POLITECNICO DI TORINO

DIGEP – DEPARTMENT OF ENGINEERING MANAGEMENT AND PRODUCTION

Master of Science Degree in Engineering and Management

Quality Assurance implementation in Industry 4.0 and 5.0 perspective: MES application and development

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List of Abbreviations

API	*Application Programming Interface*
BI	*Business Intelligence*
BSI	*British Standards Institution*
CAD/CAM	*Computer-Aided Design/ Computer-Aided Manufacturing*
CE	*Concurrent Engineering*
CMM	*Coordinate Measuring Machines*
CMMS	*Computerized Maintenance Management System*
ERP	*Enterprise Resource Planning*
GHG	*Greenhouse Gases*
GMS	*Geometrical Measuring Systems*
HMD	*Head-mounted Display*
IIoT	*Industrial Internet of Things*
IoT	*Internet of Things*
IR	*Industrial Revolution*
ISO	*International Organization for Standardization*
IT	*Information Technology*
JSON	*JavaScript Object Notation*
LIS	*Lean and Integrated System*
LP	*Lean Production*
M2M	*Machine-to-machine*
MES	*Manufacturing Execution System*

MQTT	*Message Queuing Telemetry Transport*
MTBF	*Mean Time Between Failure*
MTTR	*Mean Time to Repair*
MVS	*Machine Vision Systems*
NTP	*Normal Temperature and Pressure*
OCAP	*Out of Control Action Plan*
OPC UA	*Open Platform Communications Unified Architecture*
OT	*Operation Technology*
PCR	*Process Capability Ratio*
PDCA	*Plan-Do-Check-Act*
PLC	*Programmable Logic Controllers*
QA	*Quality Assurance*
QFD	*Quality Function Deployment*
QMS	*Quality Management System*
R&D	*Research and Development*
ROI	*Return on Investments*
RTU	*Remote Terminal Unit*
SDG	*Sustainable Development Goals*
SMEs	*Small and Medium Enterprises*
TBL	*Triple Bottom Line*
UI/UX	*User Interface/User Experience*
VSM	*Value Stream Mapping*

Introduction – Objective of the thesis

The primary purpose of the thesis is to implement a user-friendly software module which allows users to define metrics for quality control at products level of an order, and to *analyze simultaneously the measurement data received by operators and/or machines in order to determine if the process is under statistical control*; if it is not, the module must be able to suggest – through an algorithm that will be presented in the subsequent chapters – the necessary steps to bring the process under statistical control by automatically generating an Out of Control Action Plan (OCAP) report.

The analysis' objective is to identify the process drifts *in advance* with the development of models and algorithms and the support of tools like control charts, normality tests of points distribution in the control charts, statistical tests and calculation of Cp index (Process capability: it compares the tolerance range with natural variability of the process without considering the process mean) and Cpk (which compares process statistics with the tolerance range, taking into account the process mean).

The module must be designed according to regulations, in particular ISO 9001, and shaped on the concepts of Industry 4.0 and Industry 5.0.

Firstly, the thesis will provide an introduction to the MES – Manufacturing Execution System – product and how it aligns with Industry 4.0 and 5.0. Furthermore, it will explain how MES data is provided and analyzed. Since machines are interconnected (M2M) and co-work with human operators, it will introduce the most common communication protocols and discuss maintenance strategies essential to reduce failures and their consequences. Subsequently it will present a state of the art with literature review on the evolution of the industry over the centuries, until reaching the most recent techniques and innovations, which Orchestra itself is helping to enhance and provide to its customers.

In fact, the company aims to implement on-board machine quality control with the support of an operator wearing augmented reality smart glasses (Industry 5.0) and of production machineries (Industry 4.0), depending on the working processes.

Moreover, there will be a description about how RETUNER architecture can support advanced and automated QA, with a detailed explanation of the architecture, composed by SMARTEdge, SMARTHinge and MiniMES software, and a deeper illustration of advantages and limits of Industry 4.0 and its interconnections.

The thesis will also present an analysis of the problems and requirements for quality control in Industry 5.0, with a focus on Planoplast case study, and will make calculations to evaluate the production processes performance and propose corrective actions to implement the QA in the best way possible.

Subsequently, the design of a prototype integrated in the MES to control final products' quality will be developed; it will include different types of categories of production and control methods, and the design of the effective user Dashboard, which must be user friendly and intuitive with automatic generation of control charts normality tests, and other tools. Finally, there will be a conclusion based on the results obtained and the presentation of the future developments.

1. Manufacturing Execution System

The Manufacturing Execution System, also called MES, is a system used by industries to monitor and optimize the production processes, enhancing their operations effectively and efficiently, and increasing the production output.

A connected supply chain is essential for the MES market: in order to have an efficient production activity, it is necessary that the information flows across the factory. This is made possible thanks to IoT systems which detect materials' location, monitor inventory, report manufactured products passing through the entire supply chain, and help simplifying the flow of information throughout the supply chain, so that companies can respond efficiently to the changing market conditions. Due to real-time information, manufacturers can lower inventory costs, identify potential risks and achieve production according to market needs.

The necessity of the manufacturing industry to increase production, along with quality improvements, can be met with the use of advanced tools and software systems, which are offered by Manufacturing Execution Systems. The MES counts several advantages, such as the fact that it is useful to reduce production costs, improve compliance, plan orders and maximize machine loading, i.e., optimize ROI by paying back investments and generating value; moreover, the implementation of its use leads to a reduction in energy consumption and waste during the manufacturing process.

In the past, before the introduction of Industry 4.0 and Industry 5.0 concepts, MES were used as a supporting tool to keep track of production, times, and methods. With the advent of Industry 4.0, the MES assumes a more central role as it "*gives voice to machines*", which are now interconnected to the factory and can communicate with it.

1.1. Configuration of a MES in Industry 4.0 and 5.0

The information exchange between devices must follow rules and conventions outlined in communication protocols' specifications. Their aim is to provide secure and reliable exchange of data for several types of industries, and to ensure the seamless flow of information among devices from multiple vendors. The most common are OPC Unified Architecture, Modbus, MTConnect and MQTT.

The OPC-UA, whose acronym OPC stands for Open Platform Communications, is a series of specifications that define a standard interface between clients and servers as well as servers and servers, including access to real-time data, monitoring of alarms and events, access to historical data and other applications. [1]

Modbus is widely used in the industrial sector to interconnect machines' PLC, i.e., their Programmable Logic Controllers. These modules are used to allow machineries to perform several functions according to their programming and intended use. Modbus is often used to connect a supervisory computer with a Remote Terminal Unit (RTU) in supervisory control and data acquisition. [2]

MTConnect focuses on standardizing the connection and communication between production devices, enabling real-time data collection for monitoring, analyzing, and optimizing industrial operations. It has applications in several fields like machine monitoring, job scheduling, process analytics, predictive maintenance, and many more. [3]

MQTT, which stands for Message Queuing Telemetry Transport, is a protocol that aims to provide an efficient and reliable method for exchanging messages between resource-constrained devices, enabling efficient data transmission while reducing bandwidth usage and energy consumption. It is widely used for communication between sensors, control devices, and IoT applications, facilitating real-time data transmission and flexible communication management. It is used in a wide variety of industries, such as automotive, manufacturing, telecommunications, oil and gas, etc. [4]

Machines can exchange data through machine-to-machