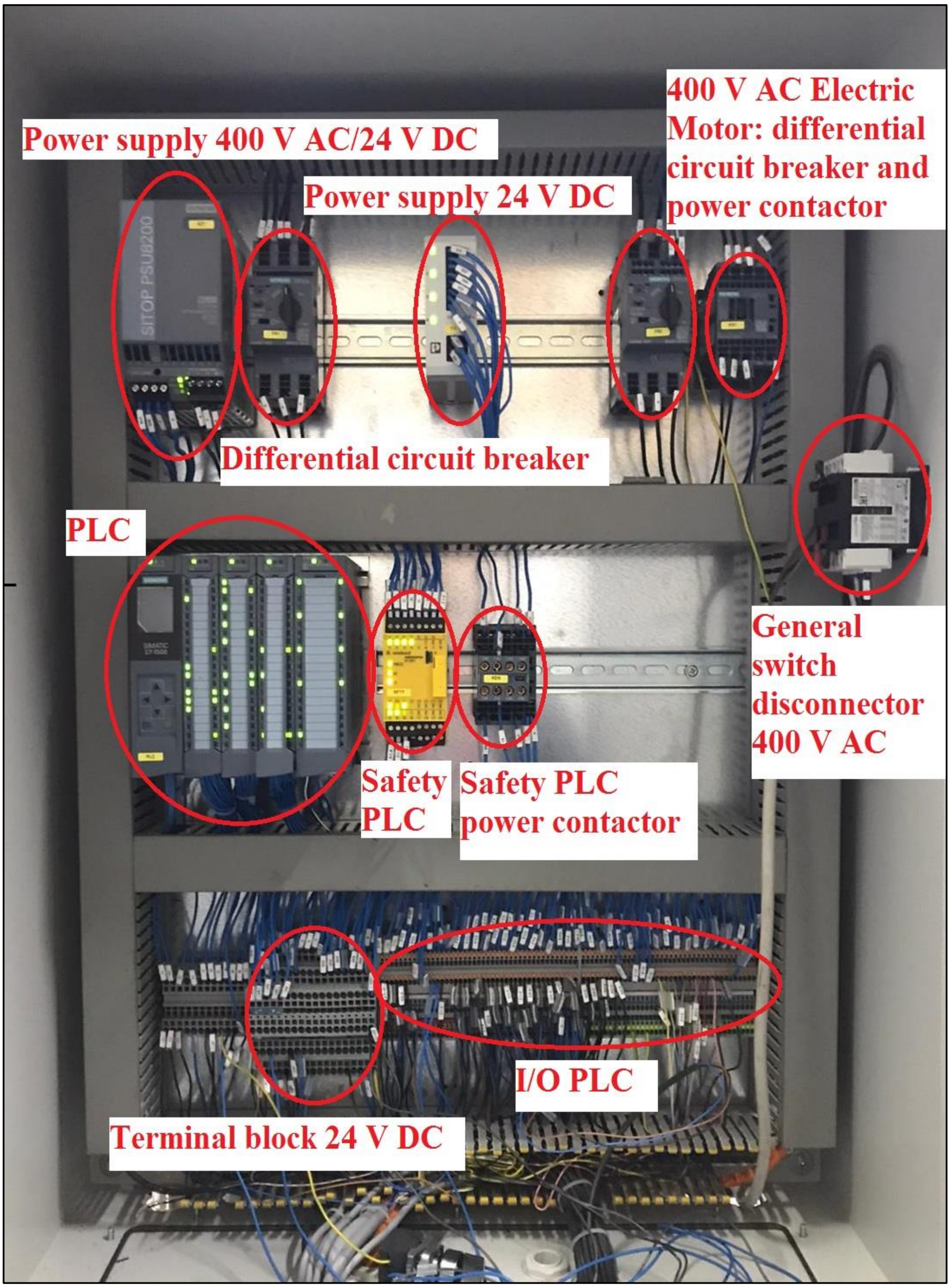


Ambiente	
Grado di protezione IP	IP66 conforme a IEC 60529
Grado di protezione IK	IK10 conforme a IEC 62262

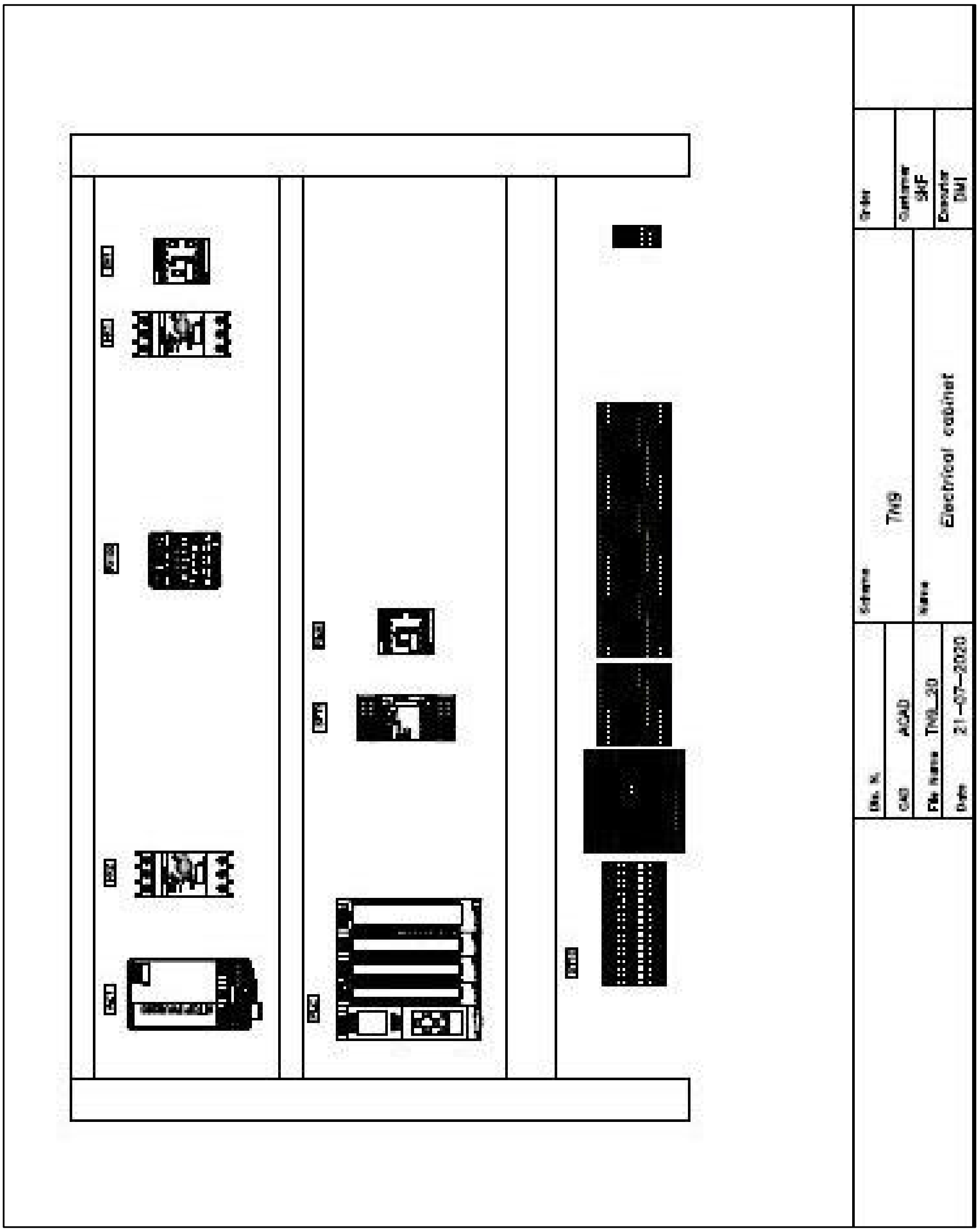
Picture 28 - IP and IK protection degree

Specifically, knowing the degrees of protection, the legislations allow defining a total protection against dust and against water projections in the form of sea waves as well as from a mechanical impact equal to 20 Joule.

After the insulating and protective box has been chosen, DMI s.r.l. the composition phase of the electrical panel begins. By way of example, in order to be able to analyze the components of the panel and their functions, in Picture 29 there is an image of the electrical panel installed on the TN9 machine (the choice of it by way of example is due to the presence, in it, of the greatest number of components in order to allow a treatment as broad and general as possible).



Picture 29 – Electric panel installed on TN9 machine



Picture 30 – Electric panel installed on the TN9 machine layout

As can be seen from the Picture just introduced, the components of a picture are:

- General switch disconnector 400 V AC: it is an electro-mechanical organ inserted in an electric circuit in order to disconnect, which means to open a circuit or a line. The purpose is to guarantee the safety of the plant and above all of the maintenance activities as it physically and visually interrupts the section of line on which you are working;
- Power supply 400 V AC/24 V DC: it is an alternating current-direct current conversion component, that is an electrical apparatus that serves to rectify the input electrical voltage at the output in order to supply electrical energy by adapting it to the use of the downstream machinery;
- Differential circuit breaker: the purpose of this switch, which trips automatically when there is a need, is to protect the electrical system from short circuit and overload as well as avoiding the risk of electrocution of people in the event of current leakage;
- Power supply 24 V DC: it is an electrical component that allows you to divide the input line into several output lines depending on how many are needed with the possibility of setting the current intensity on each line;
- Safety PLC power contactor: very useful electronic device to manage the current within a circuit and to ensure that the system performs certain actions; such an instrument is capable of breaking or establishing current in a circuit. In the case in question it is exclusively dedicated to the management of the safety circuit;
- Terminal block 24 V DC: is a modular block mounted on a mounting rail with an insulated frame that secures multiple wires together and allows you to conveniently, economically and safely distribute electrical power from a single input power source to multiple outputs. The terminals are spring loaded, a more recent alternative to the classic screw terminals, and consist of a locking component (precisely the spring) and a conductive metal strip. The terminal block has three levels that allow you to make more connections on the same block, ensuring an important saving of space. On the same terminal block we find, in the case of DMI s.r.l. electrical panel, both the 24 V DC distribution and the I/O of the PLC.

To be deeply analyzed, given the important function performed, are two components of the electrical panel: the PLC and the Safety PLC.

2.4.2.3.2 PLC choice

A programmable logic controller or PLC is a very simple computer that performs control functions for industrial automation. The PLC is a digitally operated electronic system, intended for use in the industrial sector, which uses a programmable memory for the internal storage of user-oriented instructions for the implementation of specific functions, such as logic, sequencing, timing, counting and arithmetic calculation, to control various types of machines and processes by means of both digital and analogue inputs and outputs. Both the programmable controller and the associated peripherals have been designed so that they can be easily integrated into an industrial control system and used in all the intended functions.

Contrary to what happens in wired logic, where the various components are physically connected, with the use of a PLC all the logic functions required for the automation of a machine or an industrial process are carried out following a specific program. Advantages deriving from the use of the PLC in spite of the wired logic are summarized in the following points:

- Flexibility: before the introduction of these devices, automatic machines required the use of control systems made with electromechanical components on the basis of a specific electrical diagram for each type of machine. With the introduction of programmable controllers, the wiring of the control systems is much simpler and the same type of PLC, albeit with different programs, can be mounted on machines to perform very different tasks;
- Scalability: the expansion of a system is possible by adding modules and by changing programs;
- Reliability: the probability of failure occurrence due to bad contact decreases because of using semiconductors;
- Easy change management and error correction: in the wired logic to modify the control system it is necessary to rewire the whole circuit and change the components that compose it. when a modification is made to the PLC, it is

generally not necessary to modify the wiring diagram, but it is sufficient to modify the program with a much lower cost in terms of time;

- Low costs: with the diffusion of these devices, their cost has decreased significantly. This diffusion, combined with the technological development that makes them more and more powerful and versatile, makes PLCs very advantageous also in economic terms;
- Miniaturization: the installation dimension is smaller;
- Run test: unlike hardwired logic controllers, programmable controllers can be easily tested before being mounted in the field;
- Speed in operations;
- Easiness of reprogramming: the PLC can remain connected to the programming terminal and be reprogrammed quickly according to production needs [6].

The PLC that DMI s.r.l. installs on the machines during the revamping phase, inside the electrical panel, is SIMATIC S7-1500 made by Siemens and previously presented in the Picture of the electrical panel on board the TN9 as well as in the Picture 31.

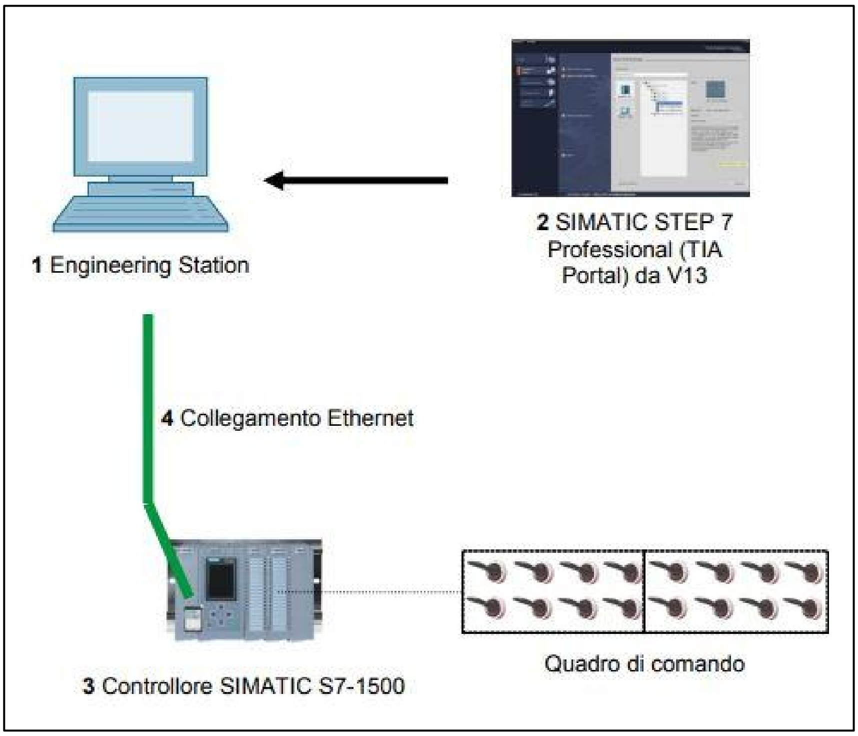
Picture 31 - Siemens SIMATIC S7-1500

The SIMATIC S7-1500 features a modular design and can be scaled in terms of its functionality, so you can adapt assemblies and functions perfectly to suit your machine design.

PLC programming is performed using SIMATIC STEP 7. SIMATIC STEP 7 is a software package created specifically for developing automation using Siemens products of the SIMATIC series. The term TIA Portal is used to define the environment in which STEP 7 works and means Totally Integrated Automation Portal; it is also referred to as an engineering platform for all automation tasks.

The TIA Portal is basically a centralized design environment characterized by an interface common user for all automation tasks with shared services (such as those of configuration, communication and diagnostics) and a single database to which others also access software packages such as SIMATIC WinCC, SINAMICS Startdrive and SIMATIC STEP 7.

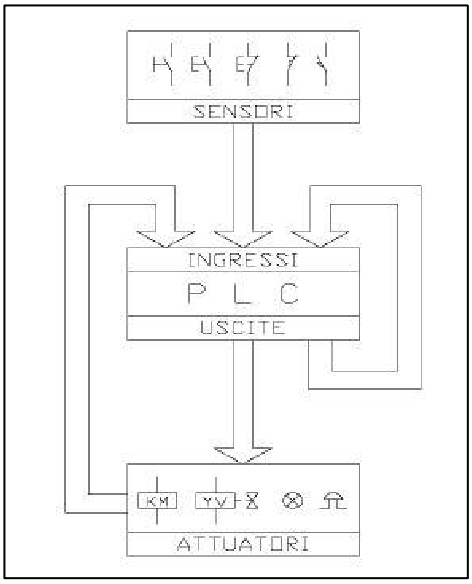
The two basic versions of SIMATIC STEP 7 are available: Basic (suitable for configuring with the S7-200 model) and Professional (suitable for configuring with S7-300, S7-400 and S7-1500 models). A diagram that summarizes the hardware and software requirements of the system for programming is shown in the following Picture 32.



Picture 32 - Hardware and software requirements for PLC programming

The modules that make up the PLC are:

- CPU: the Central Processing unit is the heart of the PLC, it contains a card with one or more microprocessors, which run the operating system and the programs (software) developed by the user, and a memory where these programs are saved [6]. The differentiation between the various CPUs occurs through the evaluation of certain characteristics such as the amount of program memory, the amount of data memory, the number and type of integrated functions and the number of manageable interfaces. The peculiarity that distinguishes the PLC from other microprocessor devices is the cyclical way of executing the program [6]. The data processing of a PLC, in fact, takes place sequentially according to the order of the instructions inside the program. The actuation (physical signal on the output, detection of the input) takes place at specific times and not during program processing. We can therefore summarize the control logic of the controller divided into three stages: acquisition of data from the sensors, program processing, and implementation of the outputs.



Picture 33 – Three stages of the PLC control logic

In the first phase, the condition of the inputs is acquired in a precise instant and a copy is made in the I/O memory area. In the second phase the inputs are processed and the outputs modified, only within the PLC memory area dedicated to them, sequentially according to the execution of the program. The third phase is a copy of the memory area, which contains the outputs, in the buffer of the output cards. The outputs in turn feed the devices, contactors and solenoid valves, which will control the actuators, electric motors and pneumatic cylinders;

- Input / output modules: these are the means by which the PLC communicates with the physical process to be controlled, detecting data from the sensors and commanding actions to the actuators. Given the characteristics of the signals in an industrial plant, there are both digital and analogue I/O modules present.

  A digital signal is an ON / OFF signal which in the memory and the PLC is interpreted as a modification of a bit 0/1 of a memory channel; the physical level of the signal is a voltage signal. 0 V means that the bit has a value of 0 because the contact is open, while 24 V means that the contact is closed and the logical value of bit is 1. Examples of digital signals can be, in input, a value 1 of the limit switch when the cylinder has reached the position or 0 when this does not happen, or at the output, the command of the monostable valve in when the logic condition of the bit becomes 1 otherwise both 0 and 1 to command the two positions of a bistable valve.

  An analogue signal, on the other hand, is a more complex signal as a physical quantity needs to be converted into voltage (0-10 V) or current (0-20 mA). An example of this signal is having the speed in rpm of a motor from the circuit that is read in voltage or current at input, while at the output I can set the motor speed from the HMI (Human Machine Interface) passing a value in rpm, which the PLC converts to the motor into voltage or current according to its operating characteristics;

- Operator interface modules (integrated with the CPU adopted by DMI s.r.l.): these are terminals consisting of a display and keyboard, which, connected to the processor module, allow the operator to view messages, alarms, control or modify the variables of the controlled process;
- Modules for network connection (integrated in the PLC CPU used by DMI s.r.l. for the revamping phase): these are modules that manage the communication protocols for the various types of computer networks to which the PLC can be connected (Ethernet, Profinet, etc.). The use of these communication protocols will be discussed later.

2.4.2.3.3 Safety PLC choice

Picture 34 - Wieland Samos PRO COMPACT series safety controller

The Safety PLC shown in the Picture 34 and in the picture reported previously is the same one used on all the machines, not just the TN9. It is a Samos PRO COMPACT SP-COP1 module safety controller by Wieland. The samosPRO Compact 24 V DC is modular and it is suitable, and therefore used in the revamping phase, for monitoring non-contact safety sensors, emergency stop buttons, protective door and door lock switches, two-hand controls as well as testable optical safety barriers, barriers photo-electric and laser scanner.

The model chosen by DMI s.r.l. allows to reach a PL (Performance Level)-e/Category 4 safety level certified by the manufacturer in accordance with EN ISO 13849-1. The component features 20 safe inputs, 4 safe outputs, a USB port and an SD slot for program memory. The programming phase is very simple, the USB port allows the cable connection to the programming terminal (the programmer's PC) on which the specialized technician performs the programming phase thanks to samosPLAN6 software from

Wieland. The program is then saved on the SD card, which is inserted into the Safety PLC.

The choice of DMI s.r.l. not to use a PLC with integrated safety circuit is due to two main reasons: firstly for economic one, secondly to avoid having to use the PLC inputs and outputs ports for a safety circuit that could easily be controlled by a separate PLC with a higher number of I/O available dedicated modules.

Using the USB port and SD memory card slot make sure that your machine can be flexibly programmed and programs can be quickly duplicated or exchanged. This speeds up commissioning and reduces machine downtimes enormously.

The Samos PLAN6 software for the samos PRO COMPACT range makes the programming phase even easier. In particular, the advantages of its use are:

- Intuitive configuration: easy entry to programming, no detailed product knowledge required, less engineering efforts;
- Simulation instead of testing: the programmed logic can be simulated real-time on the PC instead of looking for faults on the machine;
- Faster validation: in online mode with oscilloscope function, the safety functions can be quickly validated, verified and documented on-site;
- Possibility to make comfortable operations with multiple screen;
- Fast set-up of the machine through emulating missing sensor hardware with the forcing function;
- Global remote diagnostic: if an Ethernet interface is integrated, the system will be connected worldwide, saving expensive service call outs;
- One-click report generation;
- Protection against manipulation.

2.4.2.3.4 Human Machine Interface – HMI choice

The last step of the revamping phase is the installation of an HMI (Human Machine Interface) or OP (Operator Panel) and its programming. As processes become more and more complex and the needs in terms of functionality of machines and systems increase, the operator needs an efficient tool for command and control of production facilities.

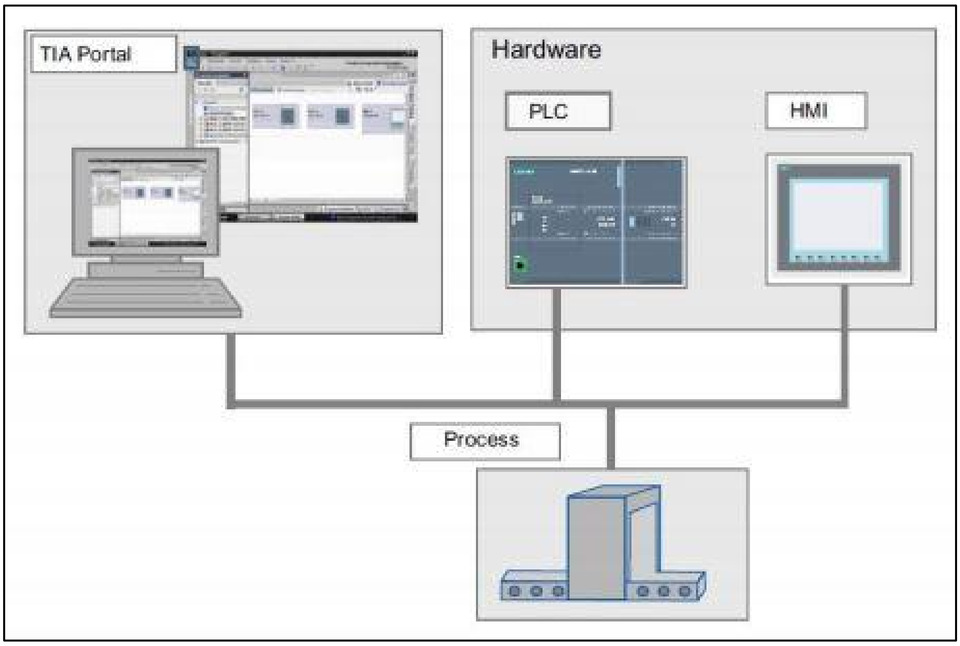
HMI systems (Human Machine Interface) they act as an interface between man (the operator) and the process (machine/plant). Control effective on the process is entrusted

to the controller. There is therefore an interface between the operator and WinCC (on the HMI device) and an interface between WinCC and the controller.
An HMI performs the following tasks:

- Representation of processes through a clear and efficient page structure: the process is displayed on the HMI device. For example, if a state changes in the process, the display on the HMI device is updated. The process can be represented on several pages with a clear and efficient structure;
- Process management: the user can manage the process with the graphic user interface. For example, it can set a set point for the controller or start a motor;
- Display of alerts: if critical states occur in a process (for example, if a certain value exceeds its limit) the system automatically displays a warning;
- Archiving of process values and messages: the HMI system can archive alarms and process values. This allows you to document the progress of the process and access the previous production data also later;
- Documentation of process values and messages: the HMI system can print a report of the messages and process values. For example you can print production data at the end of the working time;
- Management of process and machine parameters in recipes: the HMI system allows you to save parameters related to processes and machines within recipes. Parameters can, for example, be transmitted with a single operation from the panel operator to controller to adapt production to a different variant of the product;
- User Management: user rights can be set on devices to restrict what they can do by particular users.

The panel installed on the machine by DMI s.r.l. is the SIMATIC HMI TP900 Comfort by Siemens with touch control, 9 " widescreen TFT display, PROFINET interface must be vertically mounted with the possibility of flush-mounting. It is powered at 24 V DC directly from the terminal board located in the electrical panel, and connected to the CPU via Ethernet. It allows you to manage 300 recipes on a number of pages that can be extended up to 500, for each page you can have up to 400 objects.
As already mentioned, the Totally Integrated Automation Portal (TIA Portal) integrates several SIMATIC products into one software with which it is possible to increase productivity and efficiency. TIA products work together within the TIA portal for the

creation of an automation solution. In case of configuration of the HMI, you can use the TIA Portal to configure both PLC and visualization system. All data is saved in one project. The components for programming (STEP 7) and visualization (WinCC) are not separate programs, but rather editors of a system accessing a common database. A common user interface is used for access to all display and programming functions at any time.



Picture 35 - TIA products work together within the TIA portal for the creation of an automation solution

The main advantages introduced with the use of the TIA portal concern centralized management and data visualization, made user-friendly, through drug and drop operations and through graphical support for configuration and diagnostics. Centralized management also guarantees data consistency by avoiding synchronization between project participants; in fact, each variable can be created or modified in any part of the program and updated accordingly continuously.

WinCC is a powerful HMI system (Human Machine Interface), as already defined the interface between the person and the machine. WinCC allows the operation and observation of the processes that are performed in a machine. It is an engineering software for configuring SIMATIC Panels, industrial SIMATIC PCs and standard PCs.

WinCC allows you to create screens for the control and supervision of machines and plants. For create pages predefined objects are available, that allow you to reproduce the system, view the progress of the processes and specify their values. A page can be made up of static and dynamic elements. In runtime the static elements (for example text and graphics) do not vary. The dynamic elements vary according to the process. These display the current process values as follows:

- From the controller memory;
- From the memory of the operator panel in the form of alphanumeric displays, curves and graphic bars.

The input fields on the HMI device are also dynamic objects. Process values and entries are exchanged between the PLC and HMI device via tags. To create a page on the HMI, you must have already introduced the HMI device, on which the required pages will be created, in the project. To connect the SIMATIC panel during the programming phase, it will be connected to the programming terminal via Ethernet, the PLC, to which it will be connected, will be selected and then the configuration phase will begin. Once the configuration is complete, the home page will open, with the required layout. From here you can select colours, number of pages, objects and so on through drug and drop operations or with a double click until you reach the desired level of complexity of the layout.

An important aspect to keep in mind when creating the Human Machine Interface is the need to create an interaction device between the operator and the machine as user-friendly as possible. User-friendly has a very specific meaning: in this case it means that the interface designed by DMI s.r.l. will be within reach of every operator, both experienced and novice. Menu and functions are understandable, the icons are distributed in the layout of the pages in a very precise and clear way. An example of user-friendly HMI will be illustrated in the following pictures, in particular we speak about the HMI installed on the TN9 machine.

Picture 36 - Human machine interface installed on TN9 machine complete with push-button panel, siren for alarm signals and touch control panel

On the HMI presented in the previous picture you can see the touch-screen control panel, the push-button panel and the siren for displaying the status of the machine both for alarm (steady red due to a stopped cycle, red flashing due to an error in the machine) and for normal operation in case of green light. The first means of interface between the operator and the machine is certainly the push-button panel, which is why we want to briefly explain its composition; from left to right we find the following buttons:

- Key button to enable the safety controls exclusions in case of maintenance interventions;
- White button to switch between automatic or manual operations;
- Green button to control the cycle start in case of automatic operations or to control the next operation in a manual or step-by-step cycle;

- Red button to stop the cycle in automatic mode or to command a step back in manual mode operations;
- Yellow reset button that commands the return to the rest position of the actuators;
- Button with mushroom head to control the emergency status of the machine, whose operation will be detailed in the paragraph dedicated to machine safety.

As for the control panel, however, this must be designed as much as possible to make the interface user-friendly; the various screens that allow the operator to manage the machine will be presented below and their composition will be illustrated, making it clear that they are easy to understand and very intuitive.
On the left of the control panel there is the menu consisting of seven items that allow you to view the different screens. Starting from the top, you can see the screen corresponding to the item “system” which allows you to view general information about the machine:

- Status of machine ready when all stations are at rest and the LED next to each station turns green;
- Time of execution of the last cycle;
- Counter of the total pieces processed by the machine;
- Resettable partial piece counter as well as the rejection counters.

Below there is the Picture of the screen obtained directly from the HMI programming software.

Picture 37 - Main page corresponding to the selection of the system item of the TN9 control panel menu

In order to perform the diagnostic function, the operator must be able to keep the PLC inputs and outputs under control; this is possible using the screens presented below which can be reached using the items of the HMI menu such as "standard" and "digitali" presented below.

Picture 38 – Screen corresponding to the standard item on the menu

In the previous window the operator can check the standard PLC inputs and outputs corresponding to the boundary conditions of the cycle that the machine must perform, including the safety conditions that must be checked before the cycle starts.

Picture 39 – Window corresponding to the selection of the digital item from the menu

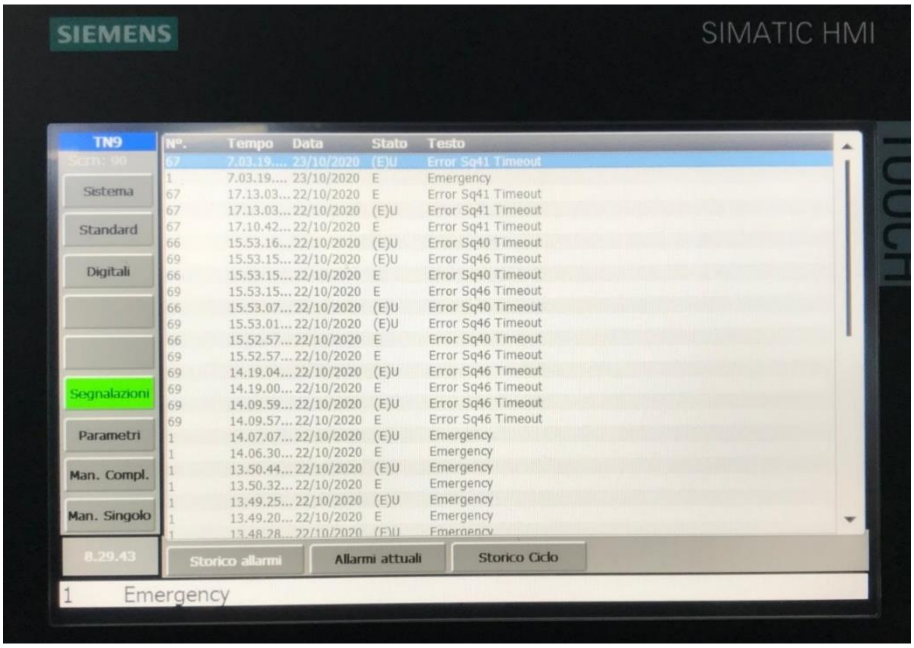
On the previous page the operator can monitor the digital inputs and outputs of the PLC to perform the diagnostics; on each page of the item “digitale” the operator can switch, at the bottom of the window, between the various stations that make up the machine to supervise the overall operating conditions of the machine. In particular, the window shows the conditions of the limit switch sensors SQ and the commands of the solenoid valves to the actuators YV.

To increase the efficiency of the supervision of the machine by the operator, it is necessary to collect as much data as possible about the operation of the machine over time, also in order to create a maintenance plan for the machinery or simply to correct frequently recurring malfunctions. In this regard, the man-machine interface allows these data to be displayed simply by accessing the “segnalazioni” item of the main menu.

In particular, the “segnalazioni” section consists of three sections:

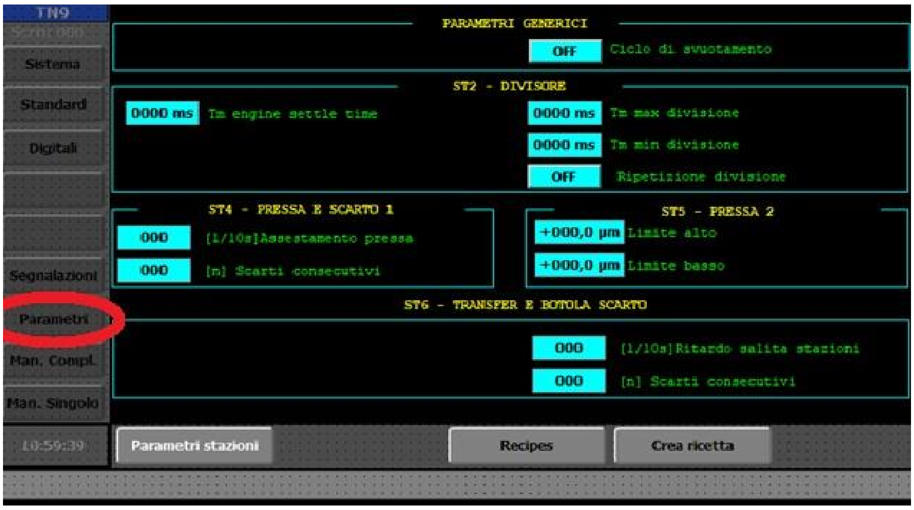
- Alarm history: in this section it is possible to view the history of the alarms that took place in terms of date and time, status (in progress or resolved) and type of error including the emergency status commanded by the operator panel
- Current alarms: allows you to view the alarms in progress which, once resolved, are removed from the section;
- Cycle history: allows the operator to view how many times and for how long the cycle has been performed in automatic or manual mode, but also for how long the machine has been stopped.

In following Picture, the window corresponding to the alarm history is reported.



Picture 40 - Alarm history section on the HMI on board of the TN9 machine

For an efficient interaction between the operator and the machine, it is necessary that the operator can actively modify the cycle performed by the latter acting on the parameters that characterize it. For this purpose, in the "parametri" section of the main menu it is possible to enter and modify the cycle parameters, from the cycle execution times of the various stations to the product parameters beyond which it will be rejected. In the same submenu, it is possible to create recipes and view existing ones. The window that gives the operator the opportunity to set parameters is shown below.



Picture 41 – Parameter setting window

To increase the machine control possibilities, the operator has complete control of both the stations and the individual actuators. For this purpose in the main menu there are the items “ciclo manuale completo” and “ciclo manuale singolo” in which, respectively, the operator can command the complete cycle of a station in manual mode by selecting the designated station, or can command an actuator as well as a motor in manual mode for the station you are interested in, simply selecting it. Also in these two windows, the LEDs can be green, if ready, or red, if the operation is in progress. In the following Pictures the windows discussed are shown.

Picture 42 – Window needed for the selection of complete cycles in manual mode for each station

Picture 43 – Window needed for the selection of a single movement of an actuator in manual mode for each station

2.5 CE marking process

The CE marking is a physical and documentary examination of a machine, a process or a part of work equipment, carried out within the regulatory framework of the Community Directives. CE marking is compulsory and must be applied before any product subject to it is placed on the market or put into service. It applies to:

- all new products, whether they are manufactured in member states of the European community or in third countries;
- used and second-hand products imported from third countries;
- substantially modified products that are subject to the directives as new products.

As regards the field of machine tools, a field in which the DMI s.r.l. has developed, the responsibility to demonstrate that the machine complies with the Machinery Directive remains with the machine manufacturer and this concerns:

- machines imported into the European Union for the first time;
- machines built for own use;
- machines built for sale in the EU;
- machines modified within their original limits;
- new machines (being placed on the market or to be put into service):
- old machines (if placed on the market or substantially modified).

In particular, the machines that make up the production line subject to revamping, which this thesis work is about, must be classified as machines that have been modified within their original limits or, in any case, modified machines so that the original Risk Assessment it cannot be applied.

For each machine making up the line, therefore, DMI s.r.l. must:

- evaluate the machinery according to the Machinery Directive;
- carry out the Risk Assessment;
- implement Risk Reduction measures;
- create the instruction manual;
- check that the machine is compliant;
- validate the machine according to the Essential Health and Safety Requirements (ESR);

- fill in the technical file
- draw up the EC Declaration of Conformity
- apply the CE plate on the machine like the one shown, as example, in Picture 44 below coming from another project developed in the past.

Picture 44 – Example of CE plate to be applied on the machines

The Machinery Directive is the means that all member countries of the European Union have adopted to establish the Essential Safety Requirements that machines must possess in order to be placed on the community market or in service. The Machinery Directive used by DMI s.r.l. is the Machinery Directive 2006/42/EC of the European Parliament and of the Council, came into force on 29 December 2009, which aims to ensure identical safety requirements for machines for each country.

For compliance with the requirements of the Machinery Directive and as part of the CE marking process, the machine must meet the Essential Health and Safety Requirements set out in Annex I. Annex I itself states that the manufacturer of a machine must ensure that a risk assessment is carried out and the machine must be designed and built taking into account the results of this assessment. The validation is completed ensuring that all requirements applicable to the machine are met.

The risk assessment is therefore necessary in order to obtain a CE marking of the machine and has as its purpose the identification of the dangers associated with the machine, the weighting and estimation of all possible risks, the definition of the required safety systems.

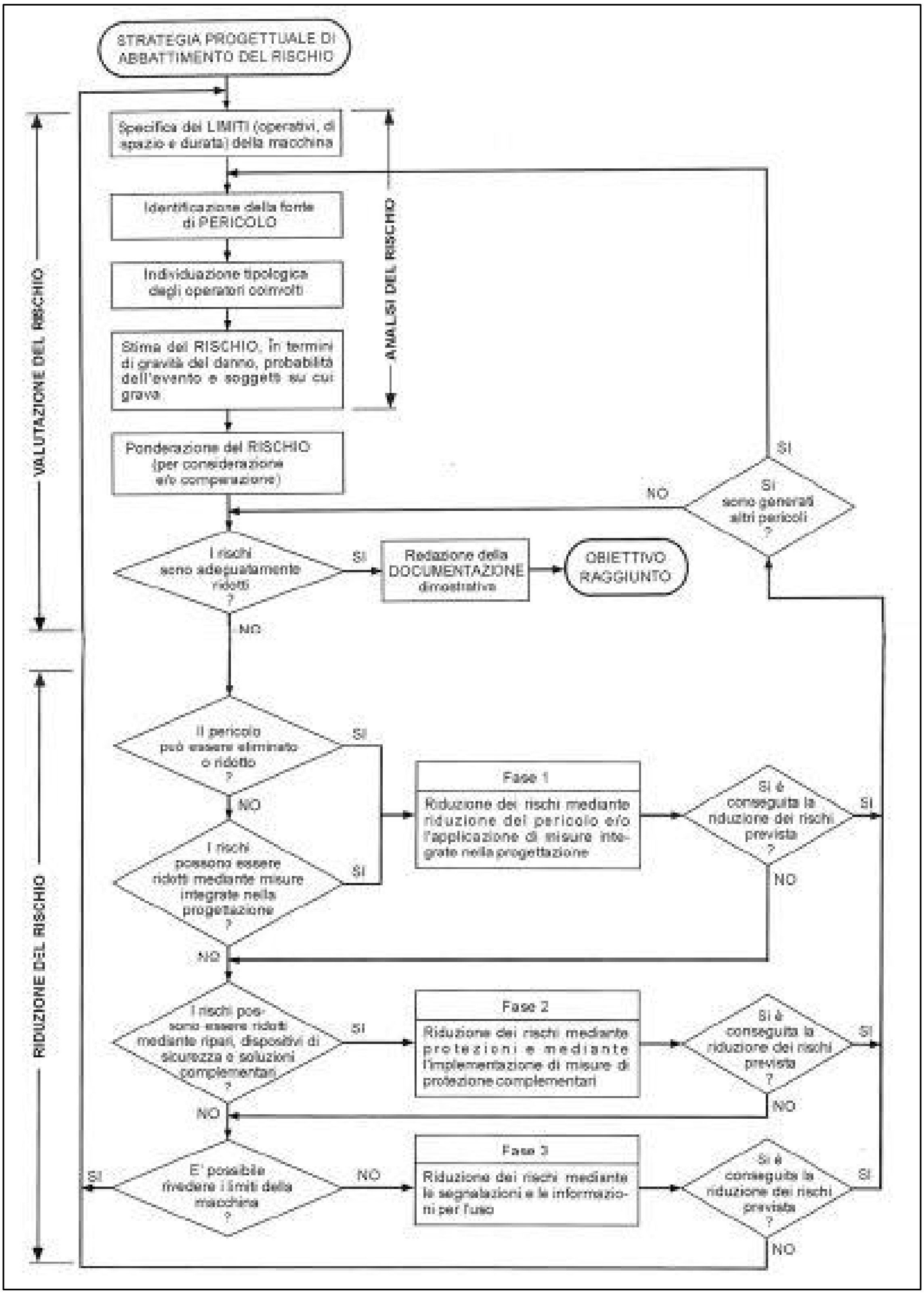
2.5.1 Risk Assessment and Risk Reduction procedure

2.5.1.1 Risk assessment procedure from ISO 12100 standard

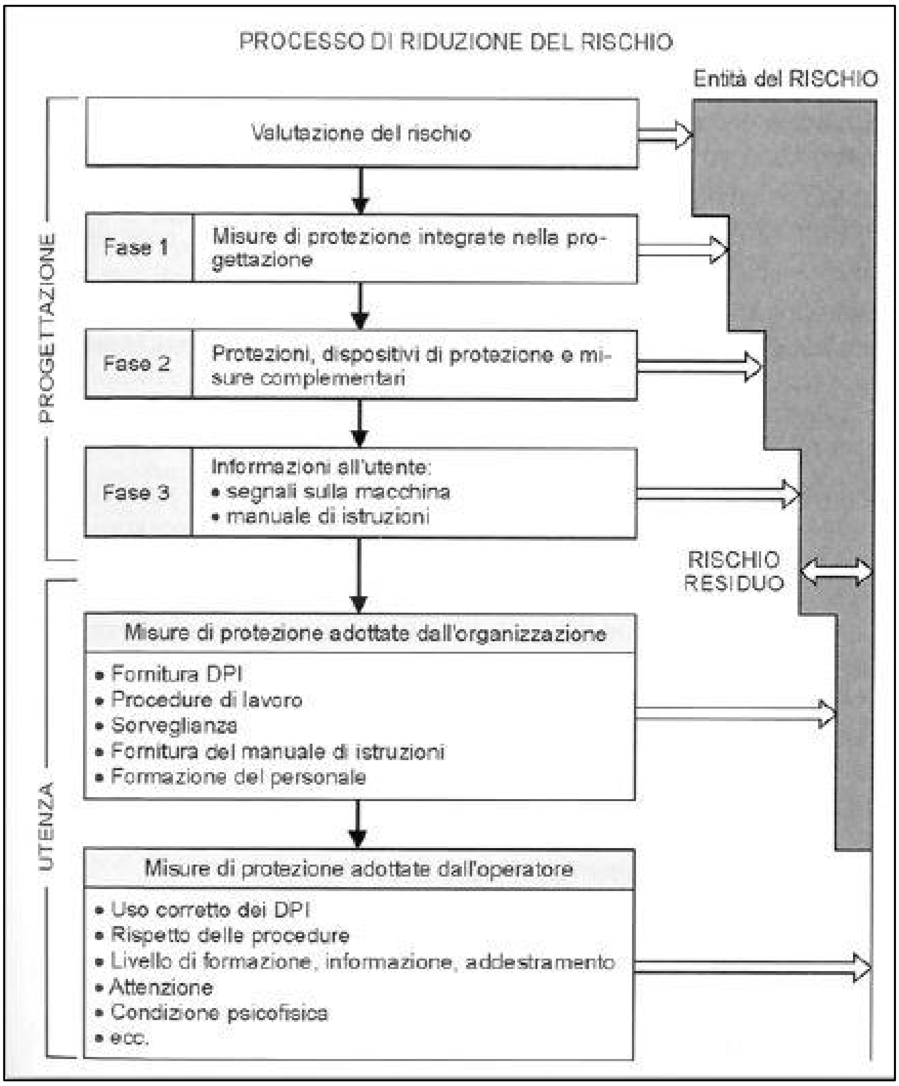
The risk assessment process is a documented physical examination and inspection of the machine carried out under the guidelines of national and international standards. The purpose of the risk assessment is:

- identify the dangers associated with the machine;
- estimate the risk;
- weighting the risk;
- determine the applicable risk reduction to reduce the assessed risks.

The risk assessment must take into account the intended use of the machine, but also the reasonably foreseeable improper use, and must also cover all the life stages of the machinery and all the personnel who will interface with it during the life of the machine. The reference standard for Risk Assessment is ISO 12100 which specifies the basic terminology, describes general procedures for identifying hazards and estimating and assessing the risks during the phases of the life cycle of the machine without, however, defining any way a method for hazard analysis and risk estimation. The following Pictures 45 and 46 show the charts used by DMI s.r.l. for Risk Assessment and suggested by ISO 12100.



Picture 45 – ISO 12100 – Risk Evaluation and Reduction chart



Picture 46 – ISO 12100 – Risk Evaluation and Reduction chart

Looking at the chart previously reported, it can be seen that the starting point of the risk analysis is the determination of the limits of the machine being analysed which include:

- limits of use:
  - operating modes and intervention procedure;
  - intended use and reasonably foreseeable misuse or malfunctions;
  - predictable levels of training;
  - exposure of other people to the hazards when it can reasonably be expected;
- space limits:
  - take into account the range of movement of the machine;

    - space necessary for the interactions of people with the machine both during use and during maintenance;
    - human operator-machine interface;
    - machine-energy source interface.
- time limits:
    - time limits due to the duration of the machine (it is reasonable to assume a machine life of 20 years);
    - periods of time between maintenance interventions.
    - environmental limits
    - limits due to routine maintenance and cleaning requirements
- limits due to the properties of the materials to be processed.

After having determined the limits of the machine, the source of the danger is identified, defined as the possible source of the damage, and an estimate of the risk is carried out. The methods to perform the risk estimation can be different, but the most used are certainly:

1. Risk matrix: this method defines the risk as a combination of probability of damage occurrence and severity of damage. In this way, iso-risk zones are outlined and a different degree is associated with each zone. In order to clarify what has been introduced, the two following Pictures 47 and 48 are reported.
   In particular, in the first Picture the risk matrix is reported, and the degree of risk is a function of severity and probability, while the second Picture summarizes hoe to interpret the resulting level of risk.

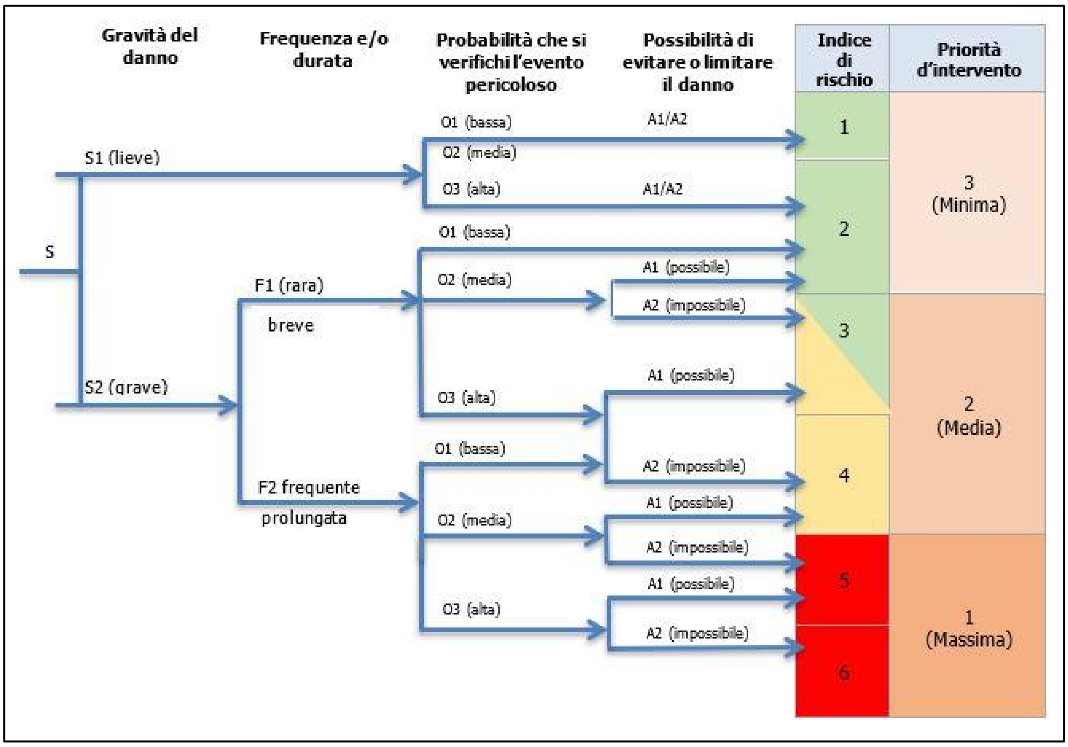
Calcolo del livello di rischio		Gravità dell'avvenimento - D1 - Catastrofica	- D2 - Grave	- D3 - Lieve	- D4 - Trascurabile
Probabilità dell'evento	Molto probabile	A	A	A	B
	Probabile	A	A	B	C
	Poco probabile	A	B	C	C
	Remoto	B	C	C	D
	Improbabile	C	C	D	D

Picture 47 - Risk matrix (from https://www.necsi.it/files/read/2286-modulo-21.pdf)

	Livello di rischio	Classificazione
Rischio elevato	A	Livello intollerabile per il quale devono essere adottate appropriate misure per ridurre il rischio, sia di carattere organizzativo/procedurale che tecnico, che prendano in considerazione anche aspetti progettuali.
	B	Livello comunque alto che necessita in ogni caso l'attuazione di appropriate misure per ridurre il rischio, sia di carattere organizzativo/procedurale che tecnico.
Rischio moderato	C	Livello intermedio ma comunque moderato per il quale è opportuno adottare appropriate misure di carattere organizzativo/procedurale e/o interventi tecnici di modesta entità per ridurre e controllare il livello di rischio.
	D	Livello accettabile per il quale non è richiesta l'attuazione di alcuna misura di riduzione del rischio. Possono essere consigliate misure di carattere organizzativo/procedurale per il mantenimento ed il controllo della situazione.

Picture 48 - Interpretation of the risk level obtained from the risk matrix (from https://www.necsi.it/files/read/2286-modulo-21.pdf)

2. Risk graph: this method allows you to define the risk index by following a graphical path on which you move by selecting the parameters characterizing the dangerous situation. In order to better present the method, the graph that characterizes it and a detailed description of the parameters to be selected to arrive at a correct risk assessment are shown below.



Picture 49 – Graph of risk (from https://www.certifico.com/marcatura-ce/documenti-direttiva-macchine/11902-stima-del-rischio-iso-tr-14121-2-p-6-3-metodo-grafico-esempio-e-scheda)

To be able to move on the graph it is necessary to know the definitions of the characteristics of the dangerous situation that is being examined. Therefore they are defined:

- S1: minimum severity of damage; the associated damage is mild and usually reversible (we speak, for example, of scratches, bruises, minor injuries that require first aid);
- S2: maximum severity of damage; the dangerous situation could create serious and usually irreversible damage, including death (such as breaking or crushing of limbs, severe injuries requiring stitches, muscle or skeletal problems);
- F1: frequency limited to twice or less per work shift or an exposure of less than 15 minutes cumulative for the whole work shift;
- F2: exposure frequency greater than twice per shift or an exposure duration greater than 15 cumulative minutes per work shift;

- O1: low probability of occurrence of a dangerous event as the inappropriate action is not foreseen and the technology used is robust and recognized;
- O2: average probability of occurrence of the dangerous event as an inappropriate action is foreseeable by trained personnel although in the last two years at least one technical failure has been observed such as the absence of a bolt;
- O3: high probability of occurrence, inappropriate action foreseeable by an untrained person with faults observed regularly as in the case of absence of guards placed between the operator and the source of danger;
- A1: there is the possibility of avoiding the damage under certain conditions; such as slow speeds, and the worker has taken a training course and is familiar with the risks;
- A2: there is no way to avoid the damage.

3. Hazard Rating Number (HRN) system: the method consists in determining the numerical value of factors such as probability of occurrence P, frequency of exposure F, severity of damage G and number of people at risk N to calculate the HRN value and determine the severity of the risk.

   The know-how of DMI s.r.l. he prefers to use this risk assessment method as the two previously introduced are too interpretable and do not lend themselves well to a precise assessment.

   The formula that allows the calculation of the Hazard Rating Number is:

$$HRN = P \cdot F \cdot G \cdot N$$

   where the parameters used will have their values assigned according to the following tables.

Probability of occurrence P		
0,033	Impossible	It cannot happen under any circumstances
1	Highly unlikely	Conceivable
1,5	Unlikely	It could happen
2	Possible	Unusual
5	Possible	It could happen
8	Likely	It wouldn't be surprising
10	Highly likely	Just to wait for it to happen
15	Certain	No doubt
Exposition frequency F		
0,5	Annual	
1	Monthly	
1,5	Weekly	
2,5	Daily	
4	Hourly	
5	Constant	
Severity of the damage G		
0,1	Scratch/bruise	
0,5	Laceration/mild health effects	
1	Fracture minor bones or temporary minor illnesses	
2	Fracture major bones or permanent minor illnesses	
4	Loss of a limb/eye or permanent serious illness	
8	Loss of two limbs/eyes or permanent serious illness	
15	Death	
Number of people at risk N		
1	1-2 people	
2	3-7 people	
4	8-15 people	
8	16-50 people	
12	More than 50 people	

Table 1 - HRN method parameters values according to ISO 12100 standard

The risk assessment is performed according to the numerical value of HRN obtained with the formula introduced; each value of the HRN parameter is associated with a degree of risk, which can be obtained from the following table.

HRN	RISK
0-1	Negligible
2-5	Very low
6-10	Low
11-50	Significant
51-100	High
101-500	Very High
501-1000	Extreme
More than 1000	Unacceptable

Table 2 - Risk evaluation according to HRN values from ISO 12100 standard

After calculating the HRN-Hazard Rating Number and associating the dangerous situation considered with a degree of risk in accordance with the table just introduced, unless the risk is negligible, a risk reduction action is carried out with the methods that will be proposed below. Once the risk reduction procedure has been completed, the new HRN value is calculated and the method, thanks to its mathematical formulation allows you to calculate the risk reduction in percentage using the following formula:

$$Risk\ Reductin\ [\%] = \frac{HRN_{without\ reduction} - HRN_{with\ reduction}}{HRN_{without\ reduction}} \cdot 100$$

2.5.1.2 Risk reduction procedure

After carrying out the risk assessment by applying ISO 12100, modifications are made to the machine in terms of safety, for example by making sure that the last roller of a roller conveyor is not motorized in order to prevent, near the loading station, the riskof entrapment of a finger or hand. If an adequate safety level is not reached during the design phase, reducing any risk present in the machine, the following three standards are used in conjunction with each other:

- ISO 12100: in addition to guiding the risk assessment procedure and its reduction, it also offers technical and specific principles for the selection of guards and protective devices as well as requirements for the design of the latter;
- ISO 14120: general requirements for protections; the standard defines the types of guards and is intended to be a guide for their choice;
- ISO 13857: safety distances; the standard is used to establish the correct safety distances to prevent dangerous situations and to establish the maximum opening allowed to the protective structures. Obviously, the distances considered are based on people who try to reach the area where the danger is located without additional help and under the conditions specified for each situation.

2.5.1.2.1 Guards and safety distance choice from ISO 14120 and ISO 13857 standards

Specifically considering the ISO 14120 standard, it defines that it is necessary that fixed guards should not be used if access to the danger area is required both during normal operation of the machine and during maintenance operations when the latter are very frequent; the same legislation also defines that the fixed guards, intended as the only measure to reduce the risk, are not to be used if there is a risk that the fixed guard will not be reassembled.

As regards, however, the ISO 13857 standard presents two tables for the evaluation of the safety distance: one refers to the upper limbs of people from three years of age and the other refers to the upper limbs of people from 14 years of age.

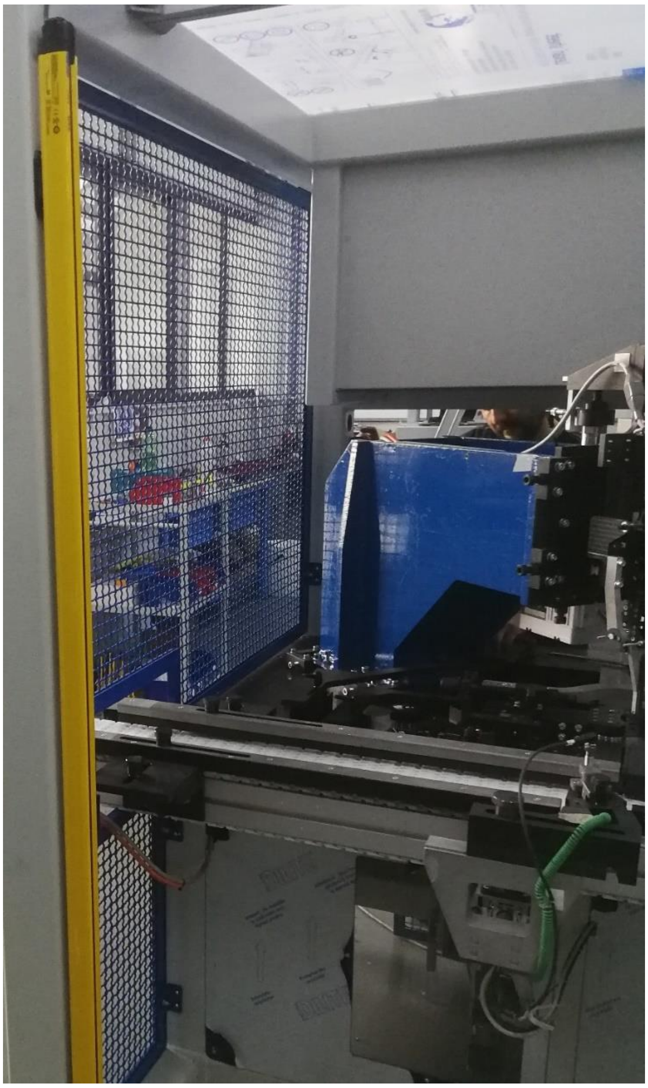
An important definition, as regards the concept of protections, comes from ISO 12100 which defines guards as physical barriers integrated into the machine to provide protection, and protective devices as a means of protection other than guards.

Excavation of guards must be inhibited as far as possible by design and must ensure good visibility to minimize the need to remove them. In general, the guards must be rigid, resistant to impacts, but also capable of containing the dangers that may arise by projection from a closed area. A classification of guards coming from ISO 14120 is:

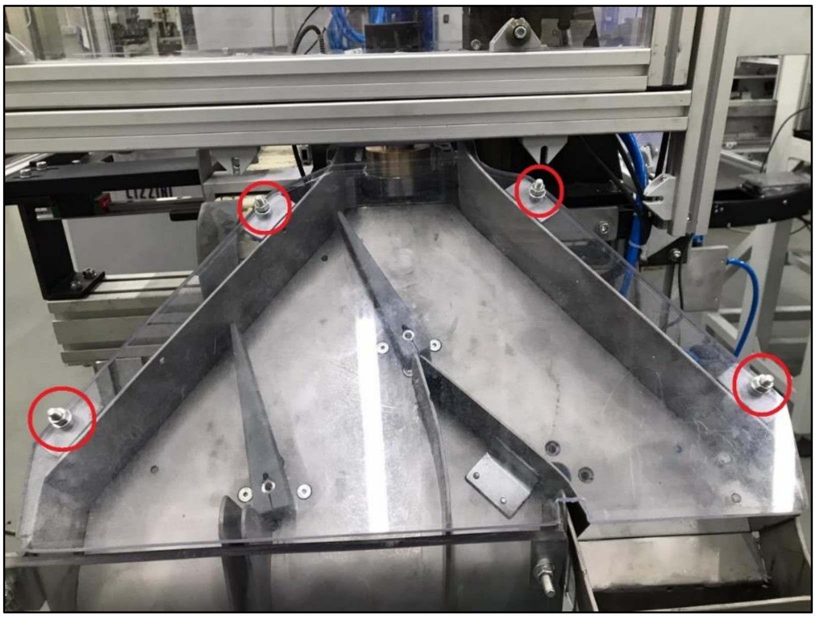
- Fixed guard: it must be held in position permanently (for example it must be welded) and can be removable when infrequent access is required. In the latter case the guard must be held in position with fasteners for which it is impossible to remove without suitable tools and, if possible, it must not be able to remain in position without its fastening. The types of fixed guards are divided into:

- Total segregation: totally preventing access to the machine transmission components;
- Spacing barrier / tunnel guard: for both solutions there is no total closure of the dangerous area, but access is prevented by the size of the guard and the distance between it and the source of danger.

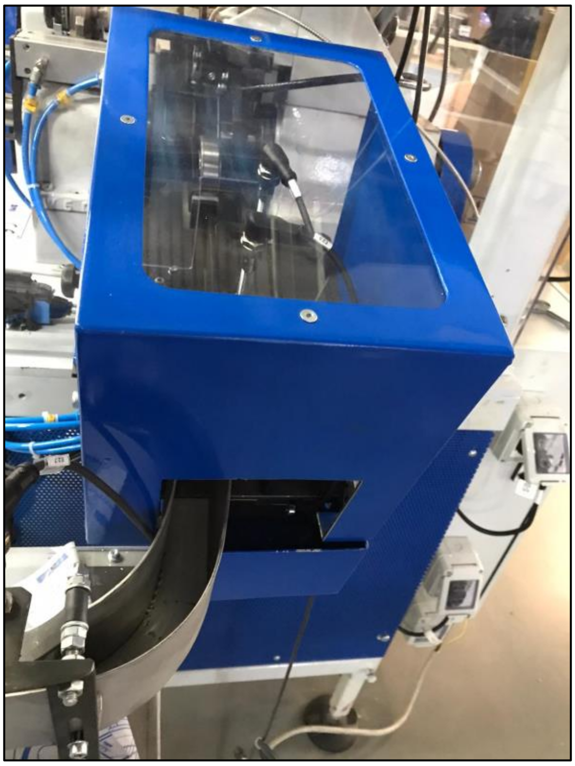
Below there are the solutions adopted by DMI s.r.l. in terms of fixed guards.



Picture 50 - Metal spacer barrier that does not completely enclose the dangerous area, intended as the area of operation of the machinery, but reduces access from the side



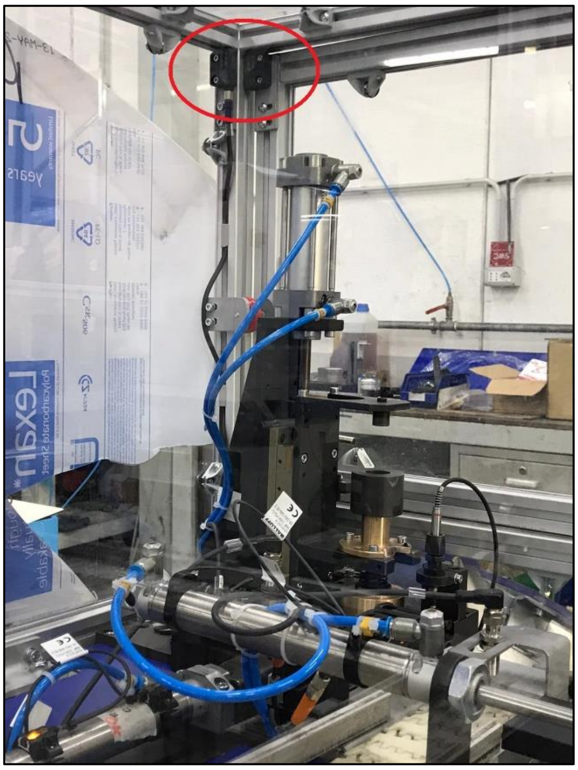
Picture 51 - Removable guard held in position by four screws, necessary to prevent contact between the operator and the ring reject selectors positioned on the output channel of the Pre-Process OR machine



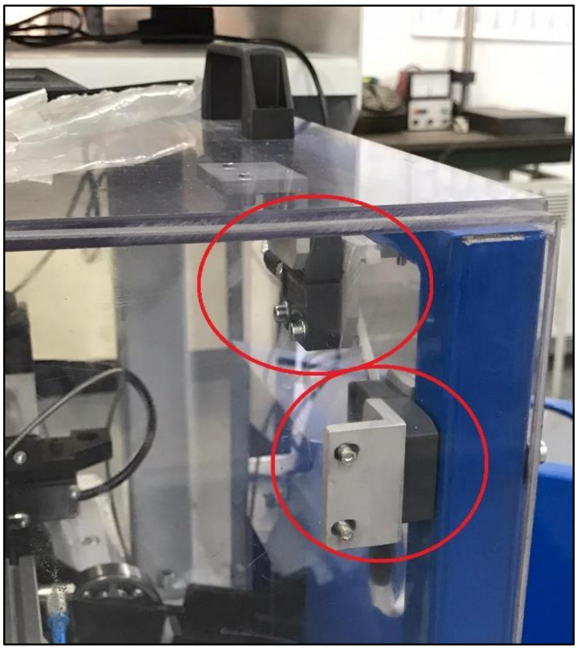
Picture 53 – Removable tunnel guard, held in position by screws, to allow the access to the position sensor in case of malfunctioning situations; it prevents the contact between the operator and the acceptance/reject selector downstream of the MVM machine

- Movable guard: connected by mechanical means, such as hinges, to the machine structure and can, therefore, be opened without specific tools. The guards belonging to this category can be divided into three groups, but no type of guard is generally used by DMI s.r.l. as the company's know-how foresees that the interlocked guards that will be presented later are used in the case of guards subject to frequent opening; the three groups, for the sake of completeness, are:
    - Manually operated guard;
    - Motorized guard: operated by an energy source other than human or by gravity;
    - Automatic closing guard: movable guard activated by an element of the machine, by the piece to be worked, or by a part of the equipment in order to open only when the piece passes and then close again as soon as the latter has passed.
- Adjustable guard: type of fixed or mobile guard which is adjustable as a whole or which integrates an adjustable part; the adjustment can be manual or automatic. An example of an adjustable guard is the telescopic guard that covers the tip of the tool while it is processing the workpiece and the adjustment, of course, is of a different degree depending on the size of the workpiece.
- Interlocked guard: the guard is associated with an interlocking device such that the dangerous functions covered by the guard cannot start until the guard is closed and, by opening the guard, all the dangerous functions of the machine are stopped. An alternative solution, not used by DMI s.r.l., is the integration of the guard locking function whereby the guard remains closed and locked until the risk associated with the dangerous function of the machine is extinguished.

  In summary, the know-how of DMI s.r.l. provides for the use of interlocked guards which, if opened while the machine is in operation, generate a pressure drop which causes the machine to stop; when the guard is closed, following the operator's cycle start command, the machine cycle can resume. Below there are examples of interlocked guard applications, with a zoom on the interlocking device, produced by Pizzato, which the company adopts for the machines in the revamping/design phase.



Picture 54 – Interlocked guard installed on the Pre-Process OR on the frontal door. When the door is opened the pressure drop and the machine stops

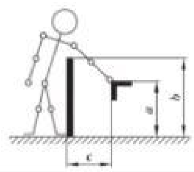


Picture 55 - Double application of interlocked guards on board of the MVM machine; both the front access door and the top access door are equipped with interlocking devices: the opening of one or the other door causes the machine to stop

Picture 56 - Interlocking device, produced by the Pizzato Elettrica Company, which DMI s.r.l. installs on any machine that requires an application

As already mentioned, the applied ISO 12100 and ISO 14120 regulations alone do not allow to reach an acceptable risk reduction threshold; it is therefore necessary to consider the ISO 13857 standard which takes into account and defines the safety distance for guards between the dangerous area and the guard itself. Specifically, the legislation consists of two tables, one to be used when the risk is high, the other to be used when the risk is low. The tables present in the standard are shown below as well as the meaning of parameters a, b and c.

Altezza della zona pericolosa[c] a	Altezza della struttura di protezione[a) b)] b									
	1 000	1 200	1 400	1 600	1 800 ③	2 000	2 200	2 400	2 500	2 700
	Distanza di sicurezza orizzontale dalla zona pericolosa, c									
2 700	0	0	0	0	0	0	0	0	0	0
2 600	900	800	700	600	600	500	400	300	100	0
2 400	1 100	1 000	900	800	700	600	400	300	100	0
2 200	1 300	1 200	1 000	900	800	600	400	300	0	0
2 000	1 400	1 300	1 100	900	800	600	400	0	0	0
1 800	1 500	1 400	1 100	900	800	600	0	0	0	0
1 600 ①	1 500	1 400	1 100	900	800 ②	500	0	0	0	0
1 400	1 500	1 400	1 100	900	800	0	0	0	0	0
1 200	1 500	1 400	1 100	900	700	0	0	0	0	0
1 000	1 500	1 400	1 000	800	0	0				
800	1 500	1 300	900	600	0	0				
600	1 400	1 300	800	0	0	0				
400	1 400	1 200	400	0	0	0				
200	1 200	900	0	0	0	0				
0	1 100	500	0	0	0	0				



a) Le strutture di protezione di meno di 1 000 mm di altezza non sono comprese in quanto non limitano sufficientemente il movimento del corpo.
b) Strutture di protezione di meno di 1 400 mm di altezza non dovrebbero essere utilizzate senza misure di sicurezza supplementari.
c) Per le zone pericolose oltre 2 700 mm, vedere punto 4.2.1.

Picture 57 - Safety distance table for high risk situation (from https://www.certifico.com/normazione/234-documenti-riservati-normazione/3749-en-13857-distanze-di-sicurezza)

Altezza della zona pericolosa[b] a	Altezza della struttura di protezione[a] b								
	1 000	1 200	1 400	1 600	1 800	2 000	2 200	2 400	2 500
	Distanza di sicurezza orizzontale dalla zona pericolosa, c								
2 500	0	0	0	0	0	0	0	0	0
2 400	100	100	100	100	100	100	100	100	0
2 200	600	600	500	500	400	350	250	0	0
2 000	1 100	900	700	600	500	350	0	0	0
1 800	1 100	1 000	900	900	600	0	0	0	0
1 600	1 300	1 000	900	900	500	0	0	0	0
1 400	1 300	1 000	900	800	100	0	0	0	0
1 200	1 400	1 000	900	500	0	0	0	0	0
1 000	1 400	1 000	900	300	0	0	0	0	0
800	1 300	900	600	0	0	0	0	0	0
600	1 200	500	0	0	0	0	0	0	0
400	1 200	300	0	0	0	0	0	0	0
200	1 100	200	0	0	0	0	0	0	0
0	1 100	200	0	0	0	0	0	0	0

a) Le strutture di protezione di meno di 1 000 mm di altezza non sono comprese in quanto non limitano sufficientemente il movimento del corpo.
b) Per le zone pericolose oltre 2 500 mm, vedere punto 4.2.1.

Picture 58 - Safety distance table for low risk situation (from https://www.certifico.com/normazione/234-documenti-riservati-normazione/3749-en-13857-distanze-di-sicurezza)

As can be easily understood, the parameters are defined as follows:

- a: height of the dangerous area;
- b: height of the protective structure;
- c: horizontal safety distance from the dangerous area.

The know-how of DMI s.r.l. provides that when the values of a and b are not present in the table, the parameter c is absolutely not calculated by interpolation, but, for even greater safety reasons, the values of a and b immediately higher than those of the problem are considered so as to obtain a horizontal distance even bigger than the minimum request.

2.5.1.2.2 Choice of safety components different from guards

I have already said that ISO 12100, which allows the assessment of the risk generated by a dangerous situation, as well as the installation of guards to achieve an adequate risk reduction just calculated, defines the installation of protection devices as a means of protection different from shelters.
It is important to notice that the protection devices just mentioned are included into a wider category of safety components. Below there is a list of the most used safety components, with a particular focus on the solutions adopted by DMI s.r.l. on the machinery under study.

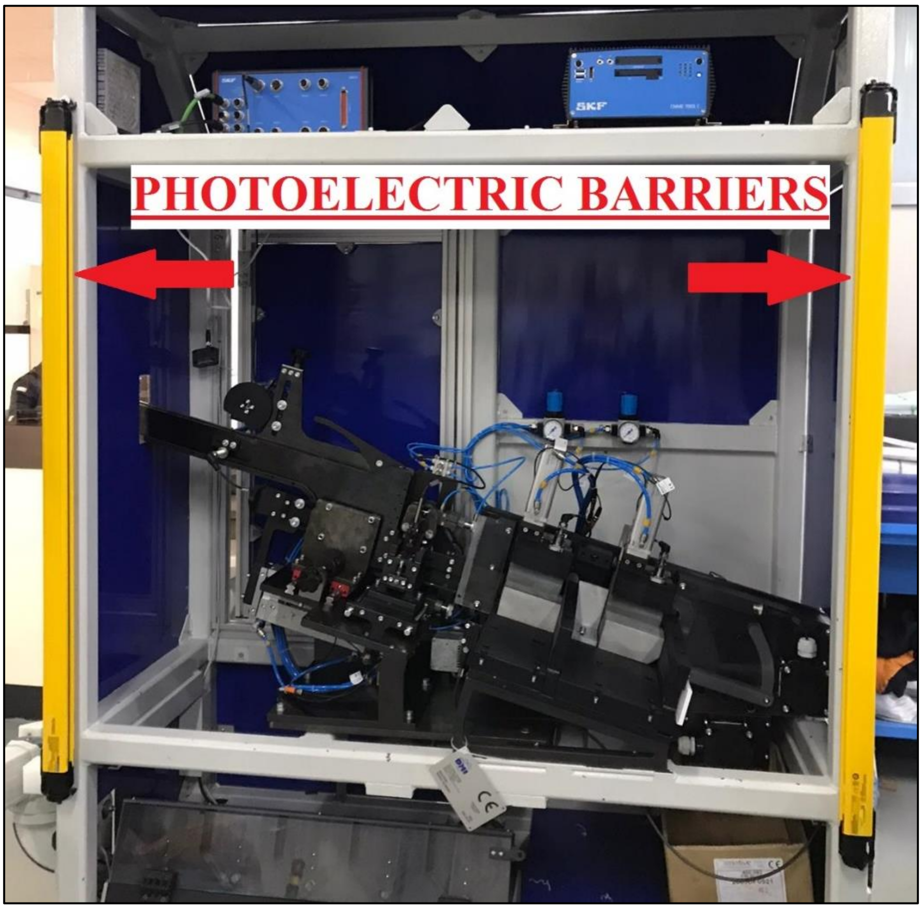
Thanks to continuous technological progress, in recent years there has been an increasingly frequent use of safety components, which make it possible to obtain an adequate risk reduction in a more flexible way than just using guards.
The safety components are therefore to be listed as follows:

- Protection devices:
  - Interlocking devices;
  - Safety barriers;
  - Safety mats;
  - Laser scanner;
  - Two-hand control;
  - Safety strips;
- Emergency stops;
- Safe command and control systems.

We now proceed to a quick analysis of the various safety components, deepening the description of those whose use is intended and preferred by DMI s.r.l.
The interlocking devices are of the mechanical, electrical or other type and their purpose is to prevent the operation of the dangerous functions of the machine in open door conditions or, better said, considering the guard with associated interlocking devices, if it is in open guard conditions, the machine is not allowed to perform dangerous actions.
A more detailed classification of the interlocking devices is provided by ISO 14119 which at this moment will not be analysed, but for the sake of completeness we want to briefly clarify the operation and applications of magnetic type devices, such as the SR series device produced by Pizzato Electtrica and reported above, which are used by DMI s.r.l. on board of the machines subjected to revamping.
The magnetic sensors of this series are of the coded type, they are composed of a sensor for detecting the magnetic field that is connected to the structure of the machine and a coded magnetic actuator to be connected to the movable guard. When the sensor and actuator are approached, therefore when the guard is closed, the sensor recognizes the actuator and activates electrical contacts that will interact with the safety PLC. The sensor is constructed in such a way that it is activated only in the presence of the correct coded actuator and not by any magnet.
The reasons justifying the use of these interlocking devices by DMI s.r.l. are:

- Insensitivity to dirt: the sensors are sealed and even in non-optimal environmental conditions the safety characteristics are not compromised;
- Wide actuation area: the magnetic sensors are equipped with a wide actuation area that makes them suitable for use with guards that are not too precise or whose mechanical characteristics may change over time;
- Operation from multiple directions: this feature allows the sensors and actuators to be positioned with maximum flexibility;
- The installation of several sensor-actuator systems on the same machine is allowed as the minimum distance required between adjacent interlocking systems is very low.

Photoelectric barriers, in particular those produced by Pilz, are among the safety components, alternatives to interlocking devices, used by DMI s.r.l. under specific conditions. These protection devices consist of a modulated light beam emitter and a receiver. The safety barrier must be placed at a minimum distance from the dangerous area and this distance is a function of the speed of approaching the dangerous area, stopping time of the dangerous function and an additional distance that depends on the resolution of the device. The functionality of the photoelectric barrier is foreseen both for any type of approach to the dangerous area, both perpendicular, horizontal and angular.
The choice of using the safety barriers, as already mentioned, depends on the working conditions of the machine they are combined with. They are to be used in the event that frequent access to the dangerous area of the machine is required, for example in the presence of very frequent loading and unloading operations, but they must absolutely not be used when parts of the machine can be projected towards the operator (in this case, in fact, the use of such protection devices would constitute the addition of other dangers). An example of the use of photoelectric barriers, manufactured by Pilz and installed on the MGI machine, is shown in the following picture.



Picture 59 - Photoelectric barriers installed on MGI machine

The safety mats, which consist of mats sensitive to the pressure generated by the presence of an operator or a load in a general sense, are used to interrupt the dangerous function of the machine if the presence is detected. Generally, therefore, these safety components are used to generate a protection area that surrounds the dangerous area of the machine, ensuring that the operator keeps the right distance from it. The know-how of DMI s.r.l. it does not provide for its use as these safety devices are subject to mechanical damage deriving for example from the fall of a tool from the operator's hands during maintenance operations.

A safety component used by DMI s.r.l. is the two-hand control. This command, often accompanied by other protective measures, is for the exclusive use of a single operator to ensure that during use the operator's hands are away from the dangerous area. There are three types of two-hand control and in the design phase DMI s.r.l. on board the machines, when required, install the most complex type of control which includes:

- Two devices (actuators) for control and simultaneous actuation with both hands, which starts the dangerous operation of the machine;
- Simultaneous activation in maintained;
- Deactivation is generated by the release of one or both control devices;
- Release of both commands before restarting;
- Both devices must be pressed within a well-defined short time interval equal to 0,5 s;
- If the time limit is exceeded, both devices must be released before the machine restarts.

For two-hand control, there are conditions to be respected regarding the positioning of the buttons on the machine: they must be far from the dangerous movements that much to make it impossible for the operator, after their release, to reach the aforementioned movements before they are arrested. This distance is equal to the product between the maximum speed of approach and the stopping time of the dangerous movement.

Picture 60 – Two-hand control installed on Pre-Process IR machine

The emergency stop is a safety component whose function is not to reduce the risk present in a specific dangerous situation such as in the case of guards and protective devices, but to interrupt the operation of a machine as quickly as possible if it could give rise to an emergency situation understood as a dangerous situation, caused by human interaction or breakdowns, which needs to be urgently stopped.

The emergency stop is not intended as a substitute for other protective measures, but as a complementary measure. Emergency stops are divided into two categories by ISO 13857 as follows:

- Category 0: machine stop by immediate removal of energy for all machine actuators;
- Category 1: Stopping of movements and operations with the energy available to the machine actuators to obtain the stop and therefore the interruption of the power supply after the stop has been obtained.

The emergency stop function is held thanks to the positive mechanical action on an actuator; the actuators can have different shapes:

- Push button switch operated with the palm of the hand or with the mushroom head;
- Wires, ropes;
- Pedals without mechanical protection;
- Handles/bars or disconnectors.

The colours of the emergency stop buttons must be red for the actuator and yellow for the back; an example is shown in the following figure.

Picture 61 – Emergency stop button with the mushroom head

There are basic requirements for the design of emergency stop actuators:

- An actuator that executes an emergency stop command must remain locked when it is operated;
- To reset the emergency stop command, the actuator must be unlocked;

- The emergency stop control device must keep the command until it is reset by a manual action on the actuator.

As regards the choice of safety control devices, for the reasons already introduced in the paragraph dedicated to the revamping of electrical components, DMI s.r.l. prefers the use of the safety PLC to that of a standard PLC, relay or safety fieldbus.
In the latter case it would not be possible to avoid errors, but only to control them while still guaranteeing a good level of security since communication errors are known as well as measures to avoid them.

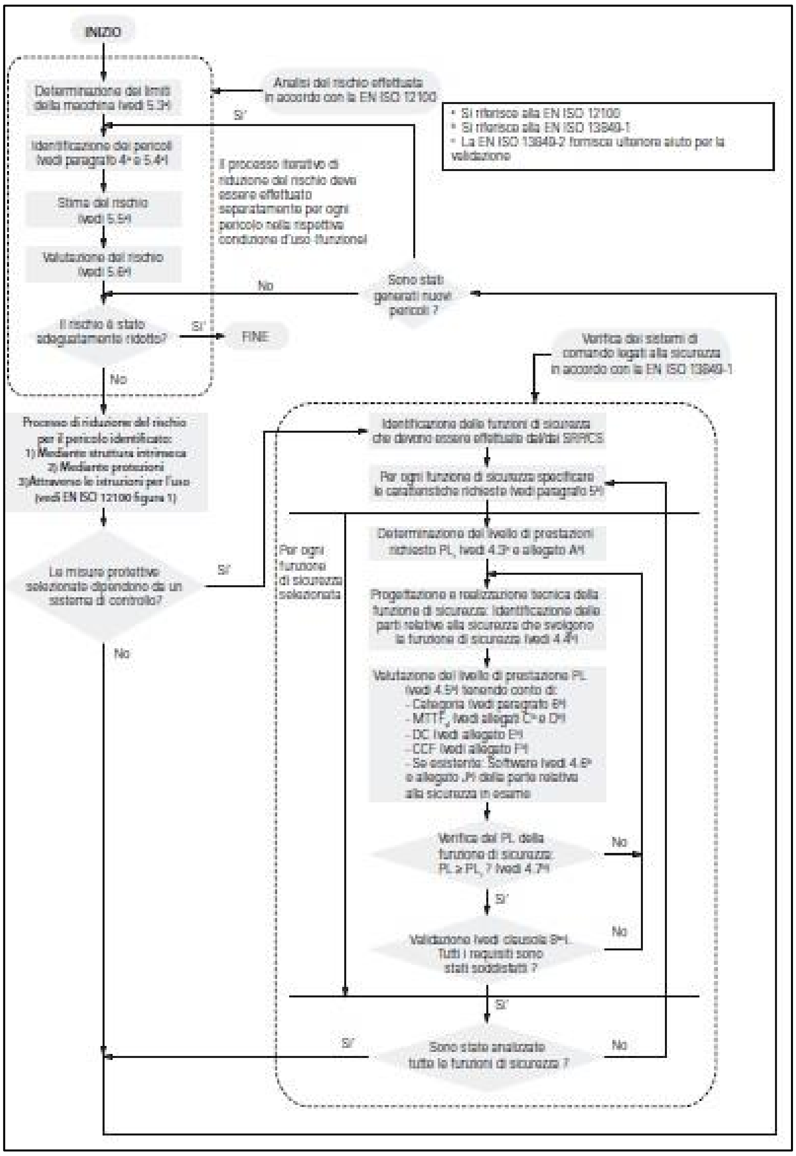
2.5.1.2.3 Residual risk management

Once an adequate level of safety has been reached, the residual risk remains to be managed; for this purpose two other steps are essential which consist in the development and implementation of working methods that control the risk and the consequent training of the personnel assigned to the work and provide clothing and personal protective equipment (safety shoes, safety helmet, protections for eyes, safety gloves and respiratory protection). In order to manage the residual risk, the user manual of the machines will report the following symbols for stimulating the use of PPE:

Picture 62 – PPE use recommendation reported on the machines user manuals

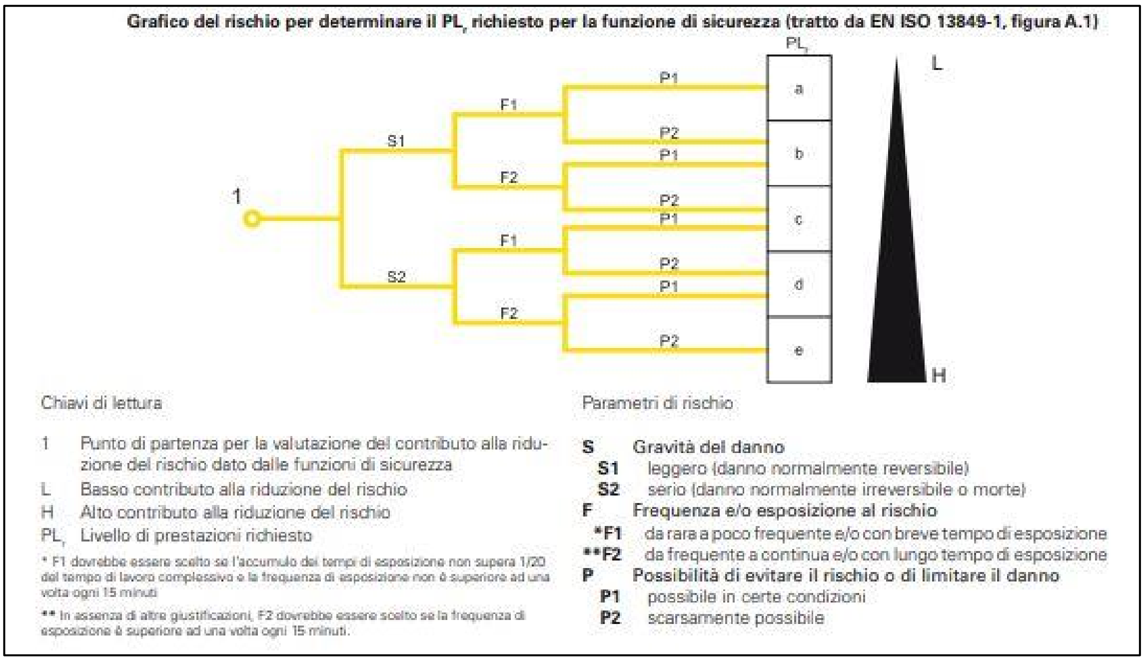
2.5.1.2.4 Risk reduction through control systems from ISO 13849

As mentioned, the reduction of risk, in addition to being performed with the use of structures as shelters and with changes in the design phase, is achieved with the use of control systems. In the event that the risk is reduced through a control system, it is necessary to consider the ISO 13849 standard, necessary to assess the efficiency and adequacy of this system. In this way, given a risk of a certain level, it is possible to follow the regulations to implement a safety function of the same or higher level. The procedure followed for the implementation of a suitable safety function is shown in the following Picture 63.



Picture 63 – Implementation of a suitable safety function chart
(from https://www.pizzato.it/media/images/catalog/item/File/Pdf/Document/introduzione_sicurezza.pdf)

As can be seen from the chart just introduced, an adequate safety function must be defined for each risk associated with the machine. The first step, therefore, is the definition of the level of performance (PL_r) required for the safety function considered which can be evaluated with a graph present in the ISO 13849-1 standard and is reported below.



Picture 64 – PL_r definition chart
(from https://www.pizzato.it/media/images/catalog/item/File/Pdf/Document/introduzione_sicurezza.pdf)

The manufacturer of the machinery, following the standard therefore, starts from point 1 of the chart and, following the diagram answering questions S, F and P, comes to define the level of safety performance necessary to reduce the risk considered. The PLs are classified on five levels, from PL-a to PL-e as the risk increases and each of them identifies an average probability of dangerous failure per hour PFHD (1/h) as shown in the following picture.

PL	Probabilità media di guasti pericolosi per ora PFHD (1/h)		
a	$\geq 10^{-5}$	e	$< 10^{-4}$
b	$\geq 3 \times 10^{-6}$	e	$< 10^{-5}$
c	$\geq 10^{-6}$	e	$< 3 \times 10^{-6}$
d	$\geq 10^{-7}$	e	$< 10^{-6}$
e	$\geq 10^{-8}$	e	$< 10^{-7}$

Picture 65 – PL and PFHD relation
(from https://www.pizzato.it/media/images/catalog/item/File/Pdf/Document/introduzione_sicurezza.pdf)

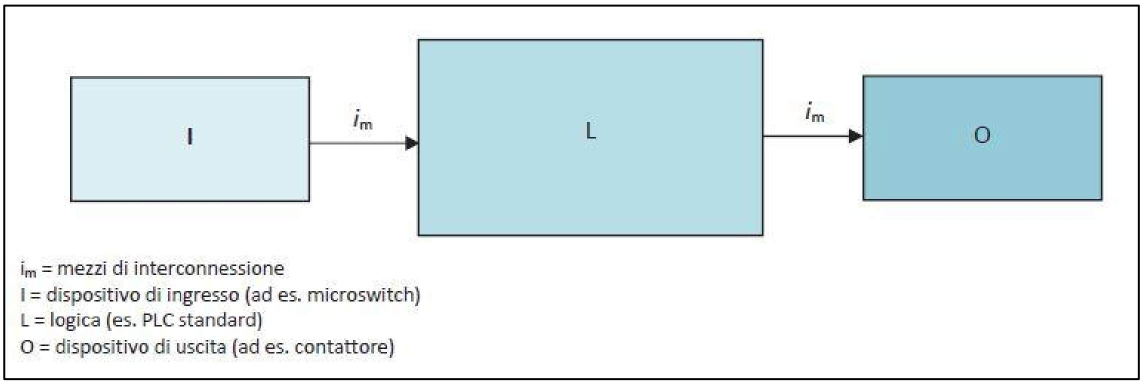
After defining the required PL_r, it is necessary to create a control system of the safety function, whose PL will be calculated, verifying that it is greater than or equal to that required. To evaluate a control system performance level, various parameters are required, such as:

- The safety category of the system, which in turn derives from the architecture of the control system and its behaviour in case of failure occurrence;
- $MTTF_D$ of the components;
- System DC;
- CCF of the system.

The control circuits can be represented by means of a logic block structure of the type:

- Input or input of signals;
- Logic or logic of signal processing;
- Control signal output or output.

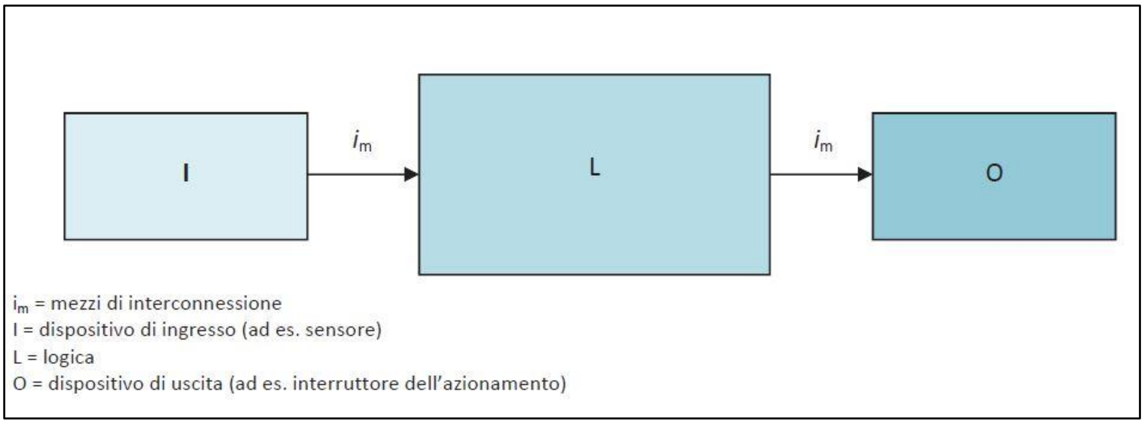
The ISO 13849-1 standard defines five circuit structures defined as system designated architectures. The architectures, combined with the requests of behaviour in case of system failure and with the minimum values of $MTTF_D$, DC and CCF, indicate the safety category of the control system as described in the following presentation.
For category B, defined the SRP / CS as the part of the control system linked to safety, it is required that the latter be designed, built, selected and assembled according to the applicable regulations and, for the specific application, the basic safety principles.
For this category there is no diagnostic coverage ($DC_{avg} = 0$) and the $MTTF_D$ of the channel can assume values from low to medium



Picture 66 - Category B system designated architecture (from https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

Being a single channel architecture, the CCF considerations are irrelevant. The behaviour of the system is such that the occurrence of an error or failure can lead to the loss of the safety function. The system architecture is shown in the previous Picture.

For the design of the category 1 control system, in addition to the requirements of category B, it is necessary that well-tried components and equally well-tried safety principles are adopted. A well-proven component is thus defined as a component widely used in the past with excellent results in similar applications or built and tested using principles that demonstrate its high reliability when used for safety applications.
For category 1 the $MTTF_D$ of the channel must be high, while the diagnostic coverage is still nil and the CCF is still irrelevant. The behaviour of the channel that realizes the safety function is such that a fault can lead to the loss of the safety function, but with a higher channel reliability than category B, as there is a mean time to dangerous failure ($MTTF_D$) higher: the probability of error occurrence is lower. The architecture of the control system for the category in question is shown below.



Picture 67 - Category 1 system designated architecture (from https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

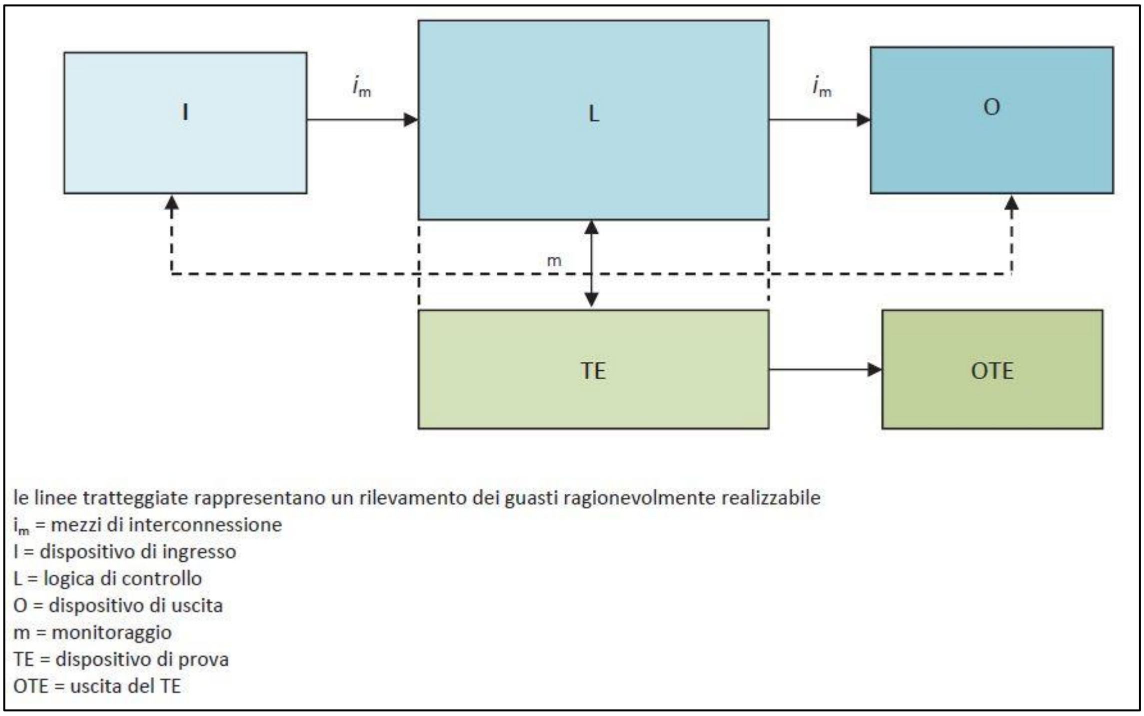
For the architecture of the category 2 control system, the requirements of category B are applied, as for category 1, with the addition of well-tested safety principles and furthermore the safety functions implemented by category 2 structures must be tested periodically and in particular:

- When the machine is turned on;
- Before the start of any dangerous situation.

The verification of the safety function must:

- Allow operation if no faults have been detected;
- Generate an OTE output that activates appropriate control actions if a fault is detected.

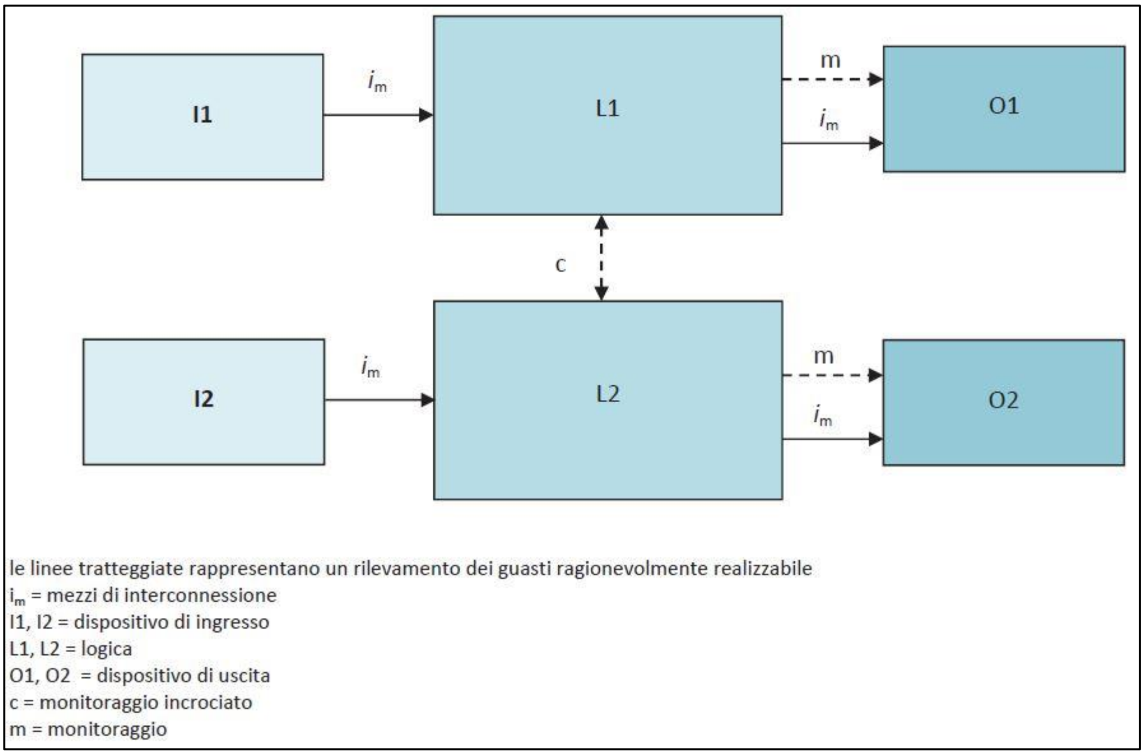
For the architecture that meets the requirements of this category, the calculations of $MTTF_D$ and DC_{avg} must take into account only the I, L and O functional channel of the following Picture without considering the test channel blocks TE and OTE. The average diagnostic coverage of the functional channel can range from low to high as well as the $MTTF_D$ depending on the required performance levels PL_r. Since there are two channels, even if one is dedicated to performing the periodic test of the safety function, measures against CCFs must be applied. The behavior of the category 2 architecture is such that the occurrence of a fault in the interval between two consecutive tests can lead to the loss of the safety function, but in the presence of a test the safety function must be detected by the test. The block diagram of the channels is shown in the following Picture.



Picture 68 - Category 2 system designated architecture (from https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

For category 3, the requirements for category B must be applied and in addition well-established safety principles must be applied. The category 3 SRP/CS must be designed so that a single fault does not lead to the loss of the safety function and is always detected; the single fault detection requirements do not mean that all faults must be detected.
Therefore, the accumulation of minor failures can lead to the loss of the safety function with consequent emergence of dangerous situations. Category 3 DC_{avg} varies from low to

medium and the $MTTF_D$ of each of the two redundant channels can vary from low to high depending on the PL_r. Being a two-channel architecture, it is necessary to apply measures against CCFs. The diagram of category 3 is shown below in order to clarify what has been said.



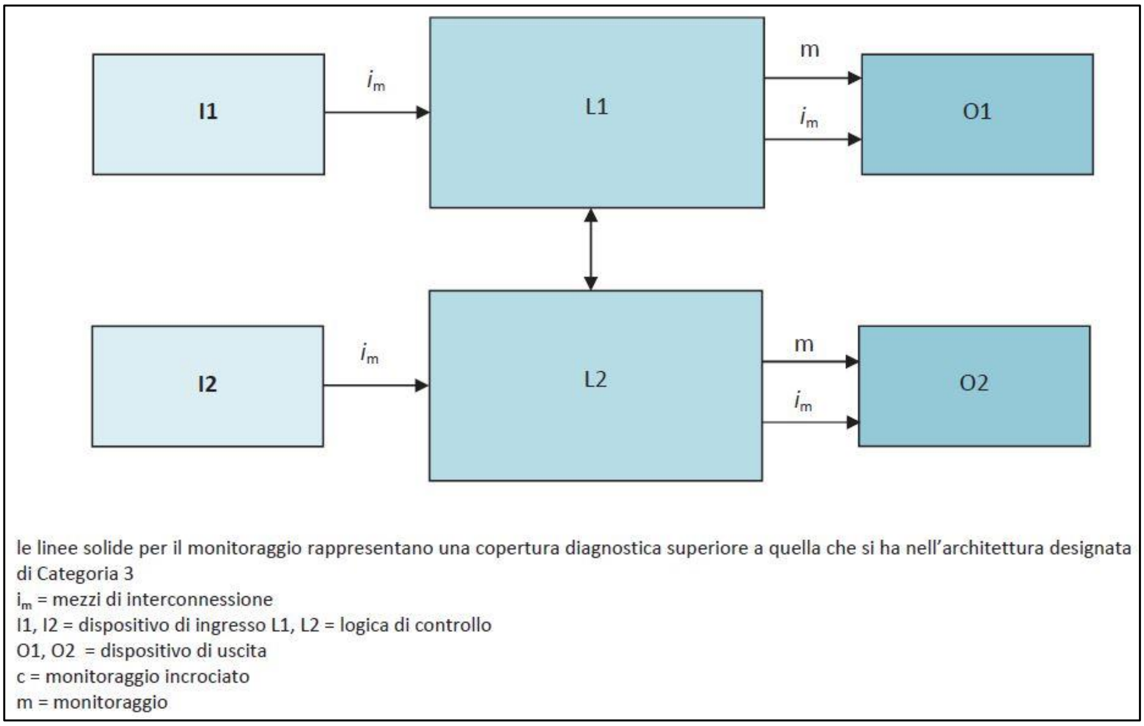
Picture 69 - Category 3 system designated architecture (from https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

Category 4, like the previous ones, requires that the same requirements of category B and in addition the well-tested safety principles are applied, furthermore the category 4 SRP/CS must be designed so that:

- A single fault does not lead to the loss of the safety function;
- The single fault must be detected in time in order to prevent the loss of the safety function;
- If detection of the fault is not possible, the accumulation of undetected faults must not lead to the loss of the safety functions.

The overall diagnostic coverage of the SRP/CS is high and includes the accumulation of faults as well as the mean time to dangerous failure. On the redundant dual-channel structure, measures against CCF must be applied.

Below is the layout of the category 4 control system architecture.



Picture 70 - Category 4 system designated architecture (from https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

The average time to dangerous failure $MTTF_D$ is a parameter that defines the quality of the system components by defining their average service life before a dangerous failure occurs, not a generic failure, and is expressed in years. The calculation of this parameter is based on the numerical values provided by the manufacturers of the individual components that make up the system, if these values are missing, ISO 13849 provides calculation tables. Based on the number value of the $MTTF_D$, this will be divided into three categories as shown in the following table.

Classificazione	Valori
Non accettabile	$MTTF_D$< 3 anni
Basso	3 anni ≤ $MTTF_D$< 10 anni
Medio	10 anni ≤ $MTTF_D$< 30 anni
Alto	30 anni ≤ $MTTF_D$ ≤ 100 anni

Picture 71 - $MTTF_D$ categories
(from https://www.pizzato.it/media/images/catalog/item/File/Pdf/Document/introduzione_sicurezza.pdf)

In the case of components subject to wear, the company that supplies these components, generally mechanical or hydraulic, provides data B10 or the number of operations that the component within which 10% of the samples have failed in a dangerous way; the ISO standard provides for formulas for the conversion of this data into $MTTF_D$. What is important for calculating the PL of the system is the calculation of the $MTTF_D$ parameter for the whole channel starting from those of the components that compose it.
In circuits with single-channel architecture, as in the cases of categories B, 1 and 2, the contribution of each component is linear and the calculation of the $MTTF_D$ is given by the following formula:

$$\frac{1}{MTTF_D} = \sum_{i=1}^{N} \frac{1}{MTTF_{D,i}}$$

In the case of two-channel systems, see architectures 3 and 4, the calculation of the mean time to dangerous failure is obtained by the symmetrization of the $MTTF_D$s of the two channels that make up the system under analysis according to the formula:

$$MTTF_D = \frac{2}{3} \cdot \left[MTTF_{DC1} + MTTF_{DC2} - \frac{1}{\frac{1}{MTTF_{DC1}} + \frac{1}{MTTF_{DC2}}} \right]$$

The DC diagnostic coverage is a parameter that measures how much the system is able to self-monitor in case of its own malfunction. The diagnostic coverage was higher the higher the number of dangerous faults that can be detected by the system. The numerical parameter DC is a percentage value that is calculated from the data provided by the manufacturer of the system components using the table in Annex E of ISO 13849-1. Since in general there are more tricks in the same circuit to detect different anomalies, an average value DC_{avg} is calculated which will fall into four possible ranges as follows:

- High DC_{avg}, $DC_{avg} \geq 99\%$;
- Medium DC_{avg}, $90\% \leq DC_{avg} < 99\%$;
- Low DC_{avg}, $60\% \leq DC_{avg} < 90\%$;
- Null DC_{avg}, $DC_{avg} < 60\%$ (admitted only for categories B or 1);

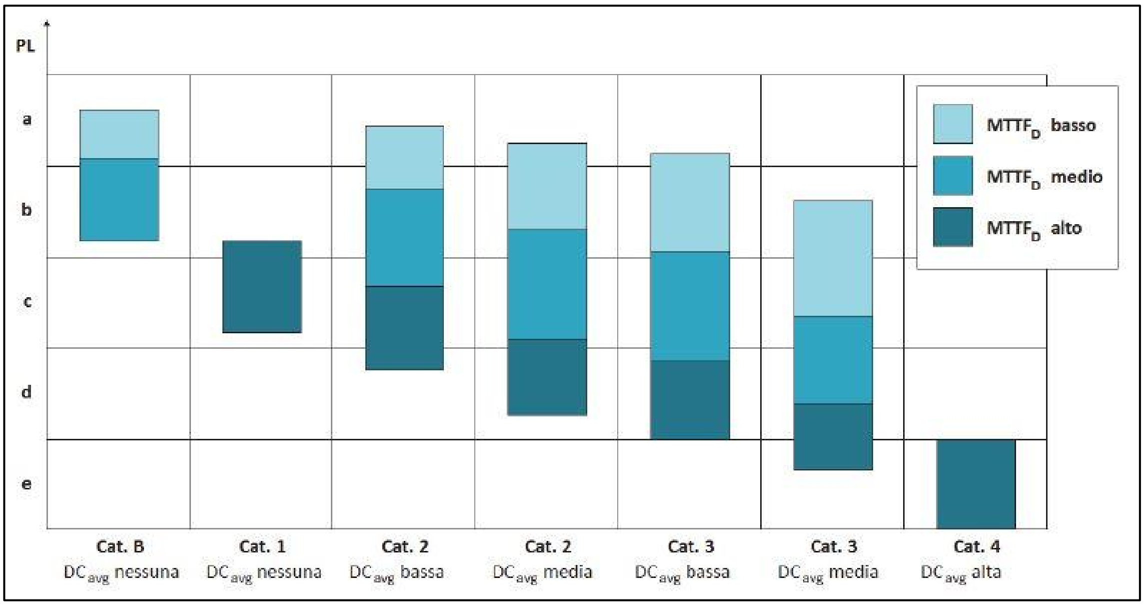
An aspect of fundamental importance to consider in the case of dual channel control systems, therefore from category 2 to 4, is the evaluation of any causes of common faults CCF that can affect the operation of the system redundancy control.

Annex F of ISO 13849-1 contains a method for assessing whether sufficient measures have been taken against CCFs. The following Picture contains a series of measures against CCF and the values associated with them: each measure contained in the list can only be associated with the value reported if the latter has been adopted, otherwise a null value. If in the end an overall value of 65 or higher is obtained, then the measures adopted are sufficient to believe that the residual fraction of the CCF is less than or equal to 2%, vice versa it is necessary to adopt new measures.

	Misure contro i CCF	**Valore**
1	**Separazione/segregazione**	
	Separazione fisica tra i percorsi dei segnali, ad esempio: – separazione nel percorso dei cavi/tubature; – rilevamento di cortocircuiti o circuiti aperti nei cavi con test dinamici; – sufficienti distanze in aria e superficiali sulle schede dei circuiti stampati.	15
2	**Diversità**	
	Sono utilizzati differenti tecnologie/progetti o principi fisici, ad esempio: – attivazione della funzione di sicurezza diversa per ogni canale (ad es.: elettronica o elettronica programmabile su uno ed elettromeccanica sull'altro); – misurazione analogica e digitale delle variabili (ad es.: distanze, pressioni, temperature) – componenti di costruttori diversi.	20
3	**Progetto/applicazione/esperienza**	
3.1	Protezione contro sovratensioni, sovracorrenti, sovrapressioni, sovratemperature, ecc.	15
3.2	Uso di componenti ben provati.	5
4	**Valutazione/analisi**	
	Per ogni SRP/CS è condotta una FMEA i cui risultati sono utilizzati per evitare CCF nel progetto.	5
5	**Competenza/addestramento**	
	Addestramento dei progettisti per comprendere le cause e le conseguenze dei CCF.	5
6	**Misure contro le influenze ambientali**	
6.1	Protezione dei sistemi elettrici/elettronici dalla contaminazione (polvere, liquidi, sporco) e dai disturbi elettromagnetici, secondo quanto riportato nelle norme applicabili. Conformità ai requisiti del costruttore per la purezza del fluido da pressurizzare (filtri del fluido, misure per impedire l'ingresso dello sporco e per lo spurgo dei gas), per i sistemi a fluido. Per i sistemi misti (a fluido ed elettrici) entrambi i criteri devono essere considerati.	25
6.2	Requisiti per l'immunità ad altre influenze ambientali (temperature, urti, vibrazioni, umidità), secondo quanto riportato nelle norme applicabili.	10

Picture 72 - Measures and associated values against CCF
(https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

After taking into consideration the parameters just presented that contribute to the calculation of the PL of the control system, it is possible to carry out an evaluation of the aforementioned PL using the graph in ISO 13849-1, point 4.5 and shown in the following picture.



Picture 73 - Relationship between PL, DCavg, Category and MTTFD
(from https://www.inail.it/cs/internet/docs/alg-pubbl-sistemi-comando-macchine-secondo-norma.pdf)

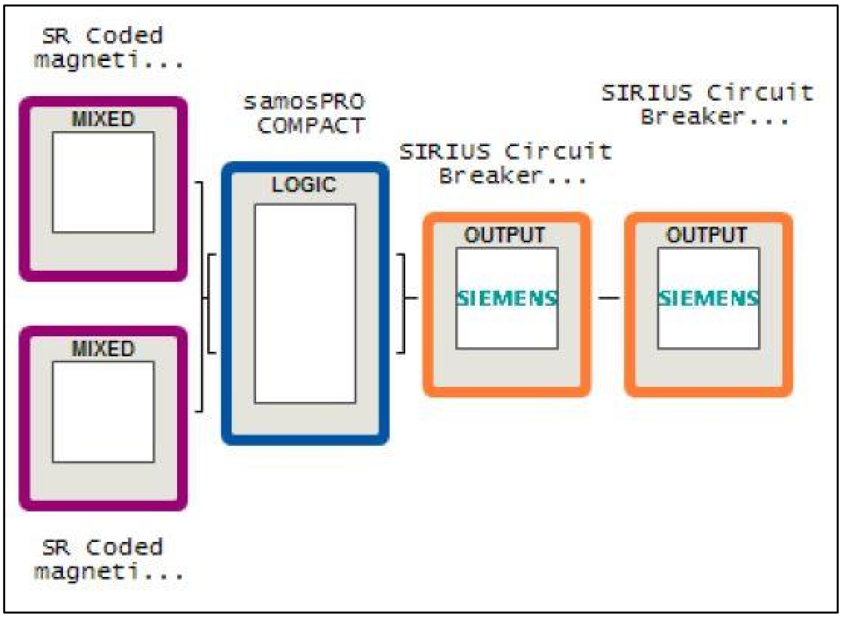
The know-how of DMI s.r.l. involves the use of the PAScal software produced by Pilz. The software allows to verify the achievement or the overcoming of the target in terms of PL simply reproducing the architecture of the control system and inserting the component that constitutes it in each logic block. By adding to the software the catalogs of the manufacturers of the components to be used, the software allows a precise calculation of all the parameters that contribute to the definition of the PL.

As an example, the calculation of the PL of the double channel system for the control of the safety function called “door” is given. First of all, in the report extrapolated from the software we can see the summary of the computation presented in the first page of the same report. The summary of the computation is here reported.

SRP/CS overview					
System/Module	Target PL	Result	CCF Factor	PFH_D	Achieved PL
door	d	Target Achieved	Target Achieved	5.70E-07	d
emergency button	d	Target Achieved	Target Achieved	5.66E-07	d

Picture 74 - Summary report of the PL computation executed for the control system "door"

The logic carried out by the safety PLC provides that when the door is opened, controlled by Pizzato magnetic sensors, a signal corresponds to the Serius series circuit breaker produced by Siemens. The designated architecture of the system is shown in the figure below.



Picture 75 - Designated architecture of the control system called "door"

As soon as the name of the components that make up the safety command and control system have passed to the software, directly from the loaded catalogues, the software extrapolates the data known by the manufacturers to complete the table that follows in the Picture 76, where the results for DC_{avg}, $MTTF_D$ and CCF computations are reported.

Subsystem/channel	PL	PFHD	Cat.	DCavg	MTTFD: Limited	MTTFD: sym.	MTTFD values for Channel 1	MTTFD values for Channel 2	DC	Mission time	CCF
door	d	5.70E-07									
Mixed	e	4.72E-08	3	90.00%	100.00 years	100.00 years	100.00 years	100.00 years			100
1.1.1.1 - SR Coded magnetic sensor (connected with Pizzato safety modules)							182648.40 years			20.00 years	
1.1.2.1 - SR Coded magnetic sensor (connected with Pizzato safety modules)								182648.40 years		20.00 years	
1.2.1.1 - samosPRO COMPACT	e	1.30E-09	4							20.00years	

Subsystem/channel	PL	PFHD	Cat.	DCavg	MTTFD: Limited	MTTFD: sym.	MTTFD values for Channel 1	MTTFD values for Channel 2	DC	Mission time	CCF
1.3.1.1 - SIRIUS Circuit Breakers | Circuit Breaker 3RV | 3RV1	d	2.61E-07	2	90.00%	91.00 years	91.32 years	91.32 years		90.00%	9.13years	100
1.4.1.1 - SIRIUS Circuit Breakers | Circuit Breaker 3RV | 3RV1	d	2.61E-07	2	90.00%	91.00 years	91.32 years	91.32 years		90.00%	9.13years	100

Picture 76 - Table from PAScal software reporting all the data required for the PL of the control system

3 MIB OR machine

The MIB OR machine has been designed to automatically perform the measurements of the outer diameter, the ovality and the conicity of the bearing outer ring. The MIB OR machine, according to DMI s.r.l. know-how, is the first machine, moving along the production line which is critical for the reasons that will be presented shortly.

As a measuring machine, the machine object of this chapter is used to select the outer rings of the bearing in production according to whether they conform to production specifications or not. The MIB OR, therefore, is a necessary machine to quantitatively and qualitatively evaluate the processes that the ring has undergone upstream of it.

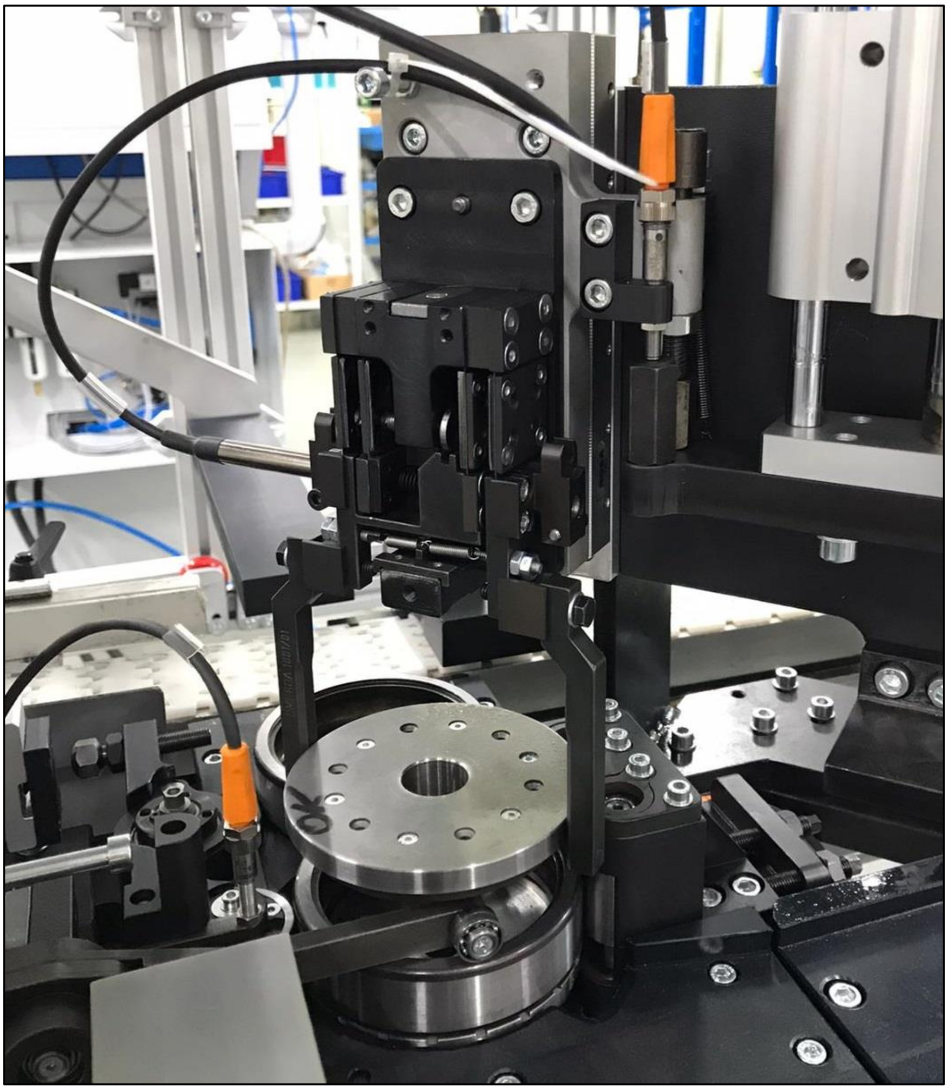
As already illustrated in the layout presented in the dedicated paragraph, the MIB OR is positioned after the CL machine which grinds the external diameter of the OR and evaluates its working quality. The CL machine, due to its size, is a key point of the line and therefore, in accordance with the know-how of DMI s.r.l., it must be subject to as few machine stops as possible.

The stop of a grinding machine such as the CL, in fact, requires quite a long time and therefore DMI s.r.l. has deemed it appropriate to equip the MIB OR machine with everything necessary to avoid the CL stop by acting directly on it through a feedback control that will be activated whenever an out of control condition is detected following a measurement. The feedback control, as well as the evaluation of the measurement and the statistical control of the latter are possible thanks to the use of GME III-General Measuring Equipment whose operation will be presented shortly.

The work cycle of the machine is very simple: the ring, after arriving at the stop station, the machine station that stops the rings that move along the line on the flexlink and cadences their entries in the machine, enters the machine and accesses the measurement station.

The measuring station is composed by a rotating plate, set in motion by an electric motor, and a set of rollers, which keep the rings in position by keeping the contact with them during the measurement. The rings start to rotate allowing the LVDT trasducer installed on the measuring head, during the rotation of the rings, to perform two diameter measurements at two different heights in order to allow an evaluation of the conicity of

the rings. Once the measurement has been detected, the software on the machine evaluates whether it conforms to the production specifications or not and commands a rejection or an in-line of the rings on the flexlink downstream of the MIB OR machine.
In the following Picture the measuring station is reported.



Picture 77 - Measurement station on MIB OR machine

Taking a look at the Picture above, you can see the measuring head, the probe in a horizontal position, the rotating plate under the measuring ring and the set of rollers used to hold the ring in position; in the background you can see the loading station pushing the rings from the flexlink to the measuring station in the close-up.

3.1 MIB OR machine revamping

3.1.1 Mechanical components revamping

The revamping of the mechanical components installed on the MIB OR machine followed a guideline already consolidated in the know-how of DMI s.r.l.

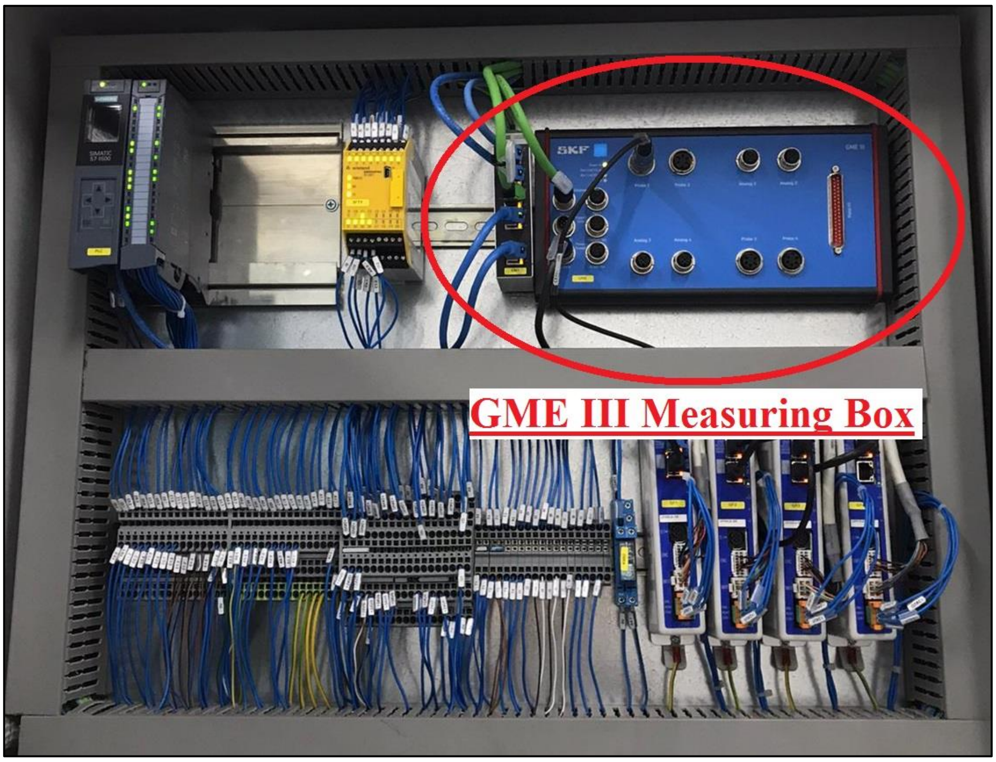
First of all, the machine was dismantled of the mechanical components, the mechanical condition of movement of the electric axes was checked and possibly replaced, the springs and screws were replaced with as many commercial components, but the key to the mechanical revamping was the replacement and redesign of a measuring head more compliant with the latest measurement standards.

For the MIB OR machine, 3D printing was used for the production of support components, and a new electric motor on the machine was installed.

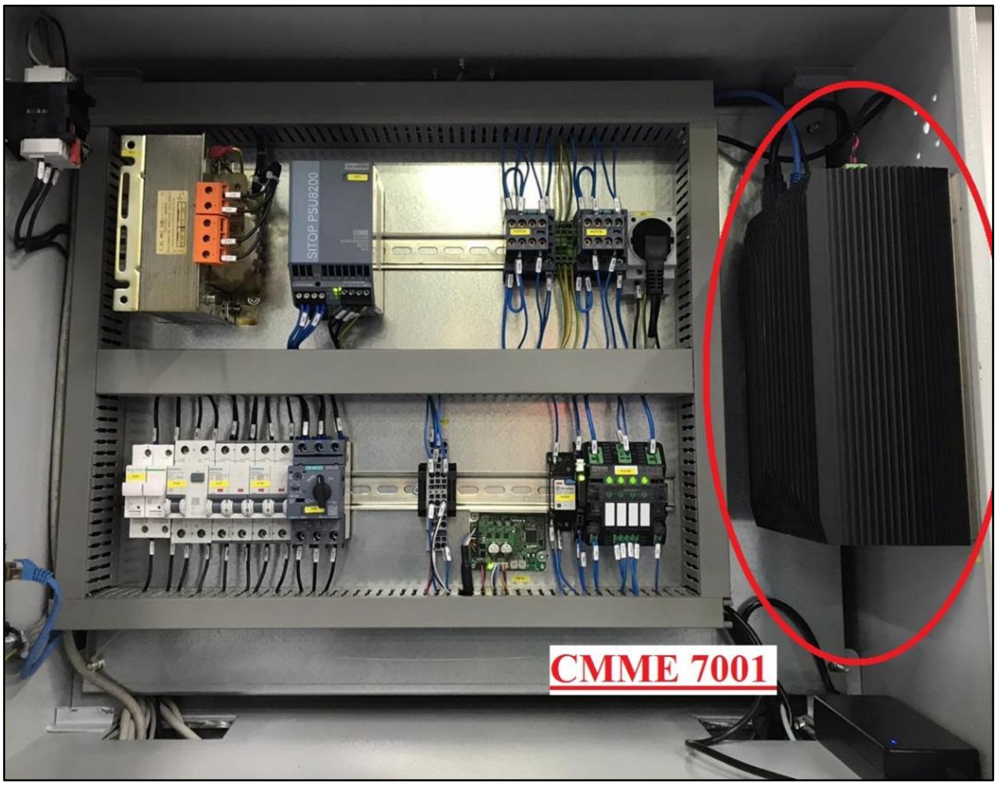
3.1.2 Electrical components revamping

The MIB OR machine appears to be a completely electric machine and therefore the absence of pneumatic components has greatly complicated the construction of electrical circuits and an electrical panel which, on board the aforementioned machine, is divided into two parts. The first part of the electrical components is installed in a panel behind the machine, while the second part of them is installed behind the operator panel.

The construction of the electrical panel is made clearer by introducing the following Pictures.



Picture 78 - GME III installed on board on MIB OR machine



Picture 79 – CMME 7001 C installed on board on MIB OR machine

As it is easy to notice, the substantial difference between the standard application electrical panel presented previously in chapter 2 and the one installed on board the MIB OR machine is, in addition to the complexity, the presence of two new components: GME III and CMME 7001. This is, in particular, the measuring box, which collects the measurement data coming from the LVDT transducer during the cycle performed by the machine and the on-board computer, connected to each other via Ethernet connection usually LAN 2 (green cables), which allows data to be displayed. Manual control of the measuring box is possible using GME III's GUI software via CMME 7001.
As done in chapter 2, if you want to describe the user-friendly HMI-Human Machine Interface, a description of the push-button panel installed on the operator panel is given and then a description of the most important windows that can be viewed on the on-board computer in the control panel.
Below is a Picture of the push-button panel so as to make clear the function of each button in the description that follows.

Picture 80 – Push-button panel installed on MIB OR machine

The functions of the buttons are:

- Step forward: in manual cycle mode, each time the button is pressed it enables a step of the cycle according to step by step;
- Man.Aut: allows the selection of the cycle in automatic or manual mode; in manual mode, the cycle can be carried out keeping the guards open as two-hand

control is required and the button that enables the latter is located on the side of the operator panel away from sources of danger;

- Stat cycle: allows you to start the cycle in automatic mode; when the light is on, the cycle is running;
- Power ON: when the magnetic switches connected to the machine guards are closed and signal that the dangerous functions are safe, pressing this button commands electrical power to the actuators;
- Machine ready: the light indicates that the machine is ready to execute the cycle as the axes are in position and the GME is ready;
- Calibration: when pressed, the button enables the calibration cycle;
- Reset: in automatic cycle conditions the machine returns to the machine ready position;
- Stop cycle: during the execution of the cycle in automatic mode, it allows the machine to conclude the cycle in progress and therefore stop at the next ready condition;
- Emergency: the button with the mushroom head allows, when pressed, to block any movement of the machine and interrupt the power supply; to be released, the button must be turned clockwise.

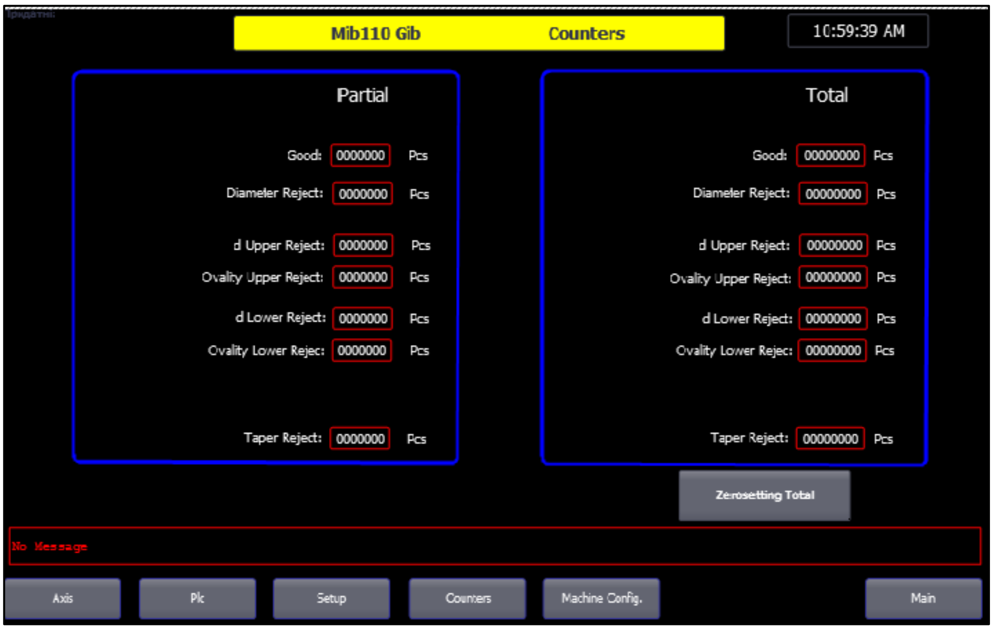
As for the control panel that allows interaction between the machine and the operator in terms of checking the machine status or setting the operating parameters, the machine is equipped with a touch screen that allows the aforementioned interaction. On the screen, as already extensively detailed in the paragraph dedicated to the human machine interface, it is possible to view the various pages which can be accessed from a main menu. Below is a brief description of the pages that allow the operator to actively interact with both the machine and the production process.

Picture 81 - Main menu page on the MIB OR control panel

On the control panel page shown above and corresponding to the main item of the menu below, all the information about the machine and the production process is reported, necessary to allow the operator to perform a complete and quick check on the most relevant parameters. In particular, it is possible to view the status of the measurement, i.e. which measurement is in progress for the ring in position under the measuring head between the two diameters, the two ovalities or the conicity, and the machine status corresponding to the various items including the status of communication with GME III. Finally, in the first section of the page just presented, data D, corresponding to the difference between the last calibration and the previous one, is reported. Below you can see the production data divided as follows:

- Cycle time relative to the last cycle performed by the machine;
- Number of pieces beyond which an automatic calibration will be commanded;
- Number of good pieces, therefore conforming to the production standard;
- Number of pieces rejected following the detection of the dimensions;
- Reset command of the counters of good/bad pieces.

If the operator wants to deepen the production data, he can access the counters item from the main interface menu and open the page illustrated in the following Picture.



Picture 82 - Page on the MIB OR control panel corresponding to the counters item

In the previously introduced page the operator can control the status of the production process. The data are displayed in two groups: Partial, the production data collected after the last counter zero-setting operation, and Total, i.e. the data collected by the machine from its installation. In particular it is possible to control the number of good parts as well as of rejected parts, but it in the last case it is possible to deepen the reason of rejection in terms of number of parts rejected due to diameter, ovality or conicity non-conformity problems. The items upper and lower in the name of the counters means that the reference dimension conforming to the production specification has been exceeded or not in production.

The machine configuration item in the selection menu at the bottom of the control panel corresponds to the page, not shown here, which allows the operator to select the language, enable or disable temperature compensation, and finally enable the modification of the set-up of the axes. Therefore, when you want to act on the set-up of the axes, you must first pass from the page just described, which is the one corresponding to the machine configuration item, to enable the change you want to make, and then access the page corresponding to the axis item in the menu in bottom of the control panel. This page is shown in the Picture below and a brief description will follow.

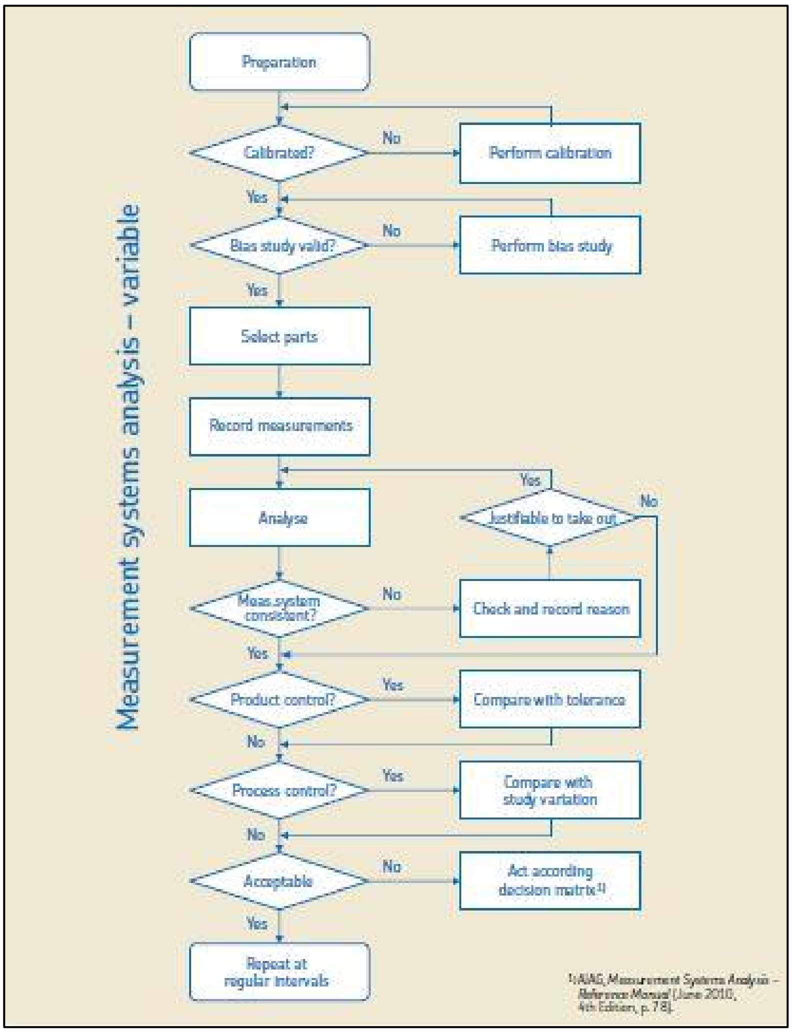
Picture 83 - MIB OR control panel page corresponding to the axis item

In the page above, it is possible to access the set-up of the axes. On the right there is the possibility to choose which axis to set among the four available, i.e. stopper, loader, measuring axis and axis to perform the rejection. On this page it is therefore possible to view the position, speed and thrust force data of the cylinder, view the status of the cylinder corresponding to the selected axis as well as the last four alarm codes for the same cylinder. Furthermore, it is possible to move the cylinder freely in the negative or positive direction by activating the Jog- and Jog + functions respectively, or to move the axis in pulse mode. Finally, it is possible to set the home position value and the work position value for the selected axis.

The page accessed by clicking on the PLC item, not further detailed and not even reported, allows you to view the status of the PLC digital inputs/outputs and is very similar to the one already presented in the paragraph dedicated to HMI in chapter 2.

3.2 Measurement system analysis

After the revamping process of the MIB OR machine has been completed, it is necessary to start analyzing the measurement system. The know-how of DMI s.r.l. provides that the guideline presented in the Measurement systems analysis-Quality Techniques QT5 brochure prepared by SKF is followed. The following flow chart shows the steps that need to be followed:



Picture 84 - Flow diagram for measurement system analysis (from QT5 brochure by SKF)

As evident in the flow diagram just presented, it is necessary to perform a variable analysis. This approach is necessary since the values presented on the control charts that can be analyzed through GME III, of the type $\overline{X} - S$, $\overline{X} - R$ or for single values X and mobile range R_{mobile}, are expressed in continuous quantitative units (in fact, these are diameters, ovalities and taper).

In order to briefly recall the concept of a control chart, this is a tool used for the continuous monitoring of a characteristic of a process. It consists of a sequential diagram characterized by an upper upper line (upper control limit UCL), a central line (central control line CCL) and a lower line (lower control limit LCL).

The samples considered in temporal order are shown on the abscissa axis, while the values of the monitored characteristic appear on the ordinates. Control charts are the starting point for assessing the out-of-control conditions of the process. The analysis of the control charts and their monitoring are the responsibility of GME III, and we will deal with them shortly in the dedicated paragraph. The introduction was only necessary to justify, at this point, the use of a flow diagram by variables rather than by attributes, as knowledge of the control charts is not necessary for the analysis of the measurement system.

The procedure followed for the study of the measurement system consists of two steps:

- Evaluation of the instrument capability, which aims to evaluate the minimum repeatability of the instrument;
- r&R evaluation, necessary in order to consider the repeatability and Reproducibility effects separately, but also as an overall error.

The first step is necessary when you want to evaluate a new measuring instrumentation and it is carried out in the manufacturer's plant, i.e. DMI s.r.l., before the shipment and installation of the machinery under study takes place. The second step, on the other hand, is necessary before final acceptance and production start-up takes place.

3.2.1 Instrument capability analysis

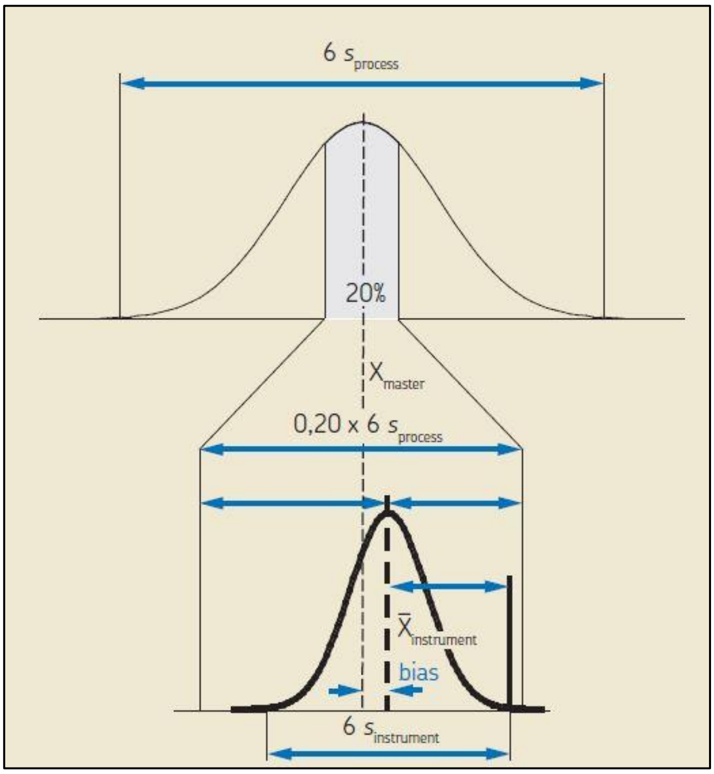
On automatic measuring equipment it is possible to detect the variability of the measuring instrument itself, corresponding to the instrument standard deviation $s_{instrument}$ coming from mechanical instability, part positioning, pick up system and electronic problems.

Instrument capability: the minimum repeatability of the instrument itself defined as $6s_{instrument}$, the instrument is capable for the parameter under investigation.

When a measuring equipment is installed along a production line, the variability due to measurement cannot be separated from variability due to product. A strategic evaluation consists in measuring the same part in the same position more than once (specifically 50 times) avoiding, in this way, the influence due to product changes.

QT5 brochure from SKF quality standard recommend to compare the instrument variation with the 20% of the process variation, i.e. $6s_{process}$, or with the 20% of the tolerance.

In the following picture the compared terms are clearly defined.



Picture 85 - Terms of comparison for instrument capability computation (from QT5 brochure by SKF)

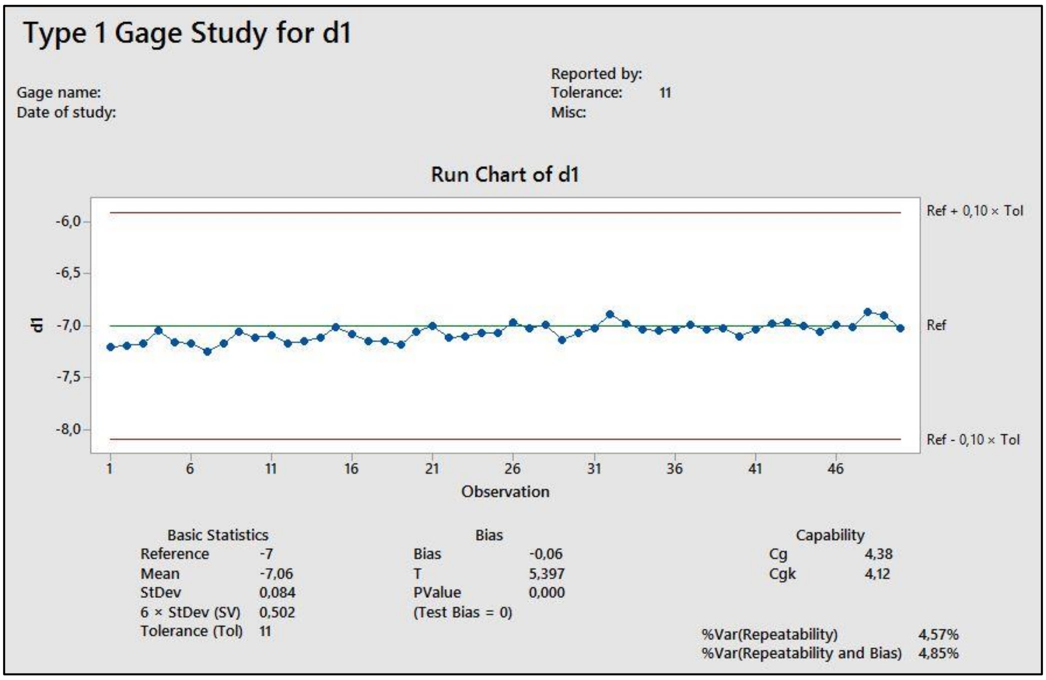
The two indices capability coefficients are expressed as:

$$C_g = \frac{0{,}2 \cdot s_{process}}{s_{instrument}}$$

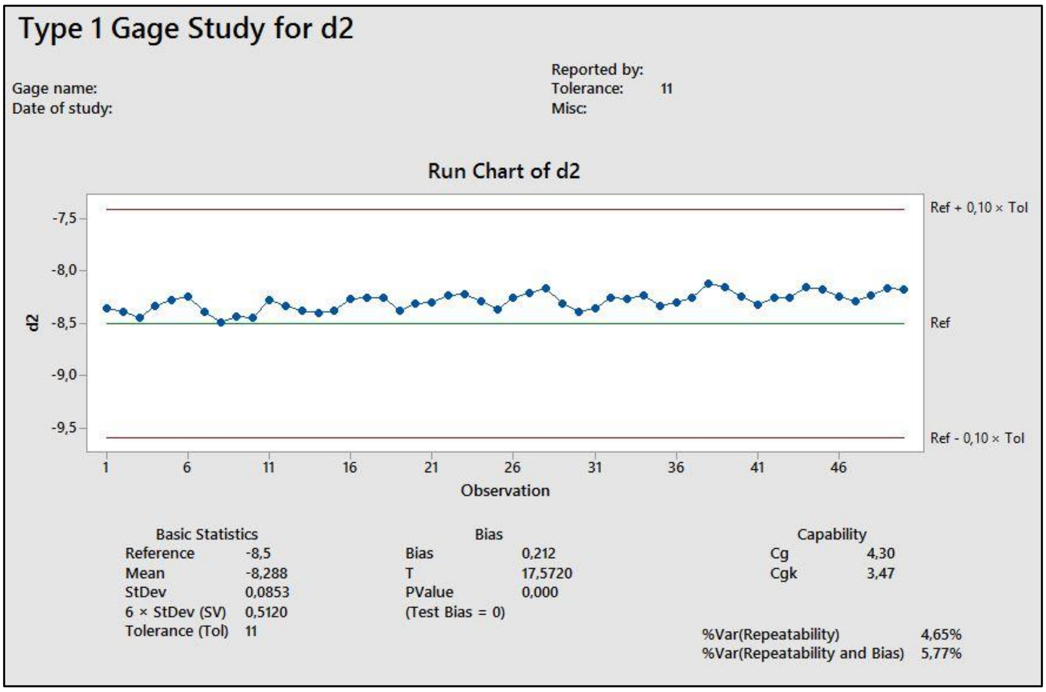
$$C_{gk} = \frac{0{,}1 \cdot 6s_{process} - |\bar{x}_{instrument} - x_{master}|}{3s_{instrument}}$$

The minimum acceptable criterion is C_g and C_{gk} = 1,33.

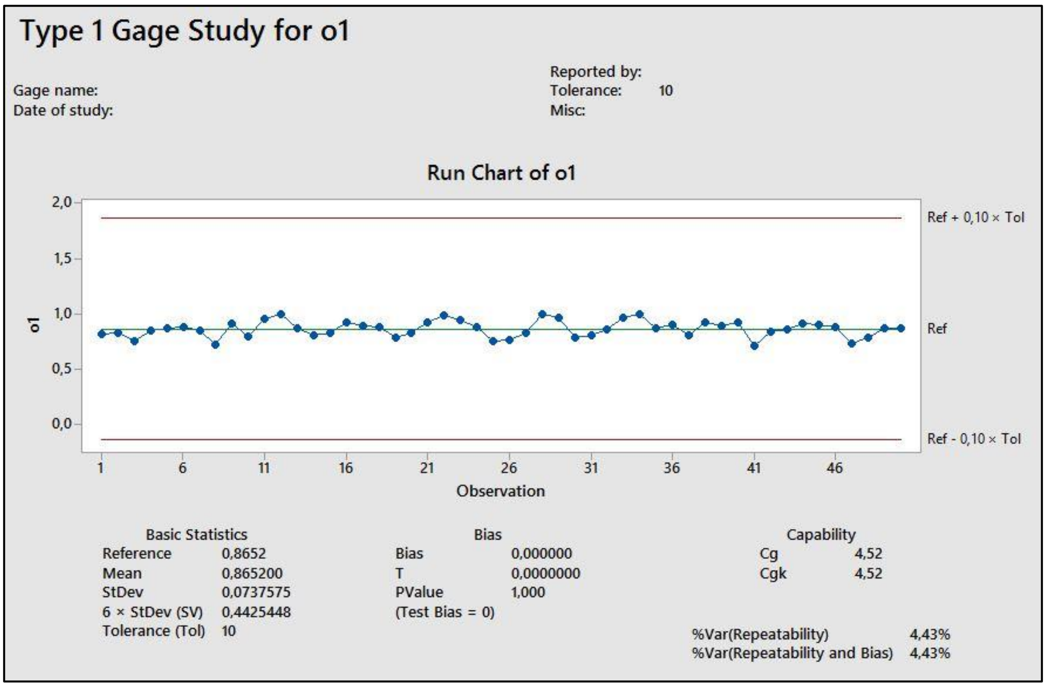
The results of the instrument capability analysis have been computed with Minitab software and are here reported. Even if it might be sufficient to consider only the direct measurements performed by the machine, i.e. the two diameters d1 and d2, the know-how of DMI s.r.l. provides that the instrument capability is calculated for all measures that can be obtained also for indirect ones such as ovality and taper.



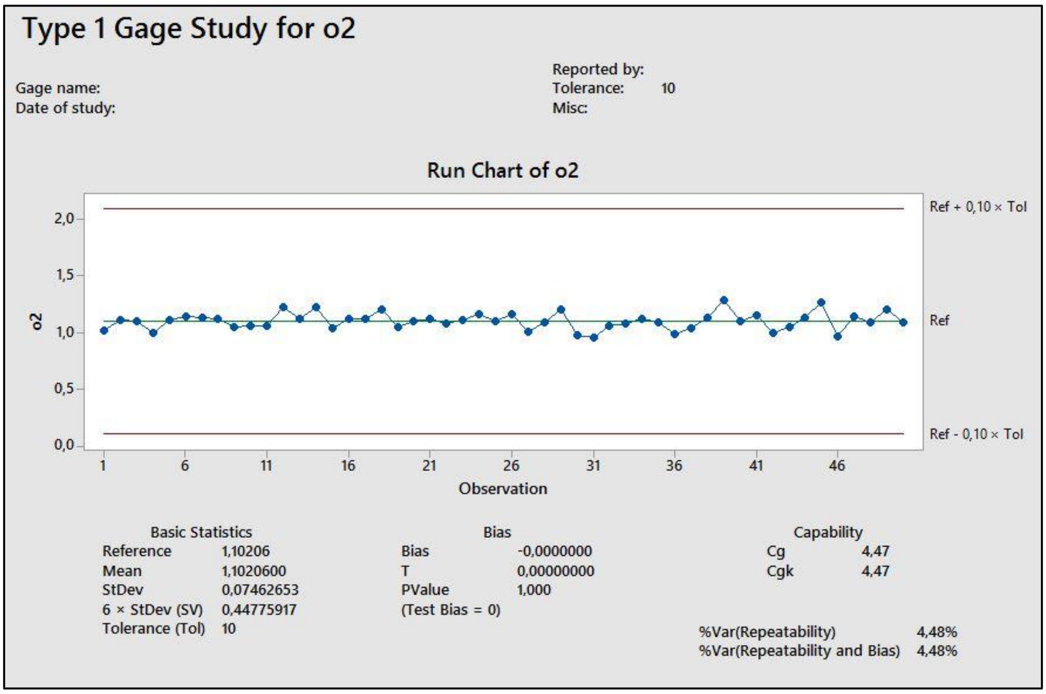
Picture 86 - Summary report from Minitab about d1 instrument capability analysis



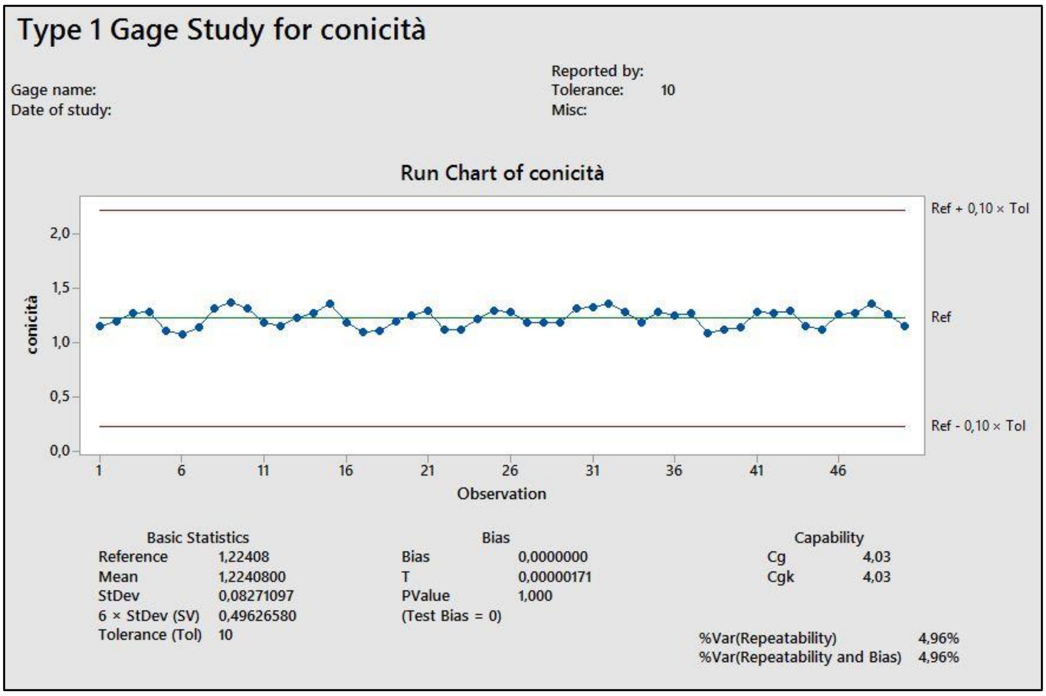
Picture 87 - Summary report from Minitab about d2 instrument capability analysis



Picture 88 - Summary report from Minitab about o1 instrument capability analysis



Picture 89 - Summary report from Minitab about o1 instrument capability analysis



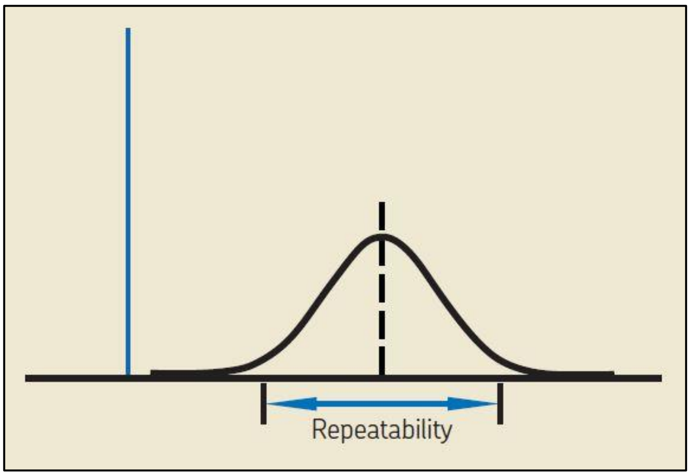
Picture 90 - Summary report from Minitab about taper instrument capability analysis

Looking at the above reported results it has been possible to assess a good capability of the instrument, this means that the measurement system can measure parts consistently and accurately. The first step of the measurement system analysis has been successfully completed so the second one can be analysed.

3.2.2 repeatability and Reproducibility (r&R) analysis

The second step of the measuring system analysis consists in the evaluation of the repeatability and reproducibility.

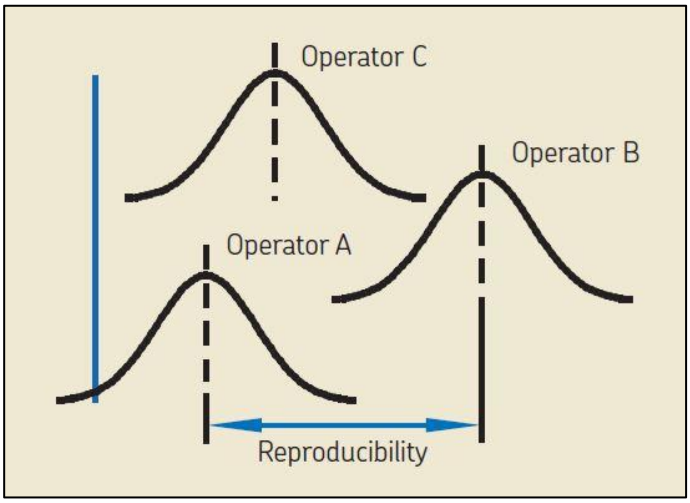
The repeatability is defined as the variation in measurements obtained with one measuring instrument when it is used several time by the same operator in the measurement of the identical characteristic on the same part. In the following picture it is possible to make the ideas clearer.



Picture 91 - Repeatability representation (from QT5 brochure by SKF)

The standard deviation of the random error occurring in every single measurement is represented by the within standard deviation. It may be expected that this standard deviation will have different values under the different conditions, i.e. different operators, different occasions and different parts. The average value for the within standard deviation for all conditions is called repeatability standard deviation which is estimated by the term s_r. The repeatability value $r = s_r$ depends solely on the repeatability standard deviation.

On the other hand the reproducibility is defined as the variation, in the average, of the measurements made by different operators using the same measuring instrument when they are measuring the same characteristic on the same part.



Picture 92 - Reproducibility representation (from QT5 brochure by SKF)

The standard deviation of the error, which consists of both random and systematic components is represented by the between standard deviation. It includes variabilities of operators. The reproducibility value R = s_R depends on the between operator standard deviation and the repeatability standard deviation.

The measurement system variation for repeatability and reproducibility (r&R) is obtained by:

$$r\&R = \sqrt{r^2 + R^2}$$

It is important to underline that for automatic equipment there is no operator influence so that the r&R is equal to the repeatability.

Once the repeatability and the reproducibility r&R is determined, it should be compared to the process variation, i.e. $6s_{process}$:

$$\%r\&R = \frac{r\&R}{s_{process}} \cdot 100$$

The computation of the parameter just presented starts from the acquisition of measurement data with GME III end the subsequent analysis with Minitab. The measurement process, according to DMI know-how and SKF quality standards, consist in the measurements performed by one operator on twenty parts, numbered from 1 to 20, repeated three times for a total of 60 measurement data.

A general guideline for the acceptance of the measuring equipment r&R, as well as the corrective actions to be taken in order to achieve a good level of this parameter, is given from SKF QT5 brochure like follows.

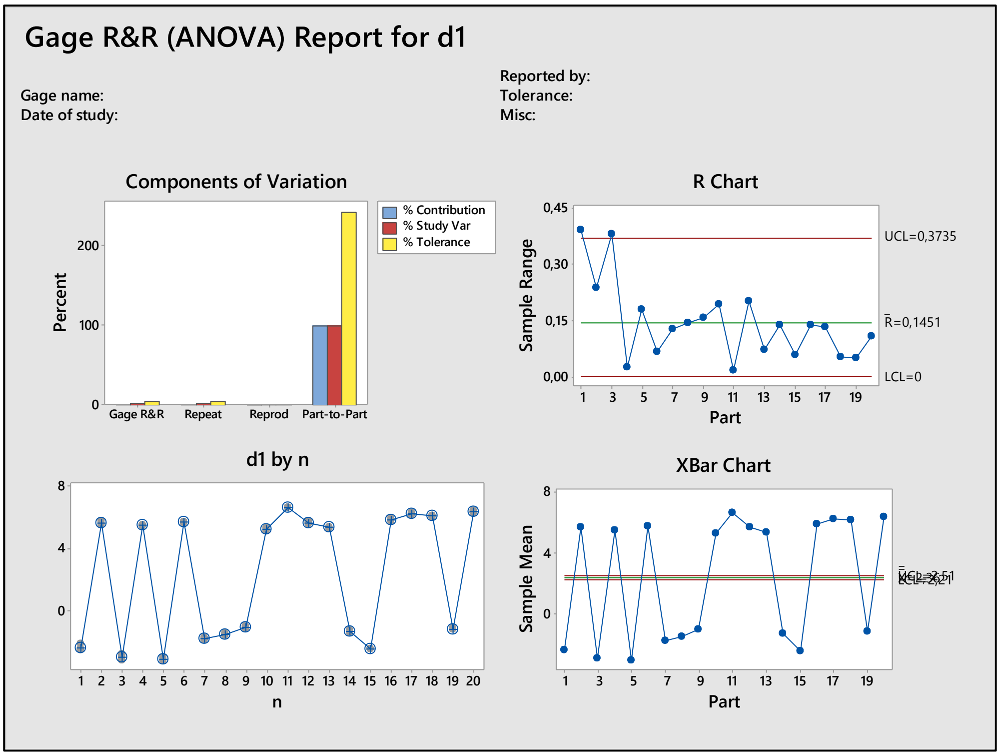
%r&R ≤ 10%	measurement system is generally considered to be **acceptable**
10% < %r&R ≤ 30%	**may be acceptable** for some applications
%r&R > 30%	measurement system is considered to be **unacceptable**

Action on measurement system

%r&R ≤ 10%	Use equipment. Recommended, especially useful when trying to sort or classify parts or when tightened process control is required.
10% < %r&R ≤ 30%	Use equipment – Decrease sorting limits for critical parameters and improve equipment. Decision should be based upon, for example, importance of application measurement, cost of measurement device, and/or cost of rework or repair. Should be approved by the customer.
%r&R > 30%	Improve equipment – Process control: Measurements mask process variation, no realistic C_p/C_{pk}. – Inspection: Decrease sorting limits by 3 times $s_{r\&R}$ on each side. Every effort should be made to improve the measurement system. This condition may be addressed by the use of an appropriate measurement strategy; for example, using the average of several readings of the same part characteristic in order to reduce final measurement variation.

Picture 93 - Acceptance criteria and possible corrective actions for measuring system %r&R study

The method of analysis selected on Minitab is the ANOVA method and the typical report is here represented.



Picture 94 - Report for d1 r&R study with Minitab

Minitab graph window output is, looking at the previously introduced Picture, composed by the following diagrams:

- Components of variations: here the sources of variations are highlighted;
- R chart: here the range of measurement values obtained for each part is reported;
- Characteristic by part: here the mean value obtained for each part in the three measurements is reported;
- X-bar chart.

On the other hand, in the following picture it is important to underline that looking at the %Study Var (%SV) column it is possible to understand how much each component accounts for as a percentage of the total variation. Another important parameter is the number of distinct categories, which represents the number of non-overlapping confidence intervals that will span the range of product variation. You need at least five distinct categories to have an adequate measuring system.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
n	19	925,085	48,6887	5655,67	0,000
Repeatability	40	0,344	0,0086		
Total	59	925,429			

α to remove interaction term = 0,05

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,0086	0,05
Repeatability	0,0086	0,05
Part-To-Part	16,2267	99,95
Total Variation	16,2353	100,00

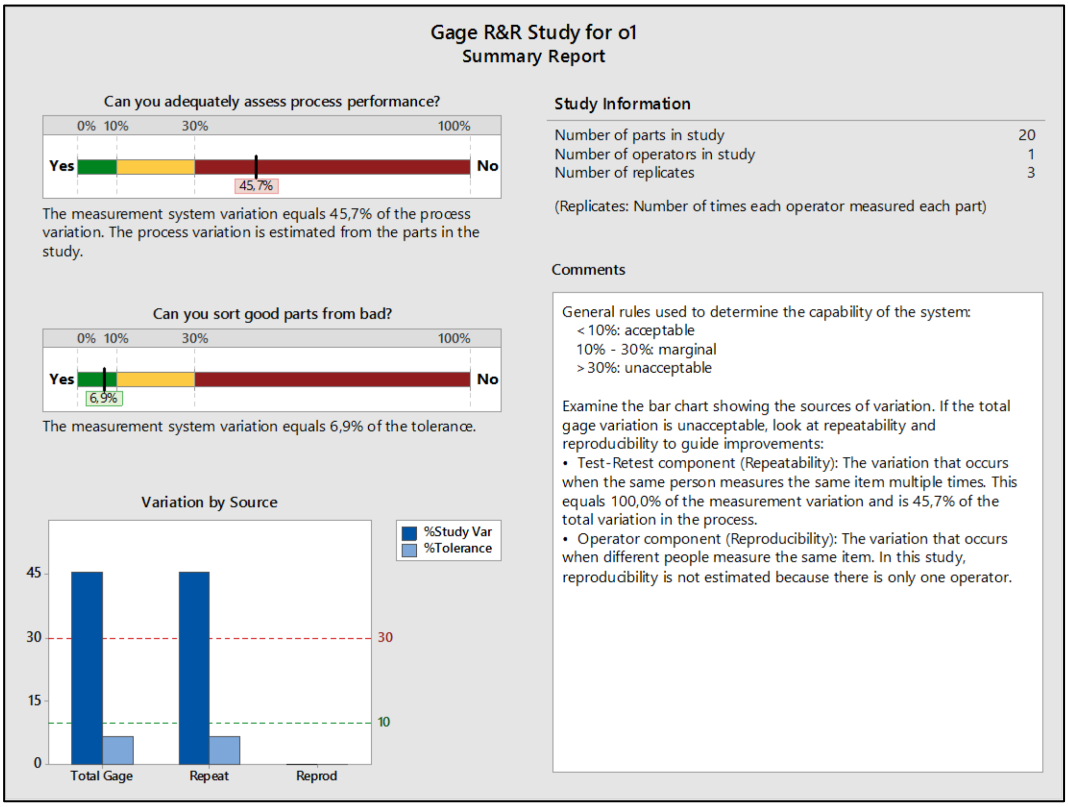
Process tolerance = 10

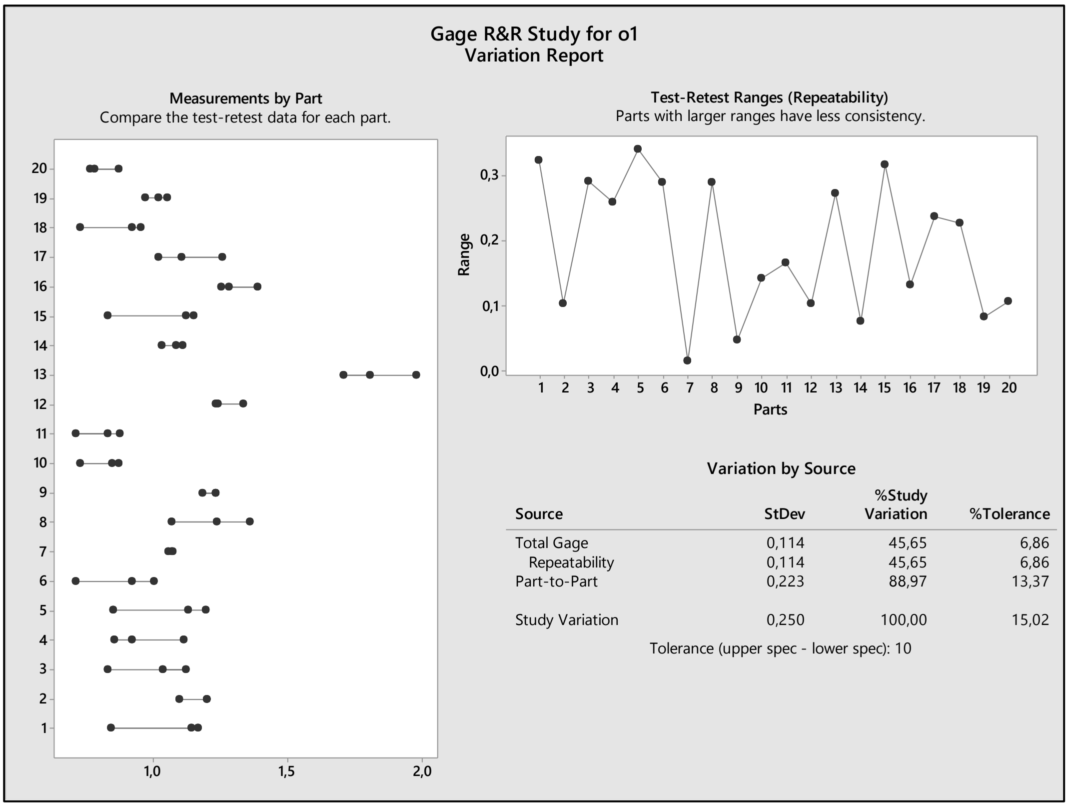
Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0,09278	0,5567	2,30	5,57
Repeatability	0,09278	0,5567	2,30	5,57
Part-To-Part	4,02824	24,1694	99,97	241,69
Total Variation	4,02930	24,1758	100,00	241,76

Number of Distinct Categories = 61

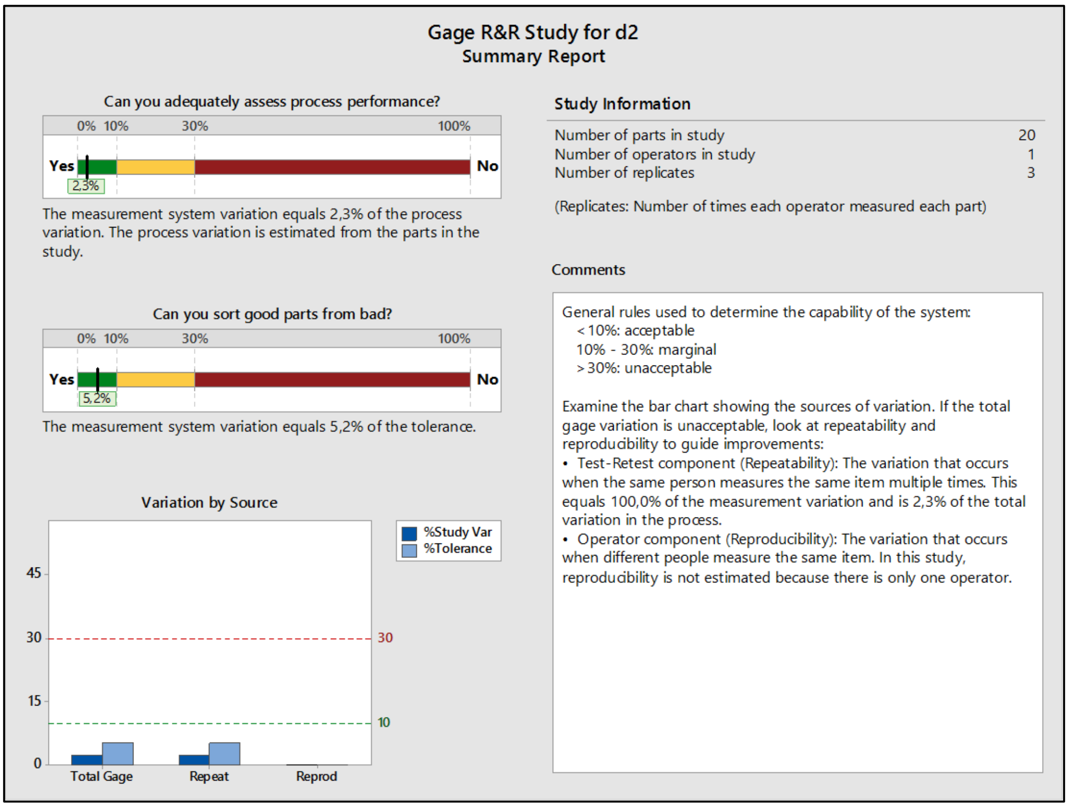
Picture 95 - Results of r&R study for d1 with Minitab

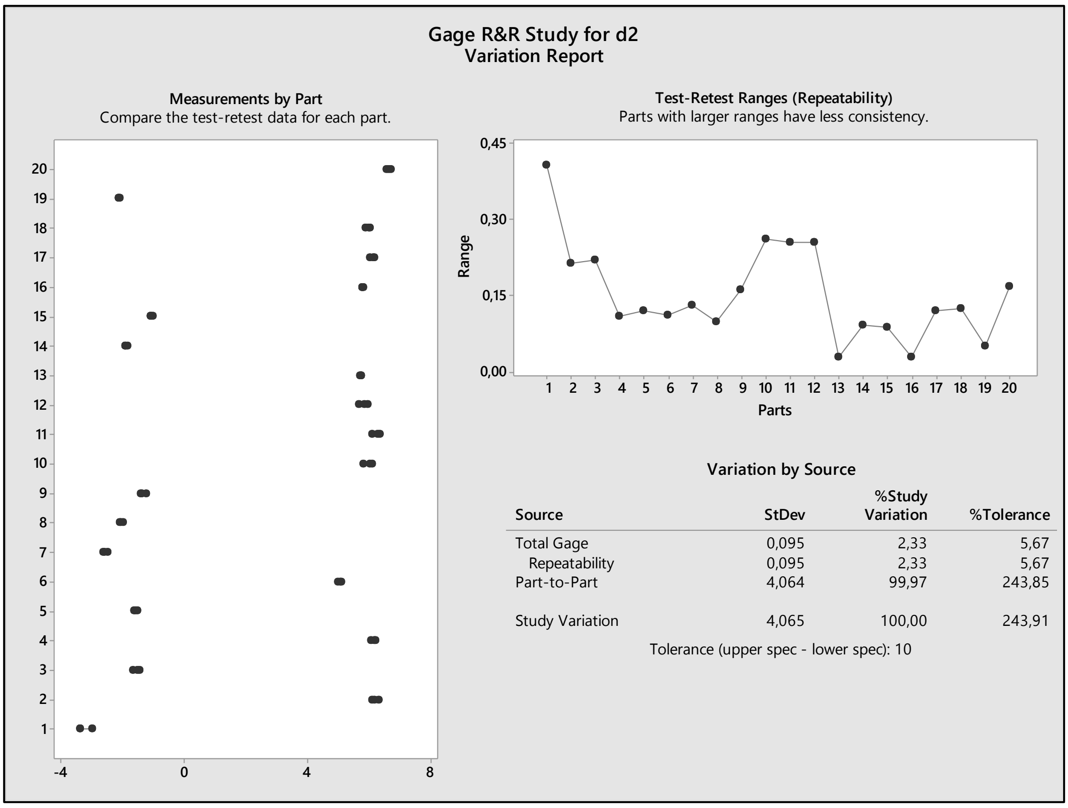
A more simple view of the results is here reported for the other parameters:



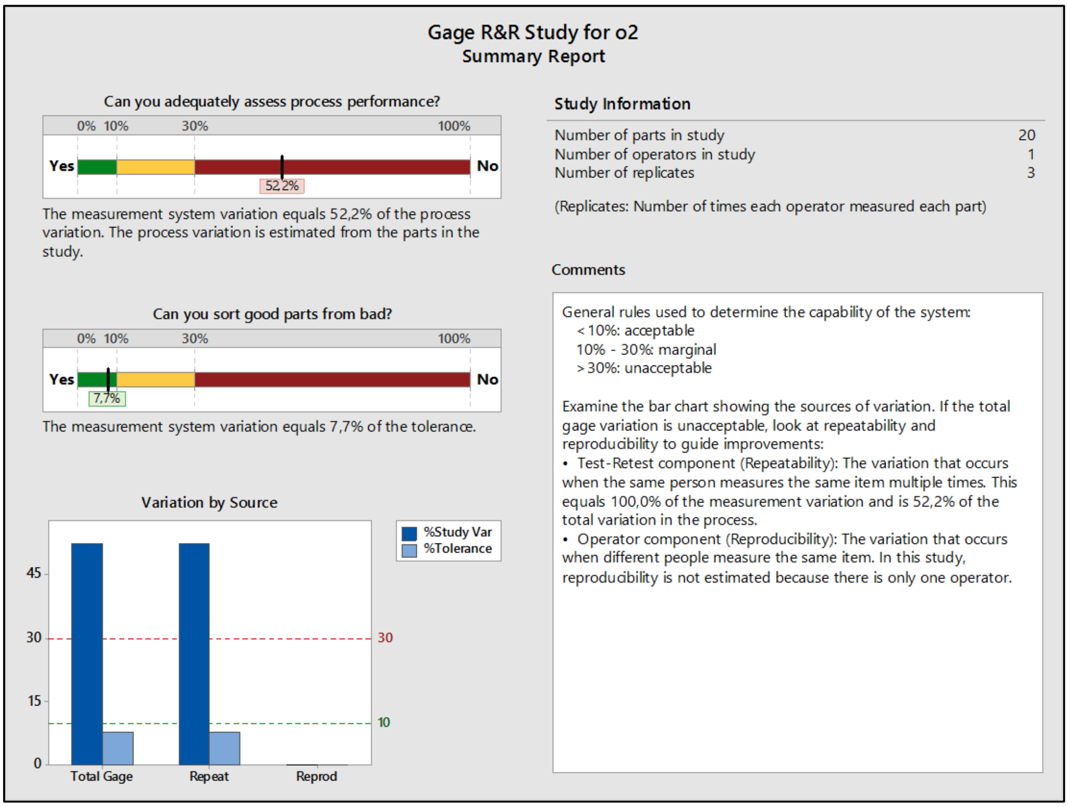


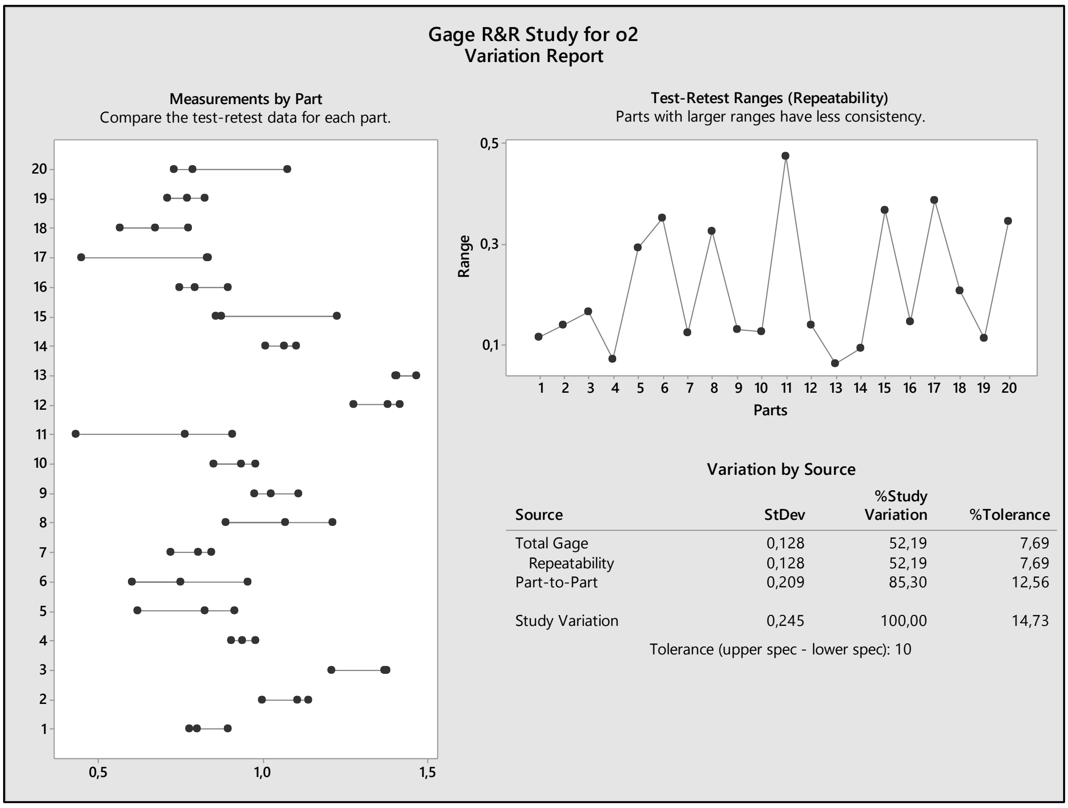
Picture 96 – r&R study summery report for o1 with Minitab



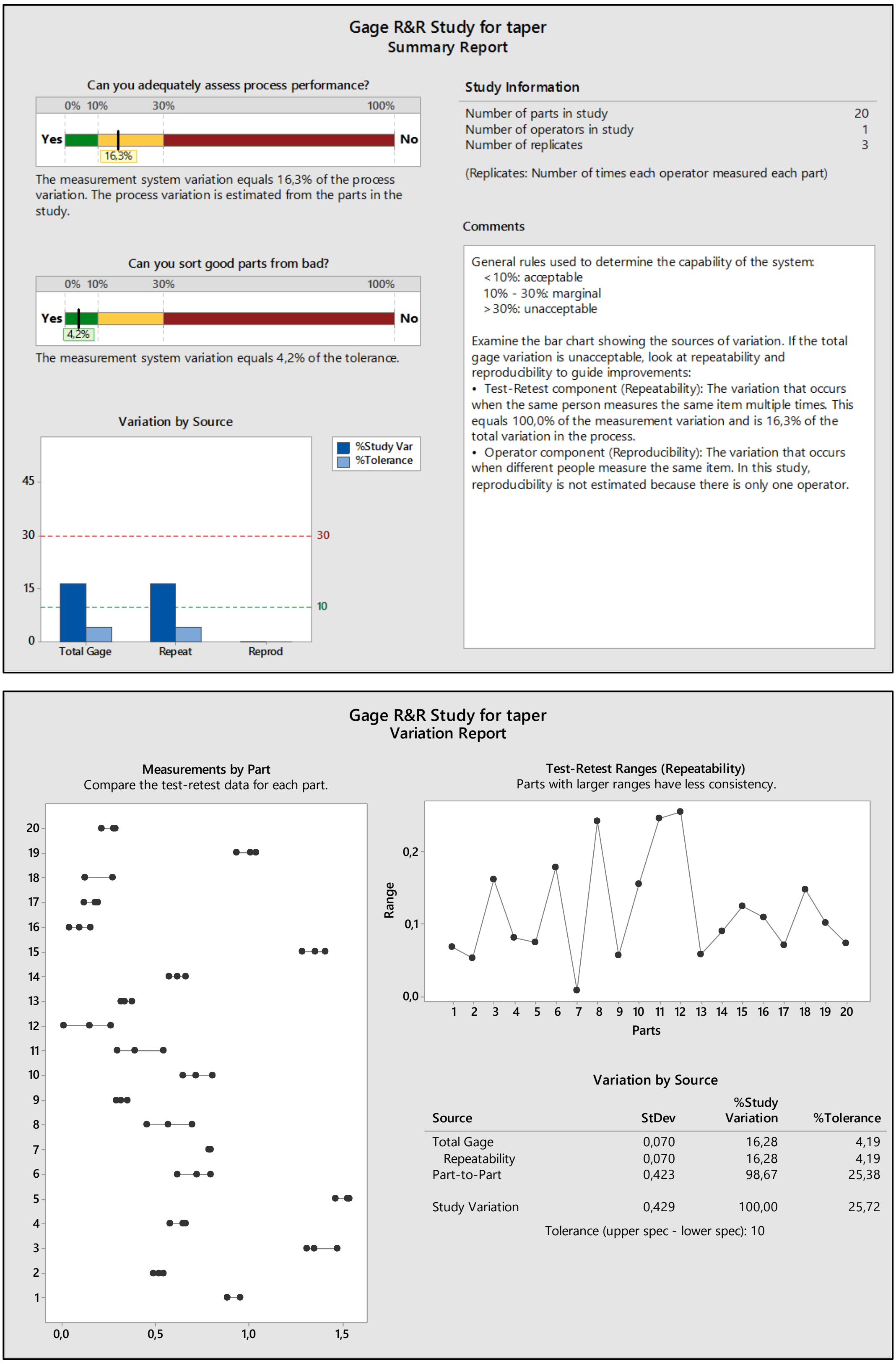


Picture 97 – r&R study summery report for d2 with Minitab





Picture 98 – r&R study summery report for o2 with Minitab



Picture 99 – r&R study summery report for taper with Minitab

After having reached, also for indirect measurements, an adequate level of %r&R, the measurement system analysis is completed and the measuring machine can be considered acceptable and its use can be recommended in applications like sorting or classifying parts, which is the application of the MIB OR machine in the SKF production line object of study.

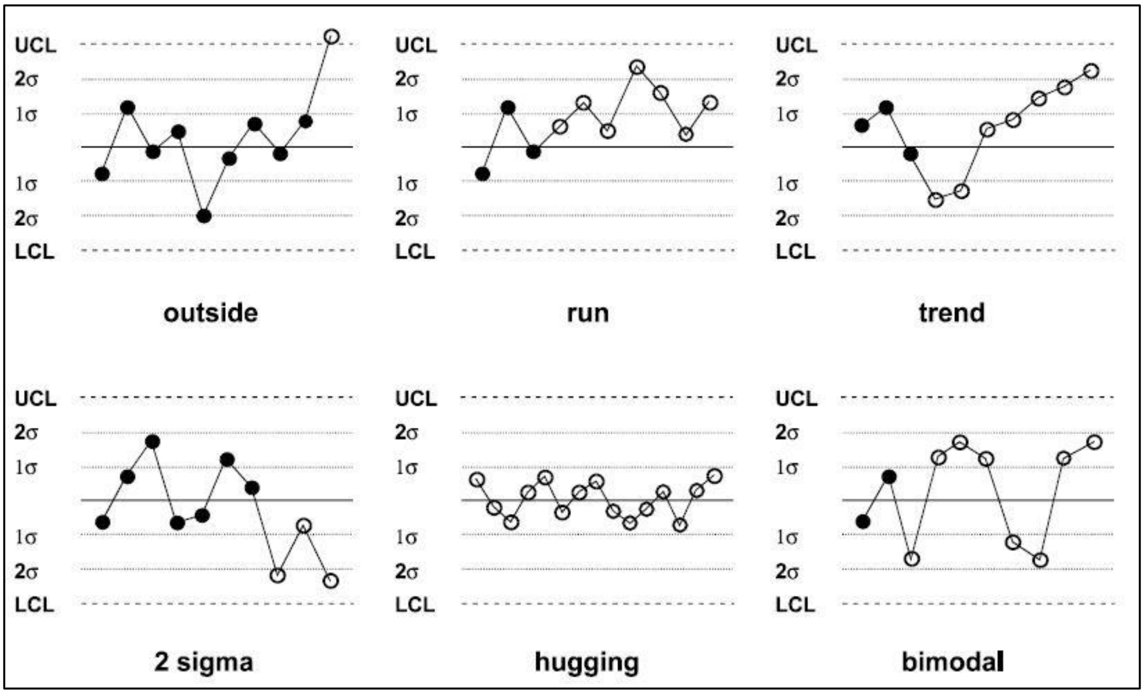
3.3 MIB OR: the first key machine for process improvement

As already mentioned, the desire to deepen the study of the MIB OR machine derives from the fact that it is placed, along the production line, after the CL machine which grinds the external diameter of the bearing OR. This last machine, due to its size, needs to be stopped as little as possible due to the time that this action would require: the dimensions of the wheels are such that it could take minutes.
The idea, according to the DMI s.r.l. know-how, is to create a system able to self-correct after the detection of an out-of-control condition, and only in case the system control condition can't be reached the operator must stop the CL machine in order to verify the occurred problem. An example is that the MIB OR machine detects a trend of measured dimensions suggesting that the CL wheels are wearing out, the CL machine is corrected by a feedback signal and, only in case the measurements do not return in under-control condition, the grinding machine can be stopped.
The choice of GME III was not even accidental, in fact this is due to the need to have numerous programmable functions available that go well beyond the collection and representation of the measurement data.
After verifying the suitability of the MIB OR machine to perform precise and consistent measurements, the same machine became the subject of study as I wanted to verify that, by enabling the temperature compensation and automated process control functions, during production simulations the process was more efficient.

3.3.1 Statistical Process Control (SPC)

The purpose of the analysis is to use the MIB OR machine to carry out a statistical process control (SPC), which consists of a methodology that uses statistical techniques in order

to define, analyse and verify the criticalities of the process that involve unwanted changes compared to normal operation. Statistical process control is based on the analysis of control charts of the type $\overline{X} - S$, $\overline{X} - R$ or for single values X and mobile range R_{mobile}.
As already mentioned, the upper and lower control limits are defined for the control charts, as well as the central line (target value), following the capability study guide reported in the SKF Quality Techniques - Process capability studies brochure QT1 and have been set on GME III at a distance of 3sigma by definition. The process by definition is said to be in out of control conditions when the measurement values fall outside the graph area between the two limits, but the SKF standard provides that other out of control conditions (OOCC) exist and are detected live by the GME III. The monitored out-of-control conditions are as follows:

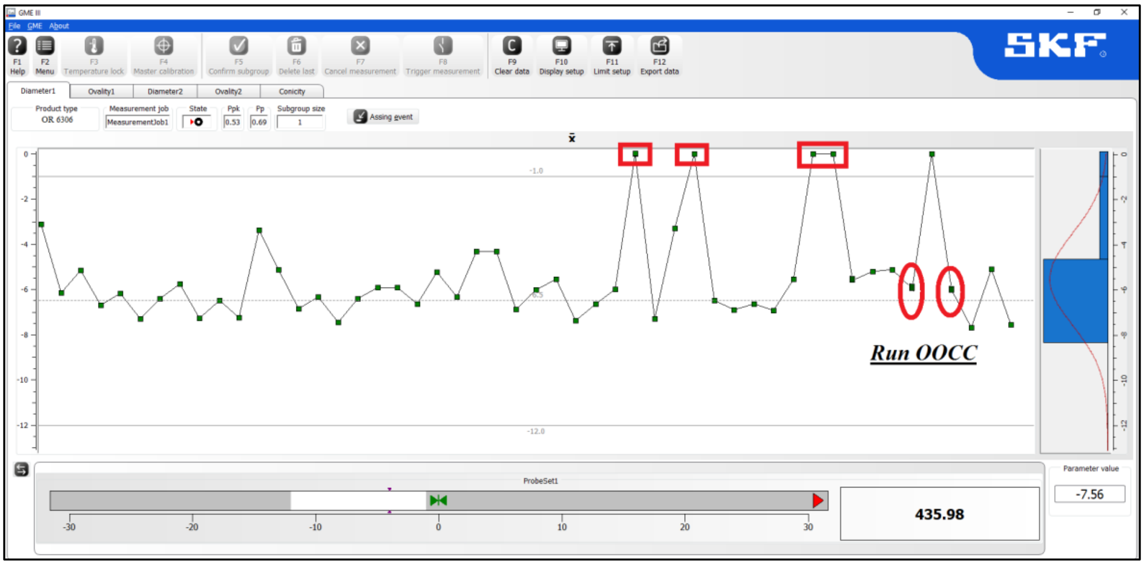


Picture 100 - OOCC representation according to SKF process quality standard (from technical documentation for general measuring equipment – GME III by SKF)

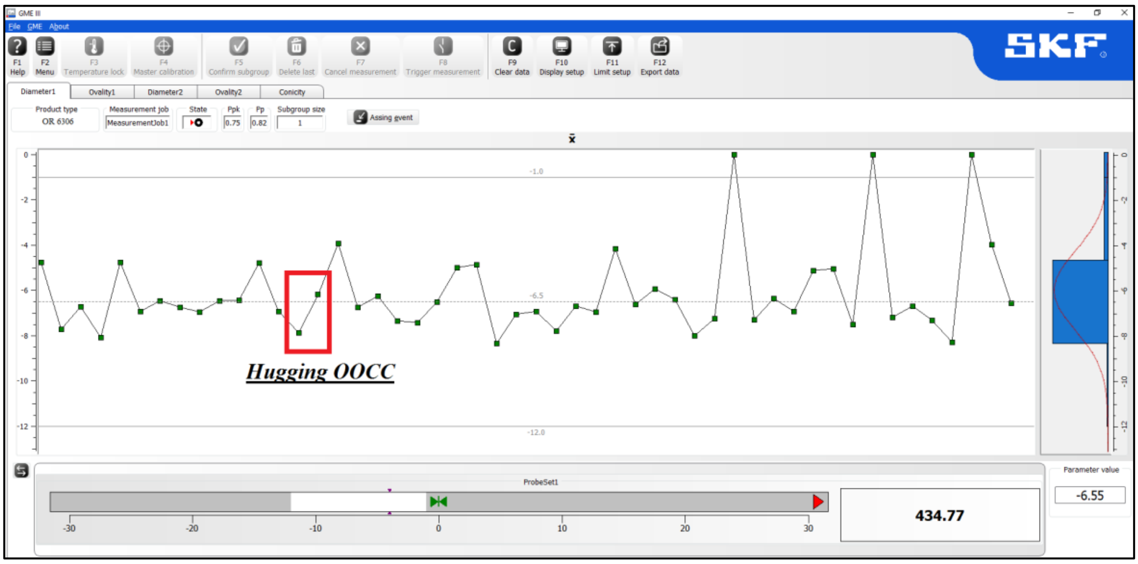
Esternamente:	Un sottogruppo superiore a UCL o inferiore a LCL.
Esecuzione:	Sette sottogruppi consecutivi sopra o sotto la linea centrale.
Trend:	In continuo aumento o diminuzione di 7 sottogruppi consecutivi.
2 Sigma:	Due dei 3 sottogruppi consecutivi oltre i 2/3 della variazione di processo UCL, LCL (2).
Hugging:	Quindici sottogruppi consecutivi entro 1/3 della variazione di processo UCL, LCL.
Bimodale:	Otto sottogruppi consecutivi oltre 1/3 della variazione di processo UCL, LCL (indipendentemente da superiore o inferiore).

Picture 101 - OOCC definition according to SKF process quality standard
(from technical documentation for general measuring equipment – GME III by SKF)

The main purpose of the statistical process control (SPC) is to help the operator to undertake solutions that allow the recovery of the optimal working conditions, therefore the first step is to enable GME III to display the OOCCs. In fact, initially used for the simple collection and representation of measurement data, GME III did not allow the display of out-of-control conditions, neither the simpler one of the outside. The initial situation was the one reported in the following pictures, the out-of-control conditions highlighted were searched for by me requiring such a time that, without a quick display, their identification, considering the speed with which the MIB OR executes the cycle (3.4 seconds), it would take too long for the operator.

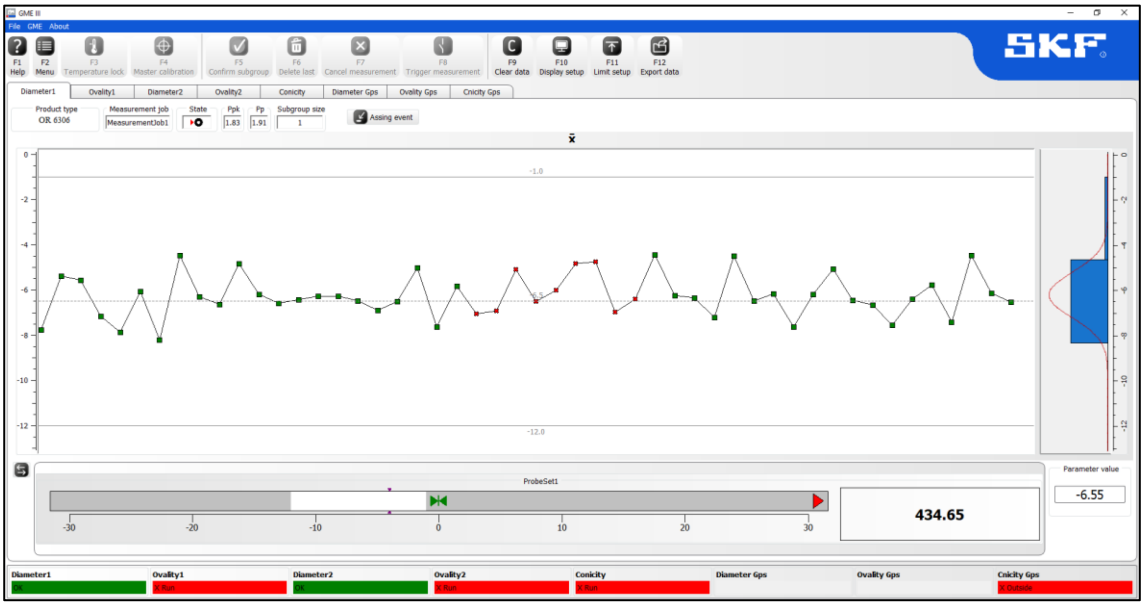


Picture 102 – Run OOCC not detected



Picture 103 – Hugging OOCC not detected

After enabling the display of the OOCCs, the operator has an easier to read control chart available, in fact it is enough to observe the following:



Picture 104 – Hugging OOCC detected

3.3.2 Temperature Compensation

At this point, after the visualization and identification of out-of-control conditions had become very simple, all that remained was to start the simulation to verify the actual improvement of the process. Before starting the simulation, as a first improvement step, to be sure of the measurement readings made by the MIB OR, it was necessary to enable the temperature compensation function.

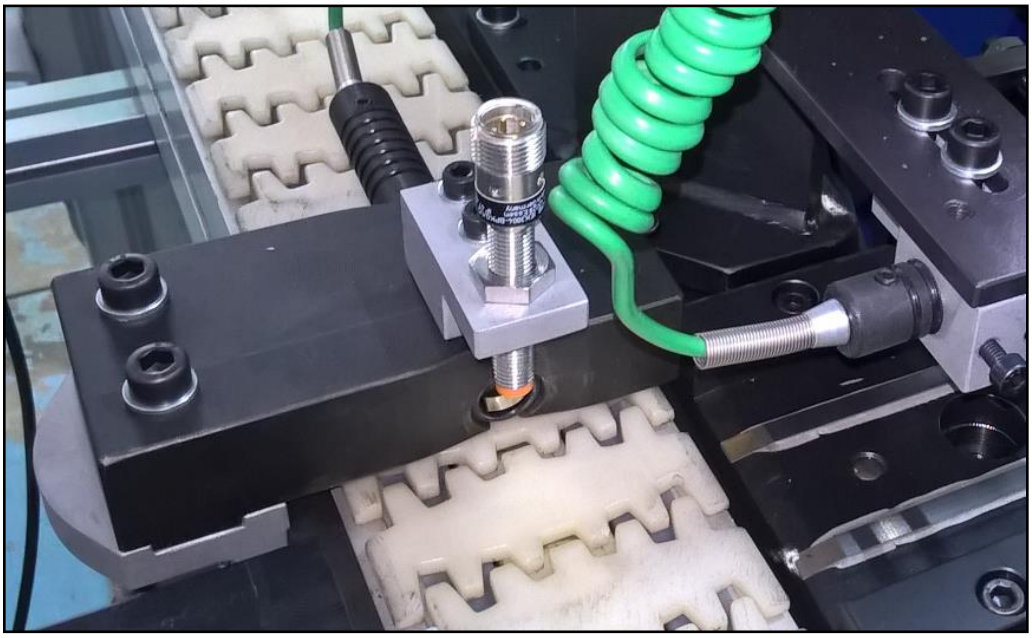
GME III is in fact able to manage the influences of the temperature on the measurement results by connecting a temperature sensor to an analogue input in order to determine the exact temperature of the ring a few moments before the start of the measurement; the temperature value read is used for an automatic correction of the measured dimension.

It is important to remember that when the temperature compensation is enabled, the temperature difference value in the compensation formula is equal to the difference between the temperature of the piece being measured and that of the master ring evaluated during the calibration phase. The following formula is explanatory of what has been said:

$$\Delta l = l_n \cdot \alpha \cdot \Delta T$$

The temperature expansion coefficient α for bearing steel, according to the Technical documentation for general measuring equipment, varies between 50 and 14 μm/(m·°C).

The just presented solution has been implemented, like reported in the following picture, by using a temperature transducer near a micro for the ring presence in correspondence of the ring stop station.

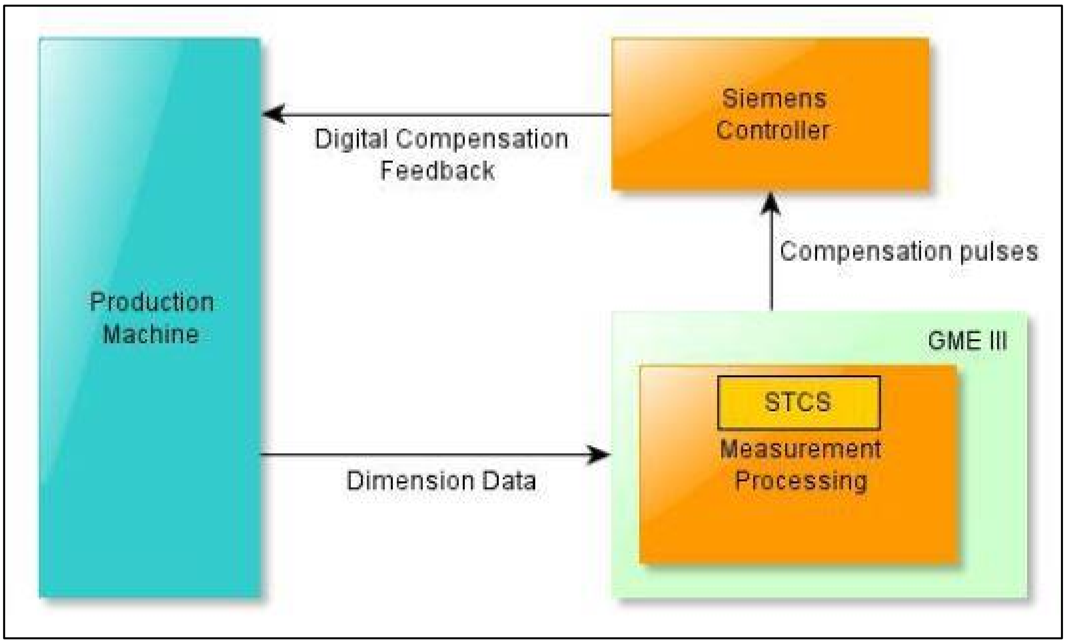


Picture 105 - Ring stop station with micro and temperature compensation probe

3.3.3 Self-Tuning Control System (STCS)

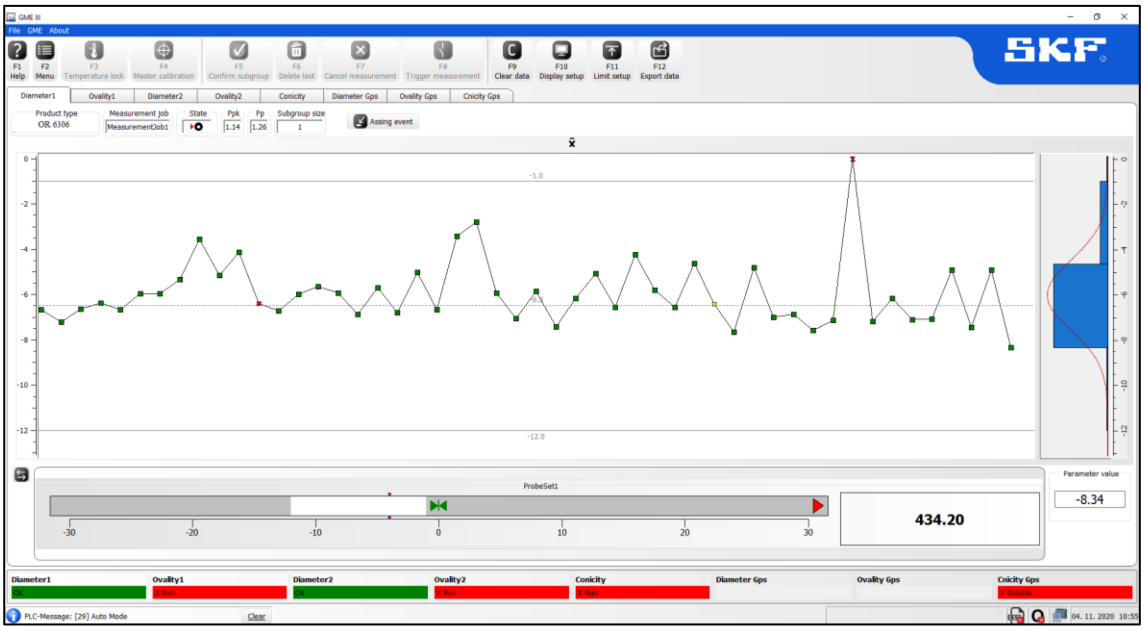
Sure of the ring characteristics reading performed by the MIB OR, it was now possible to configure a closed-loop control system capable of managing the production process of the CL grinding machine without user intervention.

In this way it is possible to implement a Self-Tuning Control System (STCS): the GME III detects a deviation from the process target, by evaluating all the possible OOCCs, and a compensation pulse is fed back to the CL from the MIB OR PLC so that the feedback tells the grinding machine to either increase or decrease the diameter.



Picture 106 – Logical scheme of a self-tuning control system

In the following picture the first result of the self-tuning control system is clear: the GME III detects a run OOCC condition and immediately the process return to under control conditions.

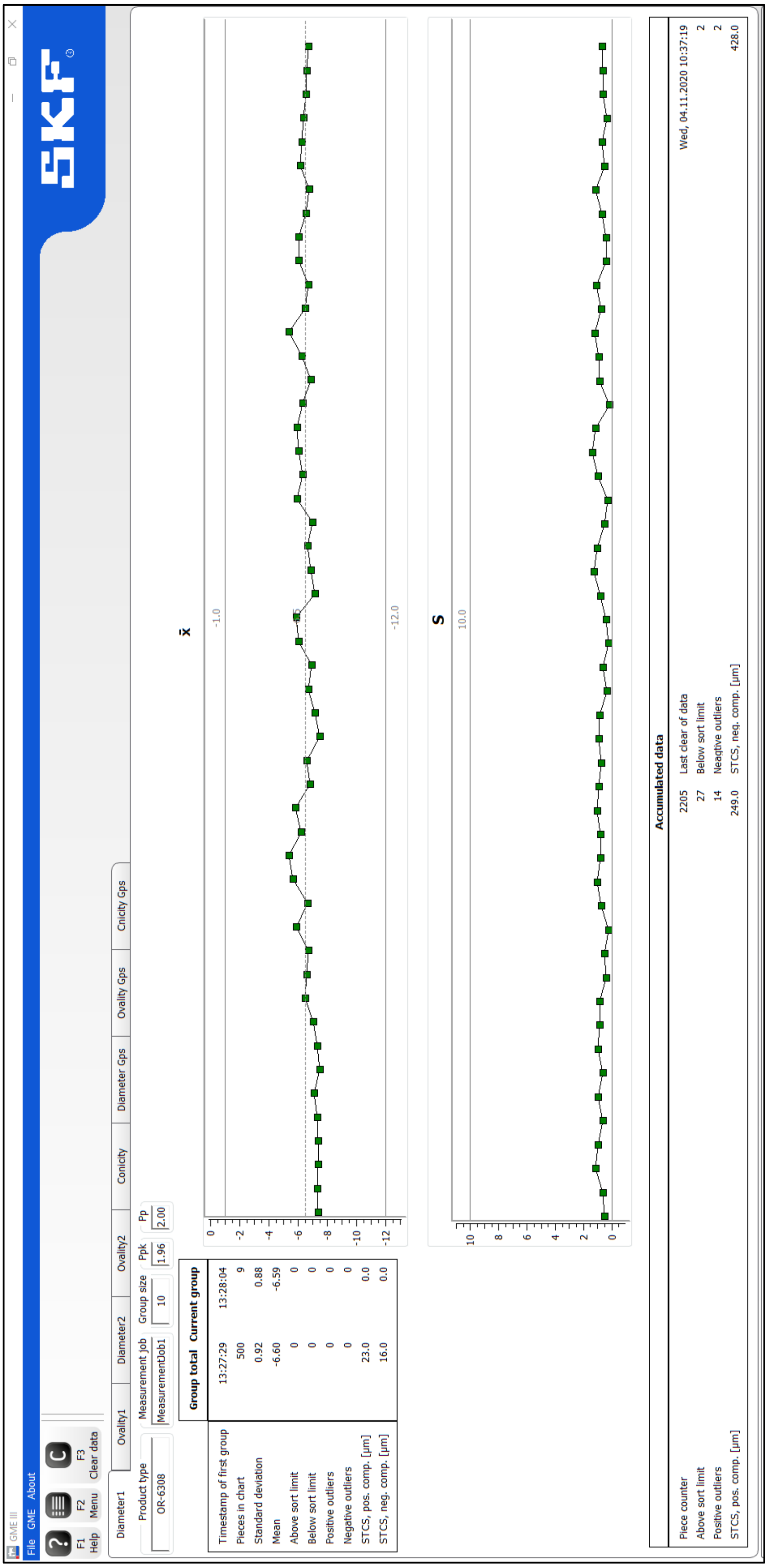


Picture 107 – After the detection of a run OOCC the MIB OR sends a feedback pulse to the CL and the process return in under-control condition

3.3.4 *Final Results Analysis*

The final results of the analysed and implemented improvement actions are shown in the following screen, which shows the history of the measurements performed by the MIB OR which shows how it was possible, after 3619 measurements, to reach an average value of diameter equal to -6.36µm very close to the target of -6.5µm and therefore perfectly acceptable.

The data are distributed with a standard deviation of 0.86. The effect of the creation of a self-tuning control system is evident from the fact that a positive compensation of 281µm and a negative compensation of 546µm were necessary, which therefore made it possible to recover a not negligible number of rings.



Picture 108 - Evaluation of the implemented solutions, leading to an improvement of the process

The last aspect that allows to evaluate the improvements made to the process is the evaluation of the P_p and P_{pk} performance indices, the calculation of which is performed directly by GME III and continuously updated. These process performance indices are calculated by analysing all the data collected by the MIB OR and not a part of them and give an indication of how the process has behaved in the past, thus being particularly suitable for the analysis of new processes being improved. .
The formulas for calculating these indices are as follows:

$$P_p = \frac{UTL - LTL}{6 \cdot s_{tot}}$$

$$P_{pk} = min\left(\frac{UTL - \bar{x}}{3 \cdot s_{tot}} ; \frac{\bar{x} - LTL}{6 \cdot s_{tot}}\right)$$

where:

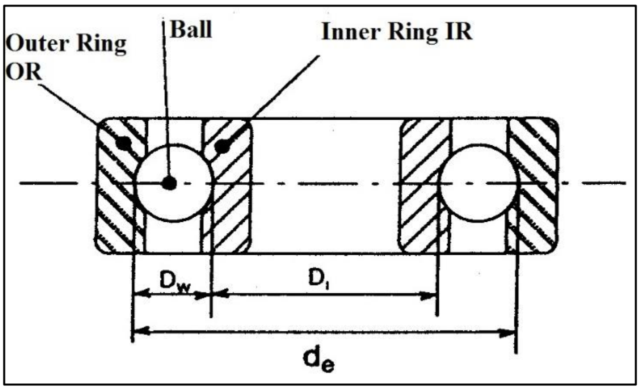
- s_{tot} is the total standard deviation;
- $\bar{x}$ is the grand average of the measurement recorded by MIB OR;
- UTL − LTL is the tolerance interval. The upper and lower tolerance limits indicate the allowable process spread according to product specification.

Giving a quick interpretation to the two formulas, it is evident that P_p is an indication of what the number of data outside the specification limits would be if the process were perfectly centred on the defined target value when this was at the centre of the specification limits. Therefore, the P_p alone does not allow to perform a complete process performance analysis because there is no information about the distance of the process from the specification limits. For the latter case, the P_{pk} comes in handy.
The quality standards of SKF suggest that the process is performing when P_{pk} is higher than 1.67. Therefore, looking at the results reported in the previous picture, the process under study is perfectly capable since $P_{pk} = 2.07$ and, given $P_p = 2.12$, since the difference between the two performance indices is very low it is centred without the need of further improvements analysis.

4 XHM80 machine

The XHM80 machine has been designed and developed to perform bearing pairing automatically. The operating cycle of the machine is rather complicated and is carried out by a Siemens S7-1500 PLC; the correct operation of the machine is necessary so that the entire SKF production line under study can have a constant operation with a high performance: the XHM80 machine, in fact, is located in a crucial point of the line, i.e. the one in which the ORs join together to form a single channel in which the assembled bearing is seen advancing rather than the rings.
The internal and external rings arrive at the machine by means of a conveyor belt, as already mentioned in the chapter dedicated to the layout, and are then loaded onto two separate machine inlet channels. The rings are then transported to their respective measuring stations where the IR and OR raceway diameters are measured. The machine cycle, controlled and commanded by the PLC, foresees that the raceway diameter of the IR is evaluated and, only if this falls within the tolerances foreseen for the bearing in production, the dimension, compliant or not, of the OR is evaluated. Once the measurement of the OR raceway diameter has been detected, the PLC commands the selection of the ball and its insertion in accordance with the need to have a radial clearance that differs as little as possible from the production specifications. The radial clearance, according to the sphere diameter under consideration is evaluated by considering the following Picture and formula:

$$RC = (\pm d_e) - (\pm D_i) - (\pm D_w \cdot 2)$$

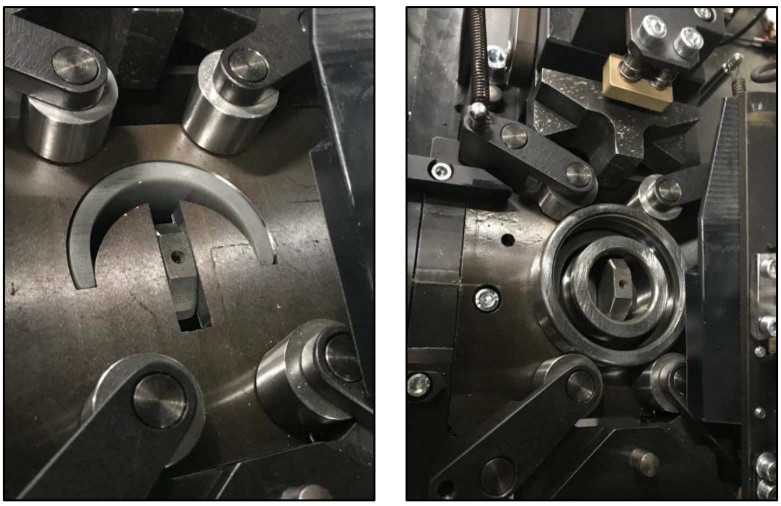


Picture 109 – Bearing Assembly dimensions

If the ball is not available, in the sense that it is not among the balls used on the machine, the OR is discarded and, keeping the IR available, the dimensions of the next OR and the possibility of coupling are evaluated. This is repeated for three successive ORs and, if the sphere is not found, then the IR and the OR are discarded together placing the IR inside the OR. The XHM80 machine uses seven shades of spheres diameters ranging from -3 μm to +3 μm. When, therefore, the sphere required by the coupling specifications is provided on the machine and is available, the PLC commands the cylinder that moves the drawer containing the eight spheres of the selected shade and the IR and OR rings can move forward, one inside the other, at the coupling station. Once at the coupling station, the balls are inserted between the rings thanks to the presence of the KFA group consisting of three components of fundamental importance to ensure correct execution of the operation of inserting the eight balls required. Specifically, the three components that make up the group are:

- Decentralizer: allows to decentralize the inner ring with respect to the outer ring in order to create the necessary space for the insertion of the balls. The movement of the decentralizer corresponds to the action of a press that ovalizes the OR in the dimension of 3-4 tenths;
- Half-moon: creates a support surface for the spheres that are inserted during the coupling phase;
- Nail: orientates the spheres during the insertion phase.

The KFA group is reported below:



Picture 110 - KFA group components

After the balls have been inserted, the bearing advances towards the machine exit station and continues its path along the production line downstream of the machine.
A fundamental role in pairing the rings and inserting the balls is played by the presence sensors positioned on the ball loading ducts which detect the presence of the balls; when these signal the lack of spheres, the motor connected to the boxes containing the spheres of different shades is activated by the PLC and allows the spheres to be reloaded in the ducts. The rotation of the motor allows to recharge all the ducts at the same time as, thanks to a belt, the motor is connected to all seven ball boxes. The picture below shows an image of the presence sensors application.

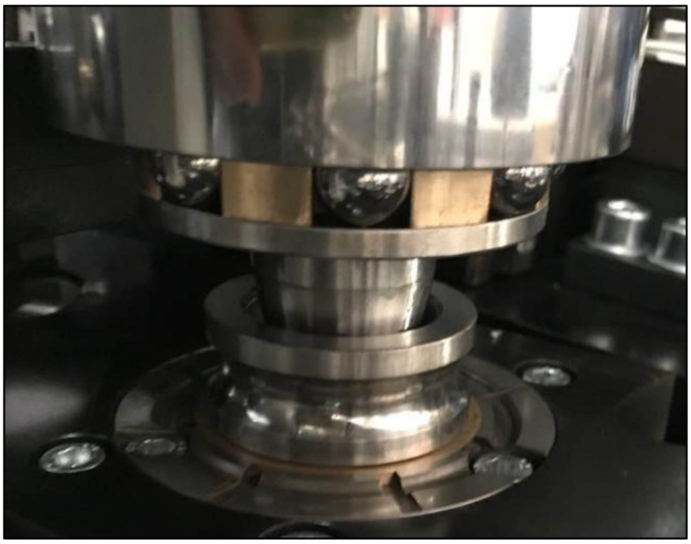
Picture 111 - Position sensor positioned along the loading duct, which allows the spheres presence detection

4.1 XHM80 Machine Revamping

4.1.1 Mechanical components revamping

As already described more than once in this thesis work, mechanical revamping consists, in accordance with the know-how of DMI s.r.l., in dismantling the machinery from mechanical components and checking them. In the case of the XHM80, screws, preload springs and fastening elements were replaced, while an important redesign was necessary,

carried out by the design team of DMI s.r.l., regarding the measuring heads of the raceway diameters of the internal and external rings, of the KFA group and the ball selection mechanism.
In particular, starting for simplicity from the KFA group already presented and visible in the previous Picture, a design of the three components mentioned above and an experimental evaluation of the application force of the press were required to ovalize the OR ring of the required size.
The group for selecting and reloading the balls inside the loading tubes has been designed thanks to a massive use of 3D printing necessary for the realization of the tubes as well as the drawers, while the transmission of the motion to move the drawers and recharging the ducts was obtained thanks to a belt transmission that connects all the drawers to a single Siemens motor of small dimensions and with reduced consumption and price thanks to the lightness of the components, obtained with 3D printing, that must be started.
A rather important work was carried out, however, in the case of the design of the measuring heads of the raceways diameters. The measuring principle of the two heads is based on the use of a cone on whose side surface the balls are placed, which will position themselves inside the raceway of the measuring ring. The cone, with a taper angle defined by the design team, allows, once the spheres have entered the raceway, to read the exact diameter corresponding to the height reached by the cone after the spheres have positioned themselves. The height reached by the cone is read thanks to the use of an LVTD probe which allows to define the diameter of the raceway as it measures the difference between the position of the spheres reached for the ring in measure and that reached by the spheres in the measure of the master sample. When the measuring cone, in fact, goes back to the rest position, the spheres lying on the cone enter the master ring.
In particular, I want to mention the design value of the taper angles equal for both measuring cones and equal to almost 5°. Below are the Pictures of the IR and OR measurement stations.



Picture 112 - IR raceway diameter measuring head

Picture 113 – OR raceway diameter measuring head

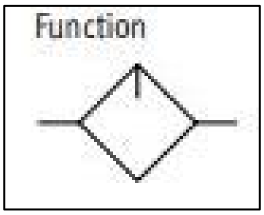
4.1.2 Pneumatic components revamping

The XHM80 machine, unlike the MIB OR previously analysed, is not a completely electric machine, which is why the pneumatic circuit on the machine needed a revision. First of all, a complete dismantling of the pneumatic components was carried out, and these were replaced with identical commercial parts. Although some of the cylinders,

following the loading and unloading tests of the chambers, were still functional, the DMI s.r.l. has preferred to perform a complete replacement, as well as for the pipes, of the same both to ensure correct operation of the machinery necessary for its key function, and to minimize the amount of air consumption.
The machine is therefore equipped with 26 actuators produced by Festo and the air consumption is around 1200 l/min and controlled by a block of monostable Festo solenoid valves powered by the terminal board present in the electrical panel on the machine, which is reported in the following Picture.

Picture 114 – Block of solenoid valves and lubricator installed on XHM80 machine

As can be seen from the previous picture, next to the solenoid valve block there is the Festo mist lubricator of the MS series. This component, whose pneumatic symbol is shown in the picture below, is connected to the air treatment unit identical to the one already presented in chapter 2 of this thesis and was necessary considering the dimensions of the cylinders that the compressed air must operate.



Picture 115 – Lubricator pneumatic symbol

4.1.3 Electrical components revamping

The revamping of the electrical components consists in the dismantling of the electrical components present on the machine and their subsequent replacement. Therefore, this procedure began with the assembly of the electrical panel in accordance with the provisions of the Machinery Directive in force.
The aforementioned panel, in the case of the XHM80 machine, appears to be very simple, in the sense that it consists of only the key elements in terms of safety and command, without the presence of additional measuring components. In the case of the XHM80, in fact, the LVTD measurement probes necessary to detect the values of raceways diameters are connected directly to the on-board Siemens S7-1500 PLC, without installing an on-board computer such as the CMME 7001 present on the MIB OR machine. The electrical panel, in the case study, appears to be composed of the same components as discussed in chapter 2 of this thesis work as evident in the following Picture.

Picture 116 - Electrical panel installed on board of XHM80 machine

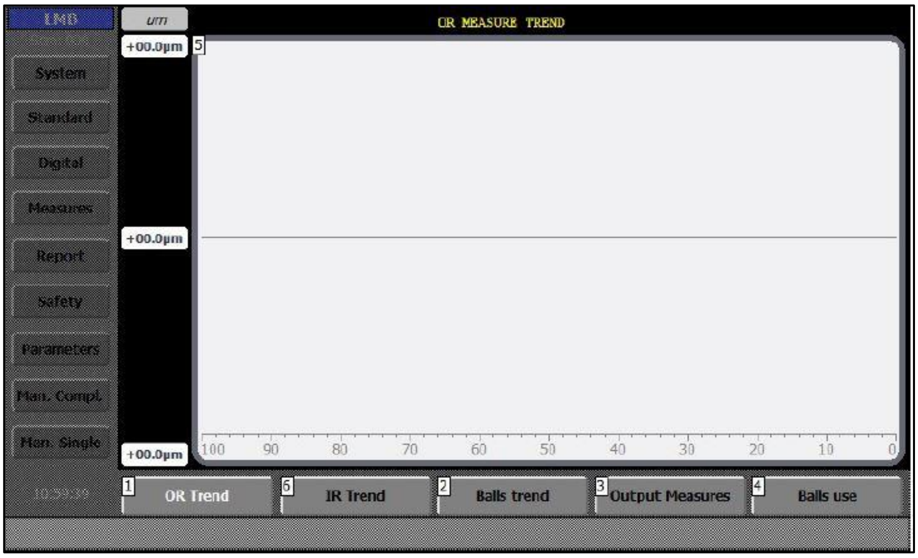
As regards the HMI-Human Machine Interface, also in this case we wanted to keep the concept of user-friendly interface and therefore we came to the conclusion that it was necessary to try to keep the same interface as standard as possible, both in the layout and in the functionality and organization of the pages. Therefore, in this paragraph only the pages that appear to be different from those present on the interface of the MIB OR and characteristics of the machine being analysed are reported.

First of all, the page containing general information on the machine status is shown in the following Picture.

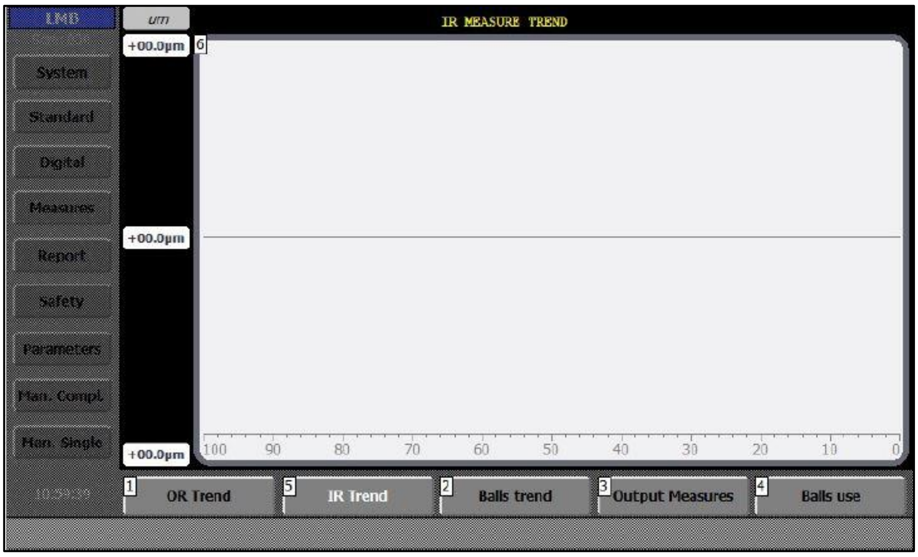
Picture 117 - Main page of the XHM80 machine Human Machine Interface

Specifically, on this HMI page it is possible to view the machine ready status, the number of pieces processed by the machine as good pieces, this counter is both resettable and not, the number of OR and IR discarded following the raceway diameter measurements performed by the machine. In the same page it is also possible to view the process parameters in terms of the last cycle time, the last measured values for IR and OR raceway diameters, the last shade of spheres used in the assembly phase and the last radial clearance value obtained. At the same time it is possible to visualize the number of enabled boxes, which will correspond to the number of shades of sphere diameter, and the target radial clearance value.

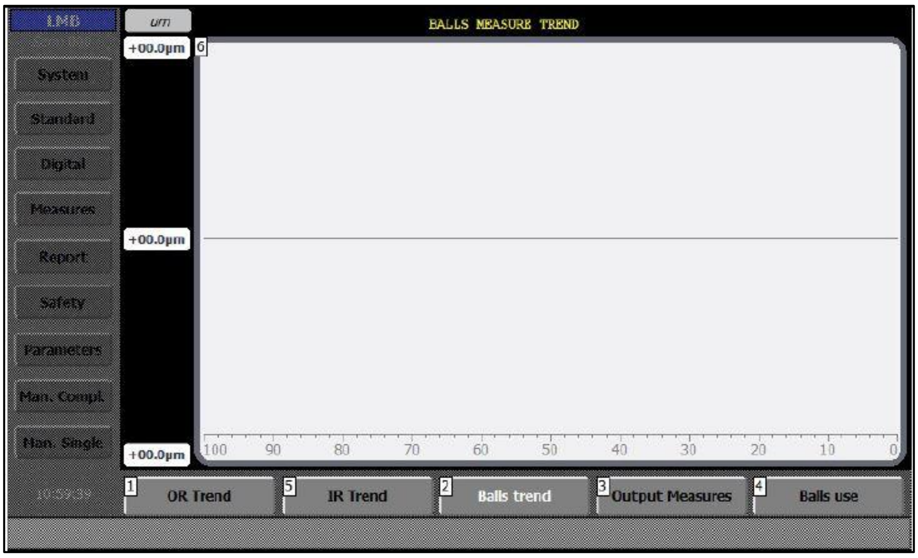
As already mentioned, the XHM80 machine does not have an on-board computer, but at the same time it must be possible for the operator to view the diameter trend in order to be able to carry out corrective actions to the machine in an attempt to have a distribution of the diameter measurements as close as possible to the target value. The same goes for the need to visualize the trend of the spheres. Therefore, the team of programmers and electricians made sure that the diameter values measured by the probes were sent directly to the PLC and that this represented the measured values step by step on a graph shown in the following pages in the following Pictures, as well as they allowed the machine to represent the trend of the consumption of the spheres, keeping in memory the sphere diameter value used to make the coupling each time.



Picture 118 – OR raceway diameter trend representation page

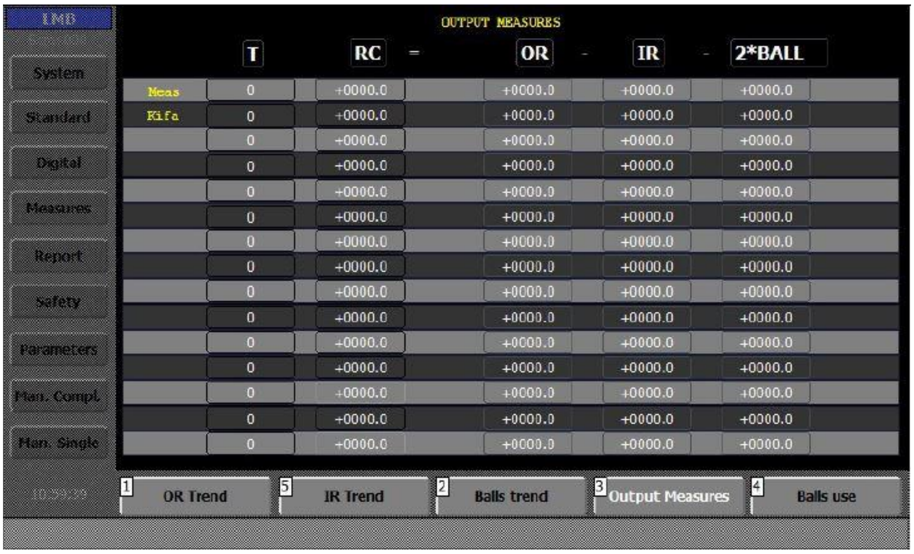


Picture 119 – IR raceway diameter trend representation page



Picture 120 – Ball diameter trend representation page

At the same time, however, the operator may need more data to be able to evaluate any malfunctions in the production process and take corrective actions. And it is precisely for this reason that the interface presents a page dedicated to the collection of the history of the measurements detected for the coupling to which is added the degree of tolerance T on the radial clearance which is, from T5 to T1, increasingly narrow. This page can be viewed in the following Picture.

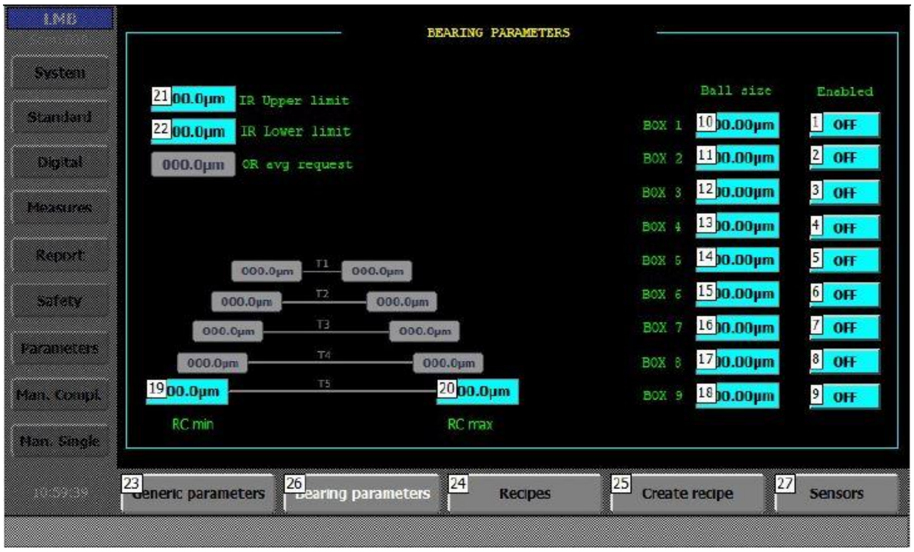


Picture 121 – Pairing parameters historical data

For the spheres, a dedicated page has also been provided in which, to avoid confusion, the diameter of the sphere is reported in correspondence with the number of the box that contains it as well as the quantity of spheres consumed for each shade of diameter both in numerical value and in green bar shape.
The diagram obtained by analysing the green bars is a histogram of consumption of the spheres and the operator can, in a very simple way, make sure that the histogram approximates as much as possible a Gaussian curve with the average value in correspondence with the sphere whose diameter shade is equal to zero, corresponding to the target ball diameter. Such page is reported in the following Picture.

Picture 122 – Ball consumption summary page

As regards the possibility of setting the production and process parameters, a dedicated page has been designed on the HMI shown in the following Picture. On this page it is possible to set the tolerance limits for the IR raceway diameter, the tolerance limits of the radial clearance T5, which an SKF proprietary algorithm will then break down into the narrowest degrees, the diameters of balls contained in each box and it is possible to enable the box. As it is evident, the XHM80 machine is designed to be able to insert 9 shades of possible sphere diameter, but following the customer's request, DMI s.r.l. has enabled only 7 of them; with simple modifications to this page it is possible to modify the number of enabled boxes.



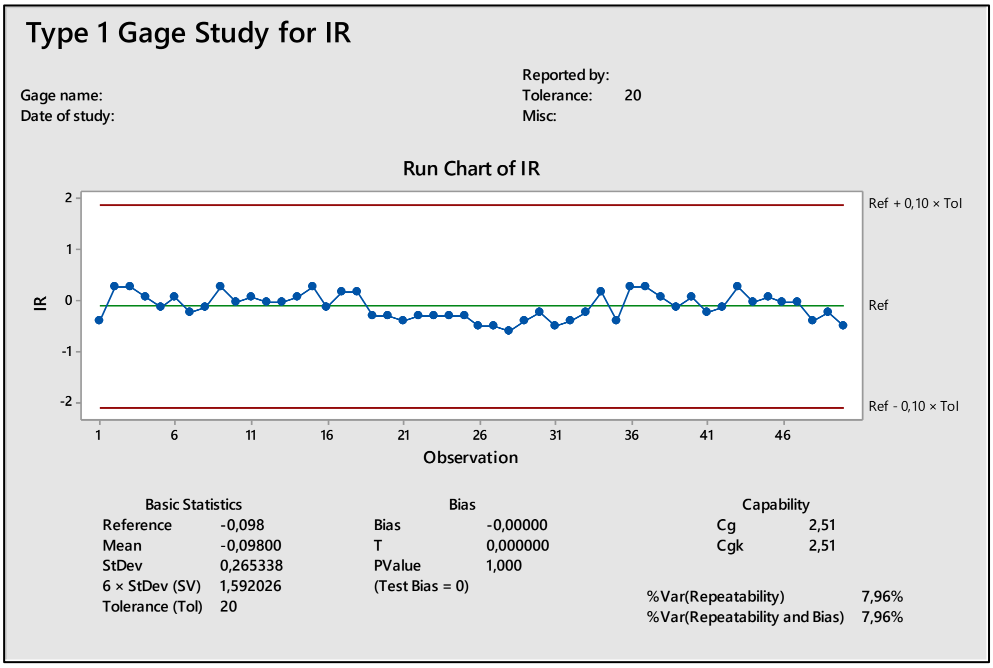
Picture 123 – Page dedicated to the setting of production and process parameter on the XHM80 machine HMI

4.2 Measurement system analysis

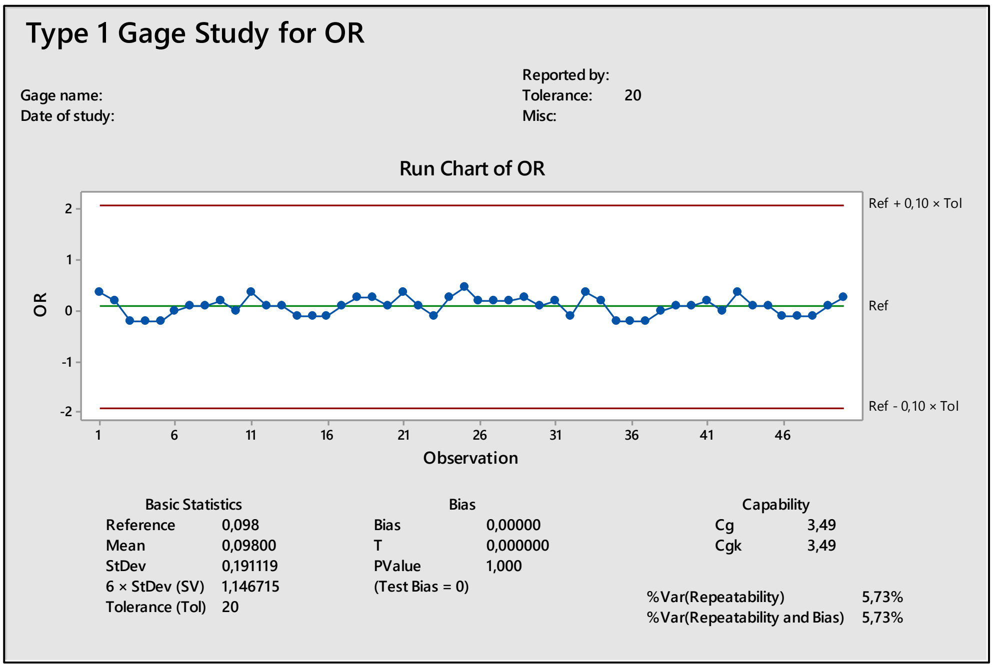
Although the XHM80 machine is a machine that carries out the bearing assembly, this operation is based on the results of the measurements performed by the machine.
For this reason, to ensure the correct functioning of the machinery it is necessary to perform an analysis of the measuring system. In the case of the XHM80, the SKF-owned QT5 brochure was followed again, but unlike the MIB OR it was not possible to carry out an r&R study. This last study, in fact, would have had the objective of verifying that, under the same conditions of IR and OR raceway diameter, the machine would have proceeded with the insertion of the same shade of diameter of the sphere. This was not practicable as it would have been necessary each time to disassemble the assembled bearing, remove the balls and measure the rings again, with the risk of damaging them during the disassembly phase, and verify the choice of the same ball as the previous assembled bearing.
Therefore, for the reason just explained, the measurement system was analysed by performing an analysis of the instrument capability and a linearity analysis.

4.2.1 *Instrument capability analysis*

As in the case of the MIB OR, the instrument capability analysis has the purpose of verifying the ability of the measuring instrument, in this case the measuring instrument are the two measuring heads, to measure the rings in a consistent and accurate way. Also in this case, the analysis and calculation of the C_g and C_{gk} values, and the verification that they were higher than 1,33, was performed with the software for statistical analysis Minitab and the results are shown in the following Pictures.



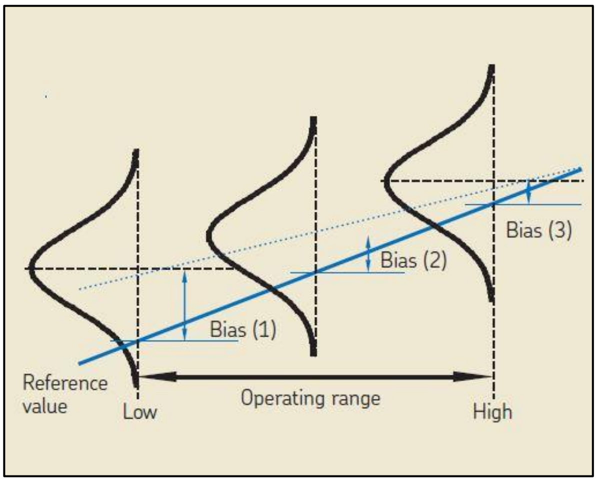
Picture 124 – Summary report from Minitab about IR raceway diameter instrument capability analysis



Picture 125 – Summary report from Minitab about OR raceway diameter instrument capability analysis

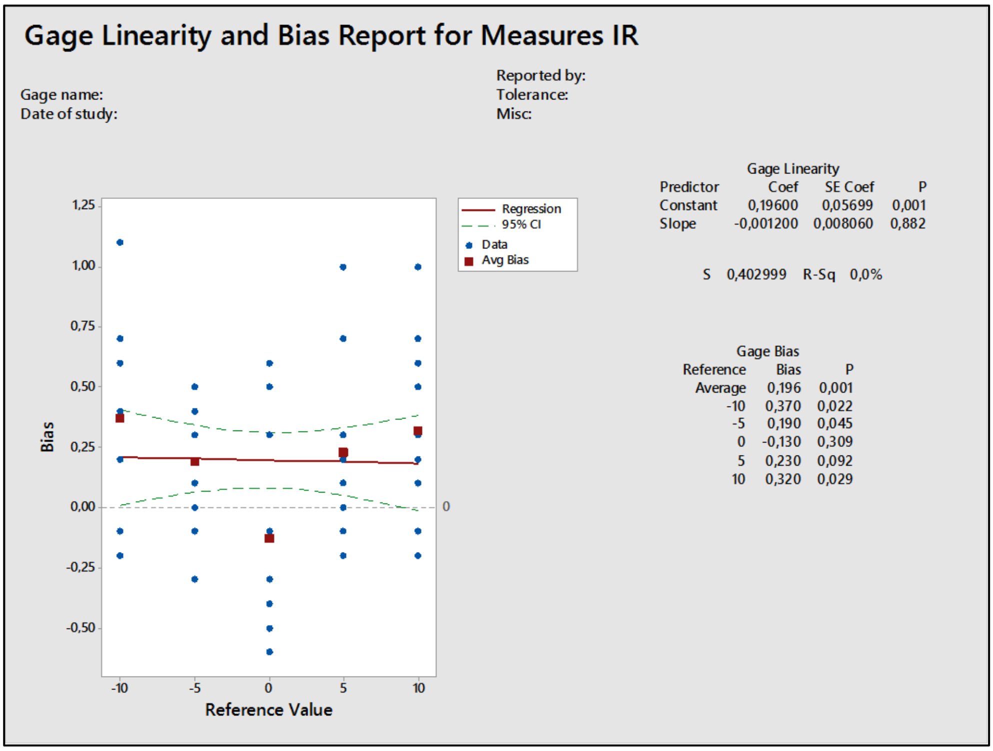
4.2.2 Linearity analysis

On SKF QT5 Measurement Systems Analysis, the linearity is defined as the difference of bias through the expected operating range of measurement of the measuring equipment. The term bias, on the same brochure, is defined as the difference between the true value (reference value) and the observed average of measurements on the same characteristic on the same part. The following Picture gives a more clear representation of these two definition.

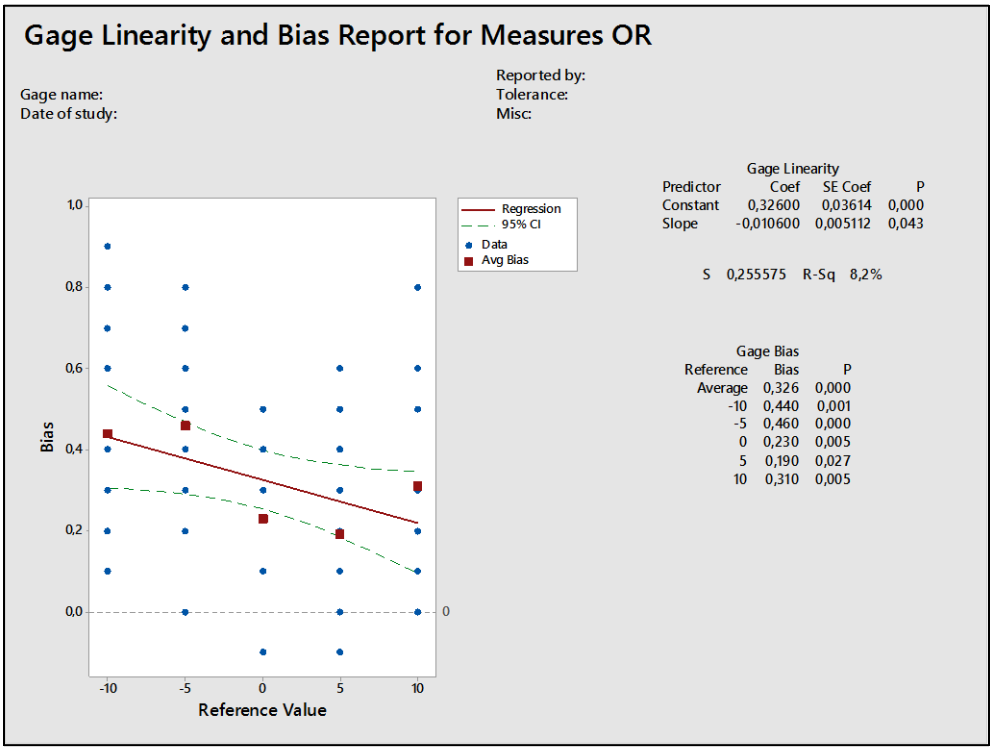


Picture 126 – Linearity and Bias representation (from QT5 brochure by SKF)

To perform a linearity study, the SKF standard requires that a number of components to be measured greater than or equal to 5 are chosen, whose dimensions cover the measurement range of the measuring system, and that each part must be measured a number of times greater or equal to 10 so that the average value of the bias can be calculated. The slope of the line that best fits the bias average versus the reference values multiplied by process variation of the parts is an index that represents the linearity of the measurement system. Therefore, in order to perform the study, I selected 5 master rings of variable size between -10 µm and + 10 µm, corresponding to the process variation, and each of them was measured 10 times. Obviously the linearity evaluation was carried out twice for the IR raceway diameter measuring head and for the OR one respectively. The summary report of the study are in the following Pictures.



Picture 127 - Summary report from Minitab about IR raceway diameter measuring head linearity study



Picture 128 - Summary report from Minitab about OR raceway diameter measuring head linearity study

Reading both reports allows to visualize the value of the slope of the regression line, which interpolates the average bias value for each part. In both cases there is a very low slope value, respectively -0.0012 in the IR case and -0.0106 in the OR case. The mean bias values are also acceptable as they are respectively 0.196 in the case of the IR raceway diameter measuring head and 0.326 in the case of the OR one.

With these data it was therefore possible to state that both measuring heads have the same accuracy for all the dimensions of the measured objects, or rather that neither of the two measuring heads is affected, in terms of measurement accuracy, by the dimensions of the ring to measure; all of this is true with a 95% confidence.

4.3 XHM80: the second key machine for process improvement

As mentioned, the study of the revision plan of the XHM80 machine was not accidental: this machine, in fact, is of crucial importance for the correct functioning of the entire production line. In fact, this machine is placed in a crucial point of the production line as it is the machine on which the IR and OR channels are joined and its correct functioning

is necessary in order to be able to place an well-assembled bearing on the remaining part of the line which is at the same time the finished product of the two previous sections of line and the raw material of the downstream section of line. The bearing assembled by the XHM80 must therefore conform as closely as possible to the production target, subject to the possibility of this being rejected in the following machines.
Essentially, my study, having completed the revamping operations, began by starting from the fundamental operations that the XHM80 machine performs: measurement of the raceway diameters of the IR and OR rings and selection and insertion of balls. As can be easily understood, the operation of selecting the spheres cannot ignore the size of the raceways and, considering that the PLC is already the best solution to choose the best possible shade of spheres. I had nothing left to think about except how to improve either the reading of the raceway diameters (in order make the PLC able to choose the exact shade of ball diameter suitable to achieve the target value of radial clearance) or modifying the dimensions of the rings that reach the machine (in order to realize a bearing assembly which needs always the same shade of ball diameter, namely the target +0 µm, with a subsequent reduction of the number of needed ball boxes).
At the end of my study about the possible improvements to the production process through the XHM80 machine, I came to put forward two improvement hypotheses, which, however, for reasons of costs necessary for their implementation, have been rejected.

4.3.1 First option for improvement

The first possibility of improvement that I studied consisted in trying to keep the layout intact, both from the point of view of the machines and from the point of view of the number of them, acting exclusively on the XHM80 machine.
This improvement option aims to try to improve the reading precision of the raceway diameters in order to be sure that the selection of the spheres performed by the PLC can lead to the insertion of spheres whose diameter shade allows to have a bearing assembled as close as possible to the production target. In this sense, it was useful to observe the measurement range within which the measurements of the IR and OR rings fall by performing further tests on the XHM80 machine, which consisted in performing a good number of measurements on the same ring for as many rings as possible.

In this way, I concluded that, although the machine was linear, the measurements of the internal rings IR, as already observed in the linearity diagram of the IR head, vary in an amplitude range greater than 1 μm. The knowledge of DMI s.r.l. foresaw that this range of variation of the measurements detected on the same part could be further restricted, but it was necessary to modify the measuring head.

A valid alternative, according to my research, consisted of replacing the mechanical measuring head with two probes, one of which connected to an LVDT probe, a solution that with high probability would have allowed reducing by almost half the amplitude of the variation range of the measures. Further confirmation of the validity of my hypothesis was given by the fact that DMI s.r.l. had already applied a similar solution on a measuring machine with excellent results. Although, however, the possibility of improvement was concrete, both the team leader and the customer, for a matter of costs, rejected my hypothesis of improvement.

4.3.2 Second option for improvement

The second improvement option, more complex in implementation, arises from the fact that it would not have been possible to change the reading ability of the size of the raceways of the rings and therefore, to make improvements to the performance of the line it would have been necessary to look elsewhere. In particular, I focused my attention on the possibility of improving the size of the raceways of the IR and OR rings that reach the XHM to be coupled. This dimensional improvement has two notable advantages:

- Firstly the fact that a smaller number of ring rejects are performed
- Secondly that, arriving at IR and OR rings, whose dimensions are as similar as possible to the target ones, one would have had the possibility of inserting spheres of the target diameter (+0 μm) having a considerable saving on the purchase by the customer of multiple shades of diameter of the spheres.

For the realization of this improvement I immediately thought about the execution of a statistical process control (SPC), as in the case of the MIB OR, about the raceways diameters of the IR and OR rings.

This was possible by installing the GME III also on the XHM80 machine so that a self-tuning control system (STCS) on the grinding machines SGB55 and SSB80, which perform the raceway grinding of the IR and OR ring respectively, were possible.
Therefore, starting from this observation, I concluded that it was necessary to install two other machines along the production line, namely Post-Process machines. The just introduced new machines needed to be installed immediately downstream of the grinding machines with post-process function, i.e. to perform a statistical control of the dimensions of the raceways of the IR and OR rings with the ability of sending feedback signals to the related grinding machines. The above applies since, if it was possible to implement an SPC on the XHM80, in the event that a bearing was found to be in out of control condition, and therefore rejected, then all the bearings positioned along the line between the XHM80 itself and the grinders would have had to be discarded.
Considering the number of machines that are in the middle and the number of rings that are in the aforementioned section of the line, this would have resulted in a waste of the production capacity of the entire line. Therefore, considering the need to purchase two new Post-Process machines and the same number of GME III and CMME 7001, the improvement option I advanced was rejected for cost reasons. In fact to justify this modification to the machinery and layout in terms of profit from production would have taken a number of years not in line with the know-how of the client company.

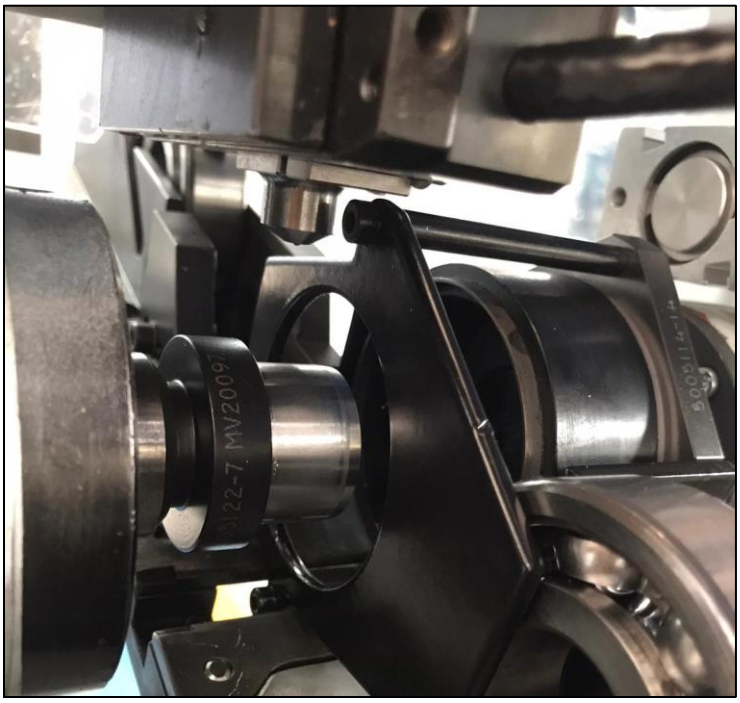
5 MVM machine

The MVM machine has been designed and built to measure the noise and vibrations generated by the bearing, by keeping the IR and OR aligned. The machinery is of primary importance for the correct operation of the line since it is equipped with the CMME 7001A measuring and analysing electronics, with BVR+ evaluation software installed. The on-board electronics therefore allows not only to classify the bearings according to noise categories defined by SKF, but also to determine the cause (defect) that generates the bearing rejection, thus allowing checking the rejection statistics and taking corrective actions, as we will see later.

The MVM machine is very simple from a mechanical and electrical point of view, just as the operating cycle is very simple. The rings feed the machine laterally through an inlet channel and then move to the first of the two measuring stations, which are mirrored to each other from the structural point of view. After being subjected to both measures (the two measurement station are needed in order to execute the measurement of noise and vibration from the two side on the bearing), depending on the outcome of these, the ring will be discarded or it will move downstream of the MVM, continuing along the production line.

The control of the eventual defects of the rings, as mentioned, takes place in the measuring stations. Here the bearing is loaded onto a nose, then set in rotation (the inner ring will rotate, in this way, at a speed controlled by the PLC with signals sent to the motor).

At the same time the outer ring is held in place by an appropriate shaping of the station and on the latter will have contact between the bearing and a MEA 200 pickup, which will send the noise and vibration data to the BVR+ software, which will perform a processing of them, whose result will be shown on the machine monitor. The following Picture shows an image of the measuring station, where the shape of the station that holds the outer ring, the measuring MEA 200 pickup and the nosepiece in place are evident.



Picture 129 - Measuring station MVM machine

5.1 MVM machine revamping

5.1.1 Mechanical and Pneumatic components revamping

As already mentioned, the MVM machine is very simple from a construction point of view and small in size. For this reason, the revamping activities of the mechanical and pneumatic components took place simultaneously and included revision of the flatness of the raceways within which the bearing rolls forward, choice of the two timing devices (cadence) for the loading activity of the measuring stations, and the motor and the belt transmission for the rotation of the nose during the measurement phases.
At the same time, the cylinders already installed on the machine were replaced with commercial ones produced by Festo, the solenoid valve block and the LFR air-treatment unit were chosen. Specifically, the cylinders that make up the pneumatic circuit on the machine are six, as well as the valves that compose the block of solenoid valves, an image of which is shown in the picture below.

Picture 130 - Block of solenoid valves installed on the MVM machine

The LFR group, on the other hand, has the standard components already presented in the previous chapters, but in addition it features two precision pressure gauges from Festo, which are necessary for adjusting the thrust force of the noses. The following picture shows a representation of what has just been said.

Picture 131 - LFR group installed on the MVM machine

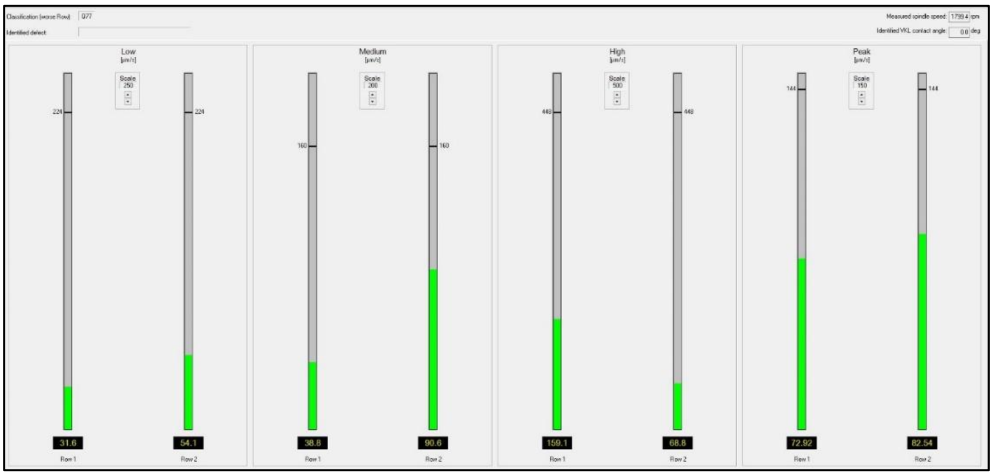
5.1.2 Electrical components revamping

As repeated several times, the revamping procedure of the electrical components present on the machine begins with the complete dismantling and composition of a new electrical panel. In the case of the MVM machine, the electrical panel is made up of the same elements already presented for the MIB OR, with the exception of the fact that in this case there is no need to install a measurement data collection box, as the pickups installed in the measuring stations communicate directly with the CMME 7001A. Therefore, an image of the electrical panel on board the MVM machine and one of the box of the CMME 7001A positioned near the monitor are shown.

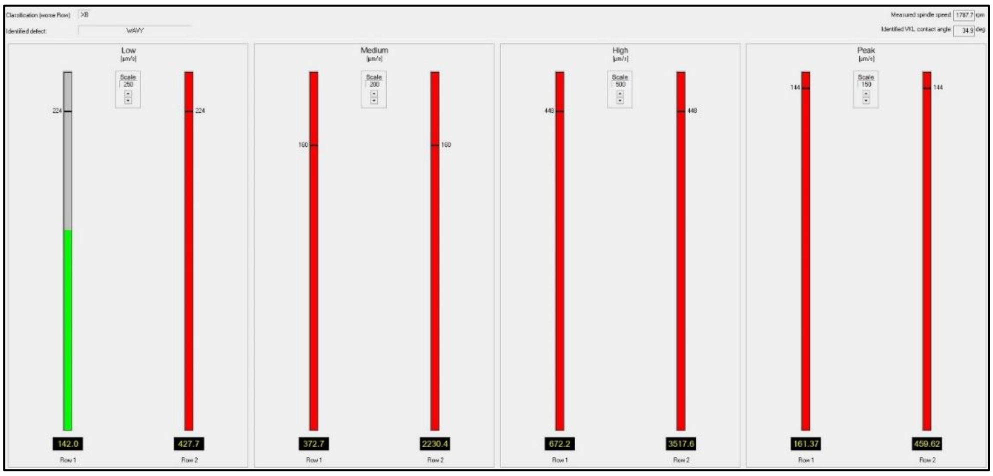
Picture 132 - Electrical panel installed on MVM machine

Picture 133 - CMME 7001A and monitor installed on MVM machine

The CMME 7001A electronics is used for noise and vibration testing. It consists of the CMME 7001A electronics and BVR+ analysing software. In the electronics, a high-precision data acquisition board (A/D card) is used to read in vibration signals from the MEA 200 pickups. This board also provide the voltage supply for the pickups.
The MEA 200 pickup works according to the inductive principle and have a velocity proportional output signal and a small amplifier is installed into the pickup housing. This is an advantage since the vibration signal is already amplified and has a high signal-to-noise ratio when fed to the A/D card. The configuration just explained is very simple also in terms of implementation since the MEA 200 pickup can be directly connected to the CMME 7001A.
The BVR+ software analyses the noise emitted by bearings and noise sources in rolling bearings. The software determines the characteristic values for the low (L), medium (M) and high (H) bands according to the AFBMA standard. It also contains the Finger Print Method (FPM) algorithms that determine the cause of bearing defects. The result of the analysis contains also a fourth parameter, the peak value used to detect the existence of the local defects and dirt, and BVR+ classifies the bearing according to the noise categories defined by SKF.
The simplest analysis performed by BVR+ software, and the related bearing classification, is the VKL analysis, based on the three band (L, M, H) and peak values.
In the following Pictures are reported the results of the analysis about a good bearing (Q77 quality class) and a bad one with waviness being the identified defect.



Picture 134 - VKL analysis result on a good bearing

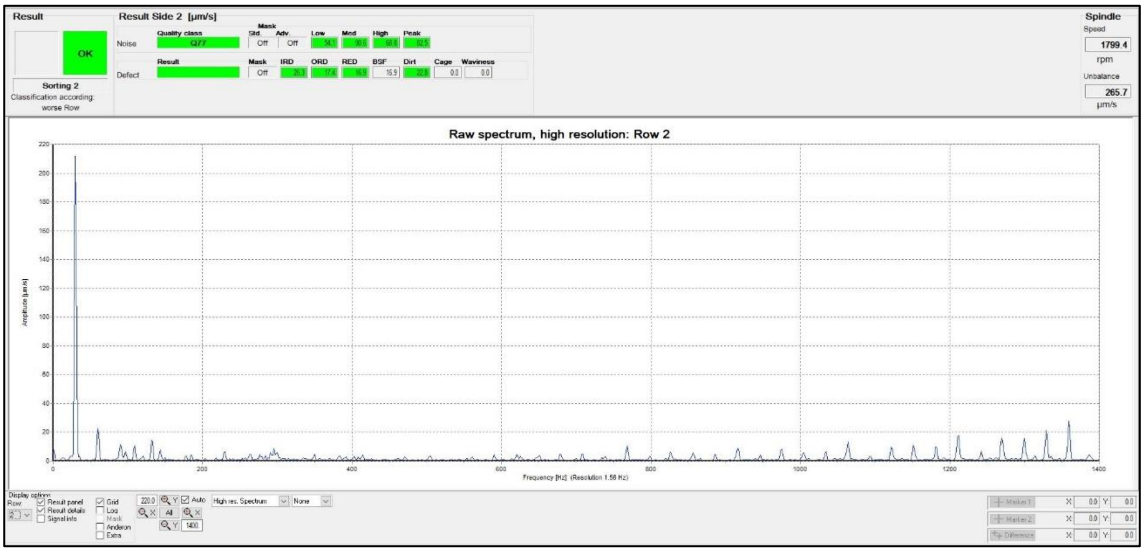


Picture 135 - VKL analysis result on a bad bearing

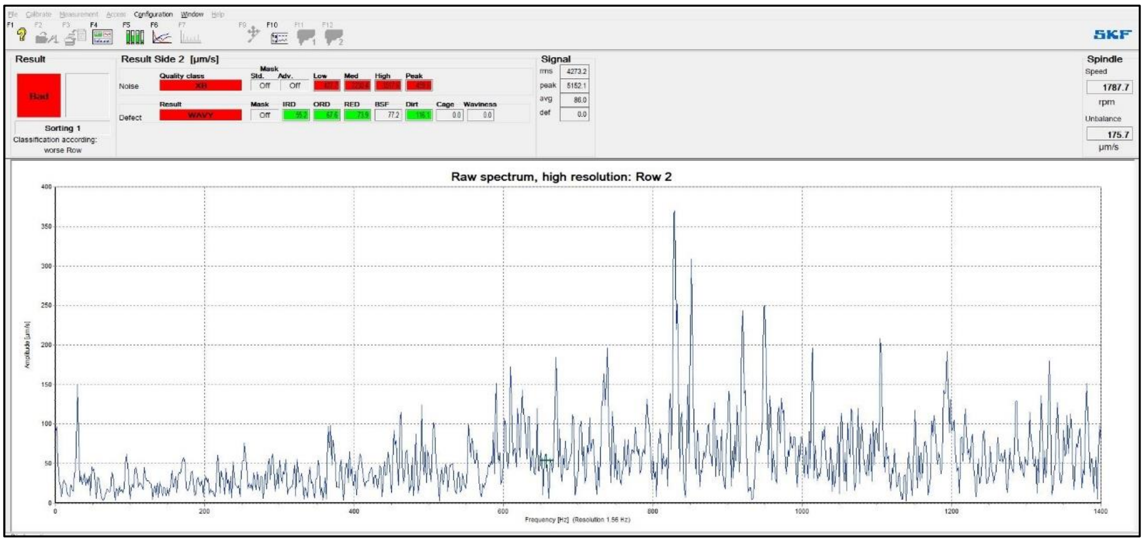
As it can be seen, the VKL analysis result screen can be divided into two parts: an information area where the classification of the bearing is reported as well as the identified defect, and the VKL chart reporting the value of the parameters on which the analysis is based and a bar chart of them. Obviously the analysis is performed for both the sides of the bearing in both the measuring station and, as it is evident from the Pictures, the classification is based on the worse side measured.

In addition to the VKL analysis, the BVR+ software performs a spectrum analysis, which shows detailed results of the analysis of the bearing vibration signals. Specifically in the result screen the frequency spectrum is reported, where the time signal is transformed into the frequency spectrum using the FFT (Fast Fourier Transformation).

The BVR+ uses a raw spectrum with the possibility to have a high resolution, as it is clear in the following Pictures. The frequency resolution is determined by the duration of the time signal that has to be transformed. The measurement period determine the resolution. The longer the measurement period, the better the spectrum resolution. In order to make clearer what I am talking about, in the following two Pictures the spectrum analyses are reported, that have been performed on the same bearings for which the results of the VKL analysis have been already reported.



Picture 136 - Spectrum analysis result on a good bearing



Picture 137 - Spectrum analysis result on a bad bearing

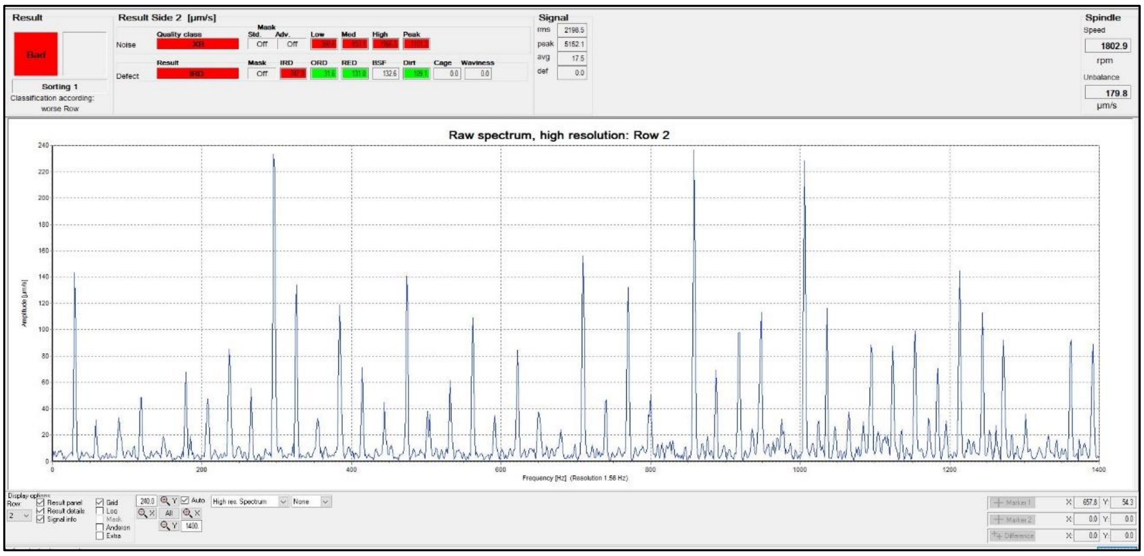
For the spectrum analysis, the result screen is divided into two parts:

- The result panel: this panel is composed by some windows reporting the result of the measurement (OK or Bad), the values of the measured parameters, the noise assigned quality class and the detected defect. In the same panel it is possible to find some informations about the spindle speed and the unbalance, which is the amplitude of the vibration signal due to the spindle unbalance;
- The chart panel: here the chart representing the signal in the frequency domain is reported.

As it can be easily understood, the defects that can be detected by the BVR+ software are related to either the components of the bearing, rolling elements, inner ring, outer ring, cage, or the dirt and waviness. In particular, the aforementioned defects are coded like follows:

- IRD: inner ring raceway defect;
- ORD: outer ring raceway defect;
- RED: rolling elements defect;
- Dirt;
- Cage;
- Waviness.

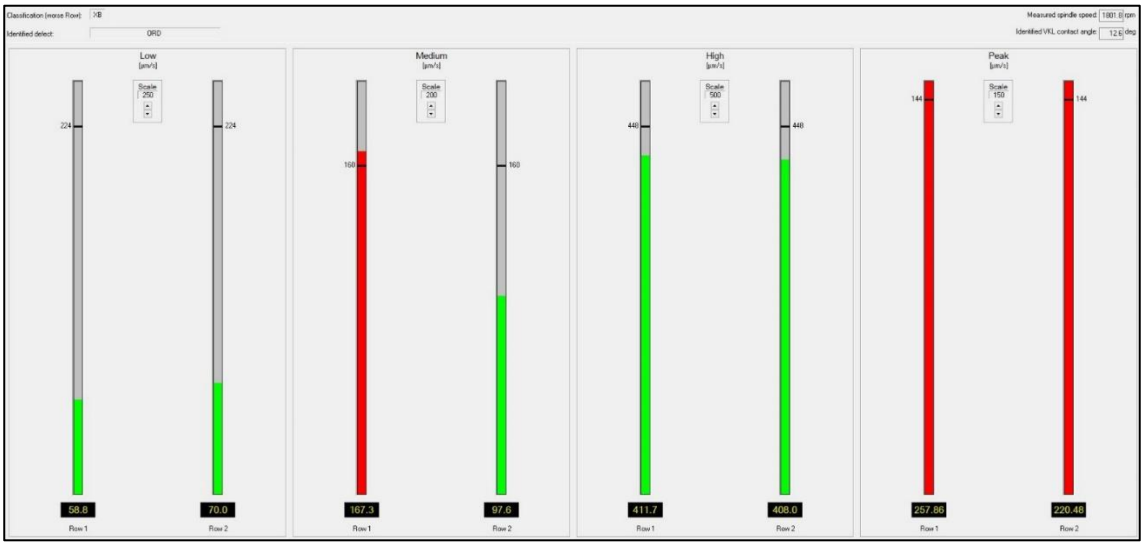
For the sake of completeness, the cases of presence of defects identified by the MVM machine in the test phases are reported, in terms of both VKL analysis and Spectrum Analysis.



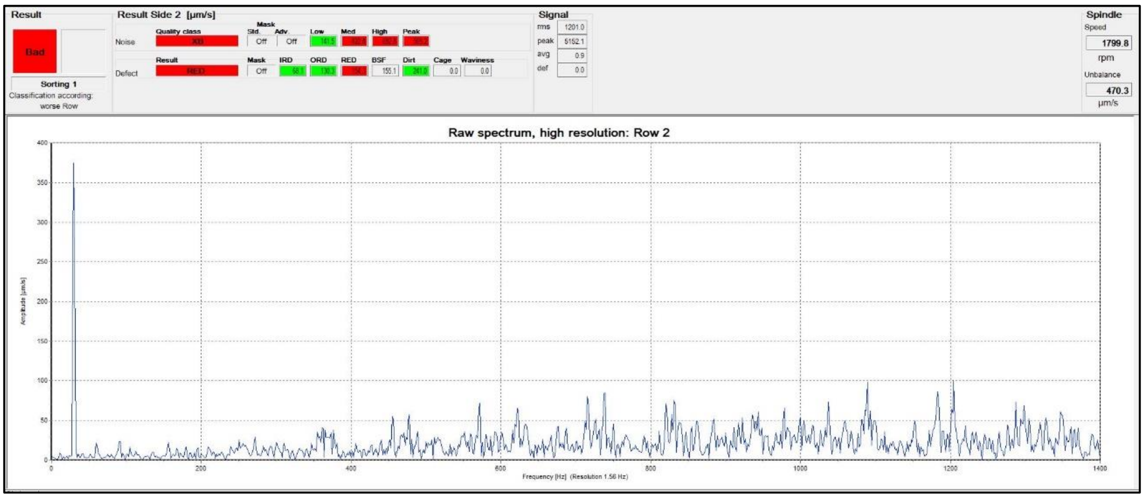
Picture 138 - IRD defect, resulting from the Spectrum analysis

Picture 139 - IRD defect, resulting from the VKL analysis

Picture 140 - ORD defect, resulting from the spectrum analysis

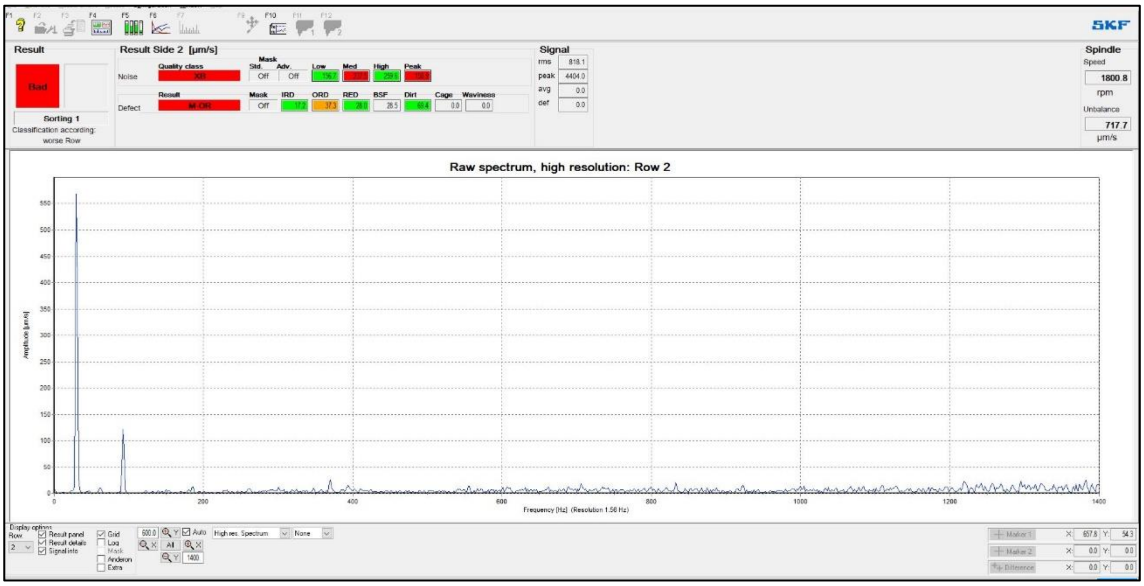


Picture 141 - ORD defect, resulting from the VKL analysis

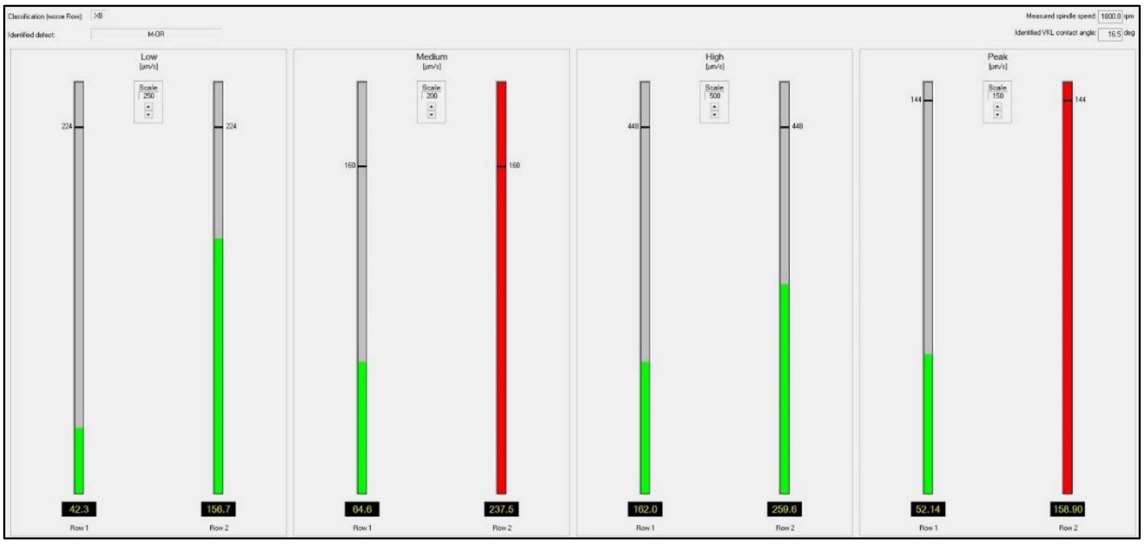


Picture 142 - RED defect, resulting from the spectrum analysis

As already said and reported in the dedicated Picture, the BVR+ software is able to identify waviness problems when it is related to both the IR and OR; at the same time it is able to detect the waviness problem also in case it is related to either the IR or the OR. In the following Picture the M-OR defect is found, which means that there is a vibration contribution of the outer ring waviness in the M band.

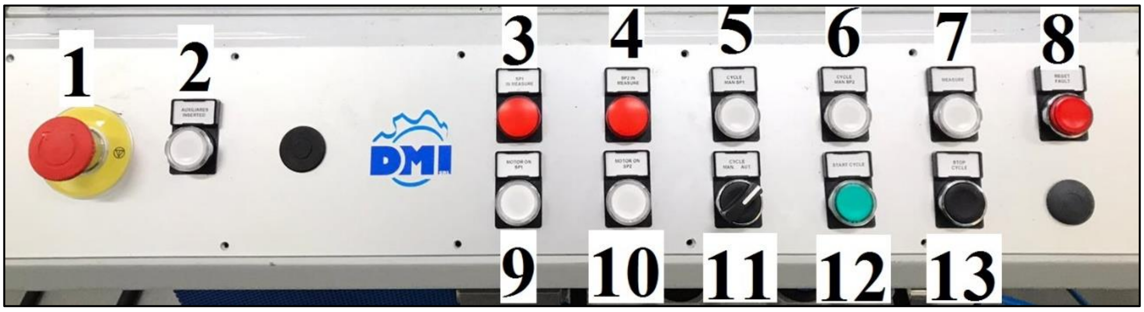


Picture 143 - M-OR defect, resulting from the spectrum analysis



Picture 144 - M-OR defect, resulting from the VKL analysis

Another important feature of the MVM machine, in addition to the predisposition to use the SKF-owned BVR+ software, in terms of revamping of the electrical components is the total absence of a control panel for the HMI interface, which is therefore reduced to just pushbutton. The on-board machine monitor, in fact, has the sole task of allowing the execution of the noise and vibration analysis software, but does not allow to control the operation of the machinery in any way. Therefore, unlike those installed on the MIB OR and XHM80 machines, the push-button panel is more complex and allows the control of actions that in the previous cases were controlled from the HMI control panel. For a more detailed description, the push-button panel is shown in the Picture below.



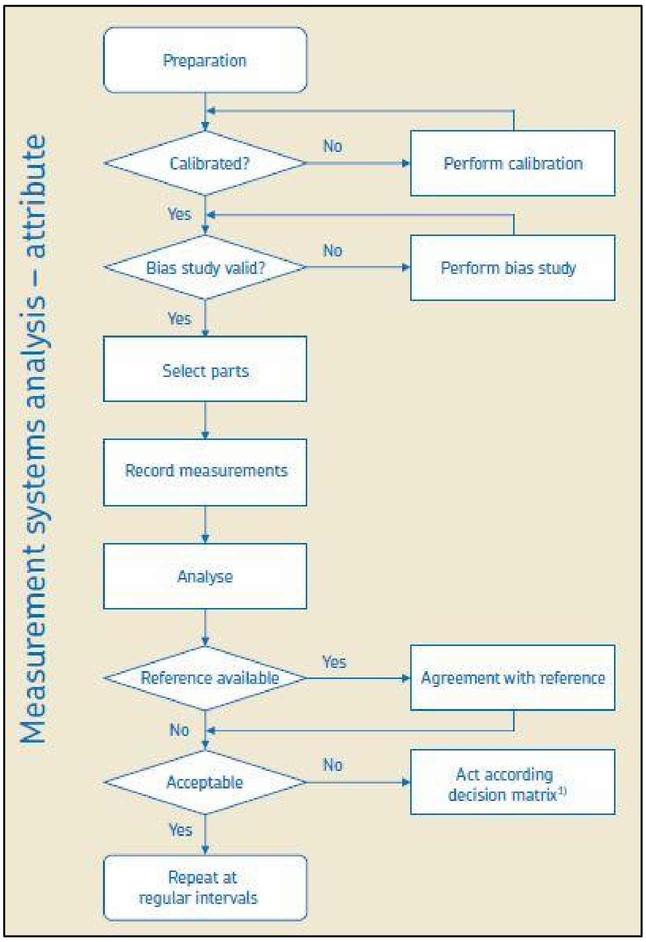
Picture 145 - Push-button panel installed on board of MVM machine

In the previous Picture, the buttons composing the push-button panel are numbered in order to describe them in a more accurate way. The buttons are:

1. Emergency mushroom pushbutton: when activated, it disconnects the control circuits and power supplies to the machine;
2. Auxiliaries insertion: reset all functions after activating the emergency button;
3. SP1 in measure: indicates the presence of the bearing on the mandrel 1;
4. SP2 in measure: indicates the presence of the bearing on the mandrel 2;
5. Cycle man SP1: it commands the loading of the bearing on the nosepiece 1;
6. Cycle man SP2: it commands the loading of the bearing on the nosepiece 2;
7. Measure: when activated commands the measurement actions;
8. Reset faults: before cycle start command, it resets all the anomalies;
9. Motor ON SP1: it starts the motor 1;
10. Motor ON SP2: it starts the motor 2;
11. Man/Aut: in manual mode it commands the step-by-step cycle; otherwise, in automatic mode it commands the automatic cycle.
12. Start cycle: when pushed it starts the cycle in automatic mode;
13. Stop cycle: when pushed it stops the cycle.

5.2 Measurement system analysis

The MVM machine, in term of quality of the measurements, had to be analysed following the attribute analysis procedure reported in the QT5 – Measurement System Analysis brochure by SKF, which is reported in the following Picture.



Picture 146 - Attribute measurement system analysis procedure (from SKF QT5 brochure)

The aforementioned analysis was required since the measuring system was an attribute measurement system. Attribute measurement system are the class of measurement system where the measurement value is one of a finite number of categories. The most common of these is a Go/No go gauge, which has only two measurement results.

The measurement system, according to SKF standard are divided among three groups in terms of type of measurement performed, as reported in the following Picture.

Attribute	No. of categories	Characteristics	Examples
Binary	2		Pass/Fail; Go/No go; On/Off; Works/Broken
Nominal	3 or more	No natural order	Red/Blue/Green; West/East/Central/North
Ordinal	3 or more	Natural order	Strongly disagree/Disagree/ Agree/Strongly agree; Low/Medium/High

Picture 147 - Type of measurement according to SKF standard (from QT5brochure by SKF)

According to SKF standard, in this way, it is possible to define the MVM machine as a binary measurement system since the result of the measurement is Good/Bad.

The κ (kappa) statistic has been proposed as a statistic for the evaluation of the binary measurement system. Kappa statistic is the measure of the degree of agreement between two raters, based on how they classify a sample of objects into a number of categories. Therefore, in this way, it is possible to establish that the κ value, ranging from 0 to 1 in case of perfect agreement, is the measure of the precision of the binary measurement system. In other words, if the MVM machine, independently from the operator, gives exact results, namely equal to actual results, it is possible to say that the machine is a good measuring system. According to the value of kappa statistic, the quality of the measurement is established as follow.

Criterion			
Kappa value	0,00–0,39	0,40–0,75	0,76–1,00
Quality of measurement	Poor	Moderate	Good to excellent

Picture 148 - Relation between kappa value and measurement quality table (from SKF QT5 brochure)

Thanks to the use of Minitab software it has been possible to compute the value of kappa by selecting a sample of 100 master bearings (Standard) selected by SKF and divided in a mix of 50/50 Good/Bad bearings. The measurements of the quality of the bearings were performed first by me (Mario) and then by my tutor (Paolo). The results of the measurements were passed to the software and the result of the kappa value computation is here reported.

Each Appraiser vs Standard

Assessment Agreement

Appraiser	# Inspected	# Matched	Percent	95% CI
Mario	100	100	100,00	(97,05; 100,00)
Paolo	100	100	100,00	(97,05; 100,00)

Matched: Appraiser's assessment across trials agrees with the known standard.

Assessment Disagreement

Appraiser	# GOOD / BAD	Percent	# BAD / GOOD	Percent	# Mixed	Percent
Mario	0	0,00	0	0,00	0	0,00
Paolo	0	0,00	0	0,00	0	0,00

GOOD / BAD: Assessments across trials = GOOD / standard = BAD.
BAD / GOOD: Assessments across trials = BAD / standard = GOOD.
Mixed: Assessments across trials are not identical.

Fleiss' Kappa Statistics

Appraiser	Response	Kappa	SE Kappa	Z	P(vs > 0)
Mario	BAD	1	0,1	10	0,0000
	GOOD	1	0,1	10	0,0000
Paolo	BAD	1	0,1	10	0,0000
	GOOD	1	0,1	10	0,0000

Between Appraisers

Assessment Agreement

# Inspected	# Matched	Percent	95% CI
100	100	100,00	(97,05; 100,00)

Matched: All appraisers' assessments agree with each other.

Fleiss' Kappa Statistics

Response	Kappa	SE Kappa	Z	P(vs > 0)
BAD	1	0,1	10	0,0000
GOOD	1	0,1	10	0,0000

All Appraisers vs Standard

Assessment Agreement

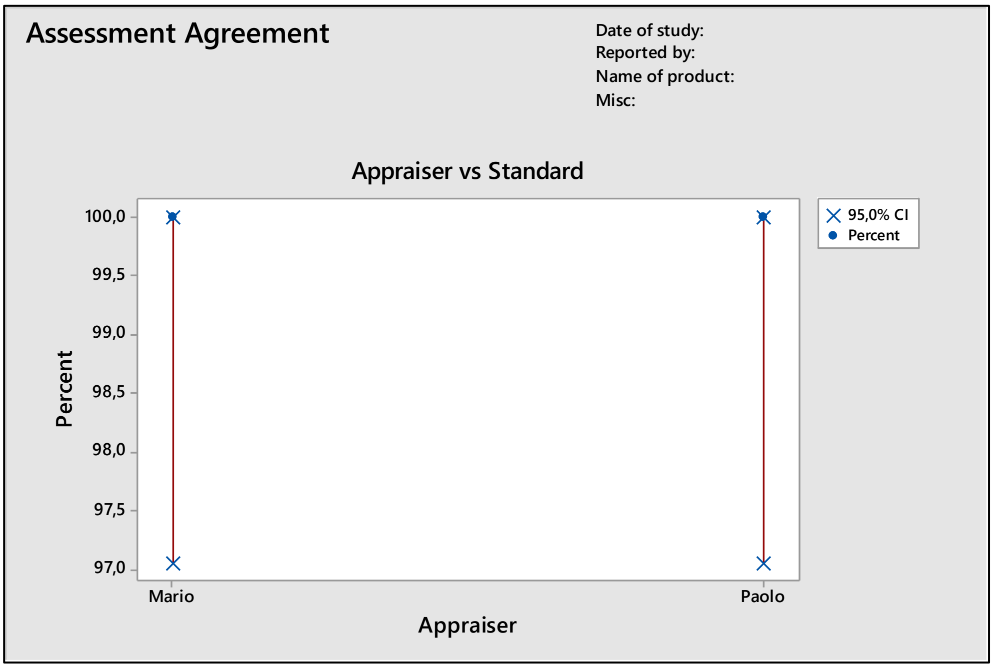
# Inspected	# Matched	Percent	95% CI
100	100	100,00	(97,05; 100,00)

Matched: All appraisers' assessments agree with the known standard.

Fleiss' Kappa Statistics

Response	Kappa	SE Kappa	Z	P(vs > 0)
BAD	1	0,0707107	14,1421	0,0000
GOOD	1	0,0707107	14,1421	0,0000

Picture 149 - Attribute agreement analysis MVM for Mario e Paolo



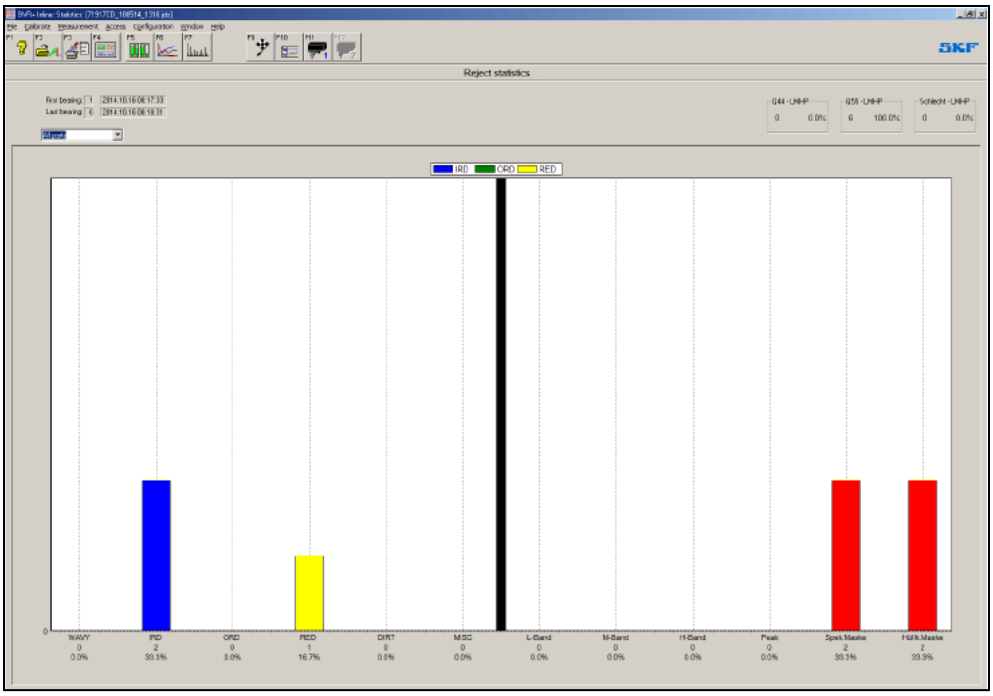
Picture 150 – Assessment agreement appraisers vs standard graphical result

Looking at the result of the agreement analysis just reported it is possible to see that the value of kappa statistic is equal to 1 and this is the reason why the binary measurement system can be said to be excellent. In other terms, the two appraisers agree each other, and both of them agree with the standard so that the machine is able to recognize a good bearing from a bad one independently from the operator and perfectly agree with the standard value corresponding to the quality of the master bearings provided by SKF.

5.3 MVM: the third key machine for process improvement

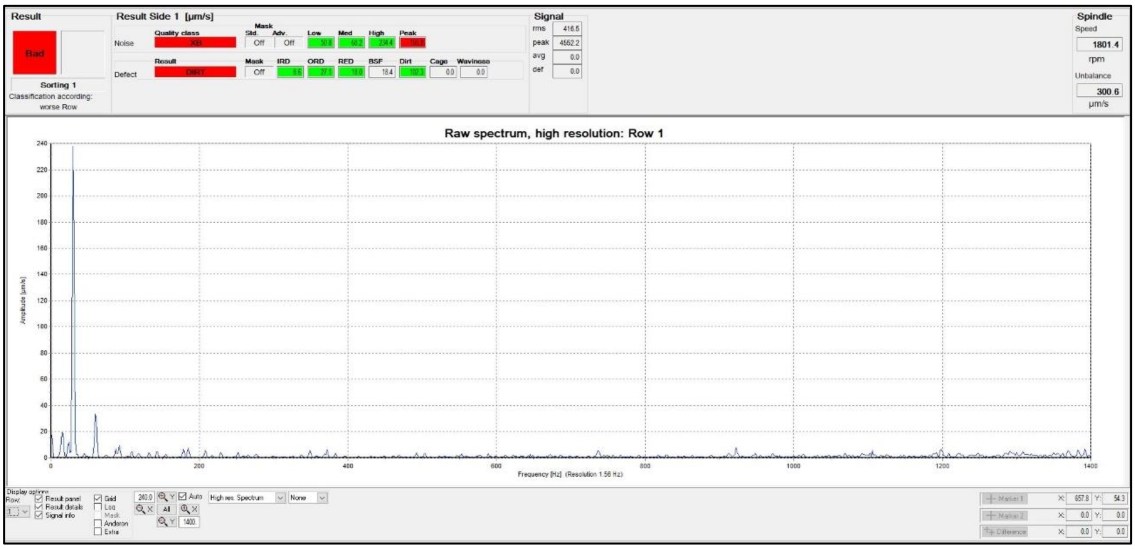
The MVM machines on the line have the task of making a final selection of the bearings in accordance with the production standard, proceeding with the rejection of the bearings considered non-compliant. For this reason, the MVM machine for measuring noise and vibrations plays a key role, but its role during the revamping and line performance evaluation process is equally key; it was in fact used to evaluate the possibility of further improving the production line thanks to the ability of the BVR+ software to identify any production defects. For this reason, I decided to carry out a study of the production line by performing production simulations and analysing the results of the measurements performed by the MVM machinery.

I took advantage of the possibility of reading the measurement statistics directly on the machine, deciding not to use the statistics about the quality classes of the bearings produced as the result of the VKL analysis, but rather I decided to use the reject statistics function, which contains the statistics about parts that were classified as rejects. An image of the statistics that can be obtained is the following, reported in the BVR+ manual as an example.



Picture 151 - Reject statistics from BVR+ manual

My observation of the statistics of rejected parts defects highlighted the presence of dirt, present in the bearings in a percentage not compliant with the client request and production standard. A screenshot of one of the dirt measurements detected is shown below.



Picture 152 - Dirt defect presence evaluated thanks to the BVR+ software

In order to solve the problem of dirt in the production phase and increase the performance of the line, my research has led to the solution that it was necessary to install washing machinery and demagnetizing machinery.

The former are machines that perform the washing of the components using water to prevent the accumulation of chips and dust, while the latter are necessary to demagnetize the rings after the grinding and pairing phases, preventing them from attracting metal particles that would damage the assembled bearing during the exercise. In the layout the washing machine always follows the demagnetizer, and, in the case of the greasing machine, in order to have a clean bearing, we find only a washing machine.

My improvement proposal was validated by the Research and Development (R&D) team and accepted by the customer by presenting the new layout with the new machinery arranged on the line in the most critical points, as evident from the Picture in the dedicated chapter, and an analysis of the costs required to implement the improvement. Therefore, in the near future, when the revamping processes of all the machinery on the line are completed and these will be tested and validated, these machines will be designed and built.

6 Conclusion and future developments

6.1 Conclusion

The aim of this thesis was the study and analysis of the improvements that can be made to the machinery making up an entire bearing production line in order to increase the performance of the line itself. Therefore, in the face of what has been said in the previous chapters, the SKF Sopot (Bulgaria) radial ball bearing production line that arrived in DMI s.r.l in non-operating conditions and dated for tens of years, has been overhauled in order to running all the machines that made it up.

At the same time, during the revamping to which the entire line was subjected, the machinery, especially those considered to be the key in terms of increasing the performance of the line, were equipped with new hardware and software technologies. Therefore, the line will certainly have a higher performance thanks to the improvements made, both in terms of reducing production costs and waste, as fully described in the chapters dedicated to the analysis of key machinery.

6.2 Possible future developments

As already mentioned, the radial bearing production line under study was revamped in order to put all the machines back into operation by applying more modern hardware and software solutions to increase the performance of the line.

At the same time, however, it is possible to foresee further improvements to which the line will possibly be subject in the future; and it is precisely these improvements that will be discussed in this paragraph.

6.2.1 Software improvement for Error & Troubleshooting functions

In the current state of the machines, as requested by the SKF Sopot customer, the machines are able to detect errors and go into an emergency state which involves stopping the machine. The detection of the error occurs thanks to the software that detects it by commanding the emergency state, but without giving any specific indication to the operator about how to identify and solve the error.

In fact, in the event of an error, the machine reports an error message on the HMI and the code that identifies it. This code is indicated and explained in the operator manual. Therefore, in order to resolve the error, if this occurs, the operator is forced to read the machine manual and make subjective decisions on the solution, all wasting a lot of time depending on the ability and promptness of the operator. To clarify with an example what the current state of the machine is, an error often detected by the machines of the line is reported, such as the non-excitation of a ring presence sensor, whose code is of the SqX type.

Therefore, it is not difficult to imagine possible future improvements of the software in order to speed up the process of error detection, identification and resolution of the same. All this is possible by implementing an Error & Troubleshooting function like the one I will present shortly.

Taking again into consideration the previous example, that is the non-excitation of a sensor that reads the presence of the ring following the action of the loading cylinder which moves the ring from the loading duct on board the machine. In order to be able to implement functions of Error & Trouble shooting, it is first of all necessary to understand how to execute and speed up the error resolution process and then transform what has been said into an extension of the software on the machine. So let's consider the case in which the above error is present, in order to implement the function of identifying and solving the problem, it must be possible, through the HMI interface, to click on the name of the error that appears on the screen. In this way will be possible to access an error solution screen in which, first of all, there is a map of the machine showing all the sensors and their position on the machine and an indicator of the one subject to the error search.

In this case it will be possible for the operator to immediately identify where the error is and click again on the indicator on the map to confirm that the problem has been identified. At this point a screen will open with the possible causes of the error, and one at a time they can be clicked to present to the operator what are the corrective actions that can be made in order to correct the error whose cause is the one clicked.

Let me clarify what has been said with an example. On the HMI screen, the message Error: SqX appears; at this point the operator clicks on the error code and a map of the machine opens which indicates to the operator where the error is located.
The operator clicks on the position indicator that appears confirming that he has identified the sensor being searched. At this point a window opens with the list of possible causes of the problem, such as the following:

- Sensor malfunction;
- Ring trapped in the loading channel;
- Cylinder not fed correctly.

At this point, clicking, one at a time until the problem is solved, on all the possible causes, the corresponding windows of suggested corrective actions will open. For example, in the first case, a screen will open with possible actions as follows:

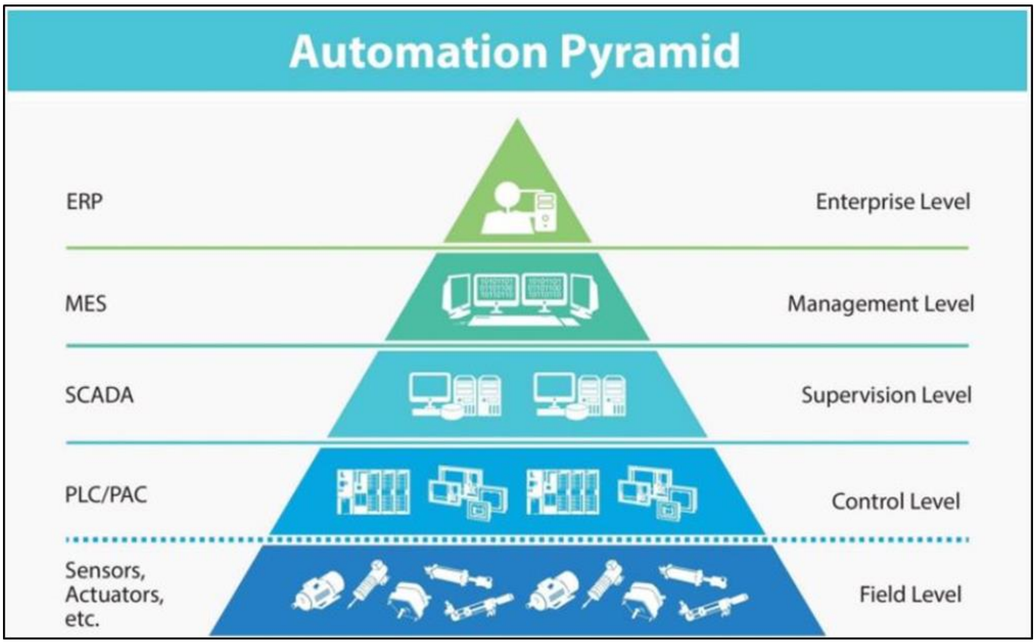
- Manually check that the sensor is able to read the presence of the ring, moving the ring closer and further away and using the LED of the sensor itself;
- Check the power supply to the sensor;
- Check that the sensor is still physically installed in its original position.

In the latter case, however, the operator could be advised to check the compressed air supply to the cylinder, possibly using a digital pressure switch.
By implementing, in this way, all the possible Error & Troubleshooting functions, it will be easier for the operator to identify and solve the error, while consequently machine downtime will be reduced, further increasing the performance of the machine in terms of productivity.

6.2.2 Digitalization of production through an increase in the level of automation in an Industry 4.0 perspective

Once the line studied in this thesis is installed in the SKF Sopot plant, it is possible that it will be necessary to achieve a high level of automation of the Bulgarian plant, requiring the implementation of software such as SCADA, MES and ERP.
Starting, therefore, from the revamped machinery, thanks to the installation of network cards on the machine and the use of the Siemens PROFINET protocol, it will be possible

to convey all the production data, through a network switch, to a SCADA server, thus allowing you to go up the automation pyramid shown below.



Picture 153 - Automation pyramid (from http://www.miac-automation.com/mes-oee-track-and-trace/)

It is therefore possible to analyze the pyramid of industrial automation from the bottom up.

SCADA software, acronym for Supervisory Control And Data Acquisition, is an information system that deals with the supervision, data collection and control of an industrial production plant. Therefore, these software acquire, process and archive a large amount of data coming from the sensors installed on the machines and processed by the PLCs. This data can then be used to increase the efficiency of production processes thanks to the implementation of more complex software solutions such as MES and ERP.

The MES, acronym for Manufacturing Execution System, is a software system that arises between ERP and SCADA systems, referring to the automation pyramid, therefore, between the decision-making level and the production level in order to put them in communication and avoid that what is produced does not coincide with what is planned. The software in question, therefore, allows the organization and control of the production department to be computerized by performing relevant functions such as:

- Sequencing of production activities based on the priorities and characteristics of each production batch;

- Monitoring of WIP (Work In Progress) activities ensuring compliance with the production schedule and avoiding bottlenecks;
- Performance analysis in real time by analyzing resources, cycle times, production costs;
- Quality control: after verifying the conformity of the finished products, the software indicates which corrective actions to take to correct any errors or slowdowns that affect the production phases;
- Maintenance activities, in fact, by analyzing the operating data of the machines, the MES software warns when it detects faults and communicates the diagnosis.

A MES system such as the one just described, which communicates with the production plant and with the ERP, is highly interconnected and is fully part of Horizontal and Vertical Integration, one of the nine pillars of industry 4.0.

ERP software, acronym for Enterprise Resource Planning, is a business management system that allows companies to have a 360° view of all the elements related to their business. From this point of view, in fact, the ERP allows to control and manage, through the dedicated modules, the inventory, orders, resources, planning, purchases, financial implications and reporting. For what has been said, therefore, Enterprise Resource Planning allows you to integrate all business activities into a single system, which is, by definition, essential to support management.

The ERP - MES integration helps to increase operational efficiency, reduce production times, increase flexibility and decision-making speed. Thanks to the ERP - MES integration, manufacturers can place new orders before a certain product runs out. In fact, the integration of real-time data on the availability of materials helps manufacturers to reduce unnecessary interruptions and delays.

6.2.3 Implementation of a traceability solution through a Data Matrix Code

In recent years, in order to ensure complete traceability of the controls and information collected throughout the bearing manufacturing process, SKF has designed a system for digital measurement and archiving of data using a Data Matrix code marked on the bearing surface [http://www.disloman.it/skf/].

In this context, therefore, it is not difficult to think that traceability solutions like this will be implemented in the coming months for the production of the SKF Sopot line.
The Data Matrix is a standard code (reference standard ISO / IEC TR 29158), made up of a square or rectangular matrix of black and white cells. In SKF's design, it is laser-marked on the outer surface of the bearing and contains a unique bearing identification code. The latter is the access key to a Database, which contains all the information collected station after station in digital format [http://www.disloman.it/skf/].
The rings, both IR and OR, are marked downstream of the grinding operations, where they are machined to reach the dimensions and finishes required by the drawing and not before as the action of the grinding machines would ruin the Data Matrix code. As already explained in the previous chapters, downstream of the grinding machines, the rings are subject to a series of checks and operations that begin with dimensional control and end with packaging. It is precisely in this phase of the production process that the traceability solution with Data Matrix is implemented.
The first step is to perform, along the line, a series of dimensional and geometric checks whose measurement results are historicized thanks to the Data Matrix. Each station of the production line, in fact, is equipped with a vision tool that allows the reading of the code and the identification of the piece and that connects to the Database to update the data, inserting the results of the records obtained at the station.
Once all the above checks have been carried out, the bearings will be paired in the dedicated station and thanks to the sequential reading of the two rings, internal and external, it is possible to associate the two rings and use, from this operation on, the Data matrix of the external ring. as a reference for the assembled bearing.
This system is therefore suitable not only for the traceability of the checks carried out on the bearing, but also for the traceability of the product and its components. In fact, in the assembly station, the bearing Data Matrix is associated with information relating to the batch of origin of each component, whether it is a semi-finished product, as in the case of cages, or a product purchased outside the factory as in the case of the balls, and all information relating to the manufacturing batch to which the customer's order code corresponds.

The collection and digital archive of information is used to automate the data collection process of a bearing and to avoid errors due to the operator in the case of filling in the labels manually.
In conclusion, therefore, thanks to the implementation of this traceability solution, it is possible to perform an effective management of complaints if the bearings return from the field of application, but also to perform a real-time control on the progress of production and implement suitable solutions in terms of maintenance of machinery.

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Mario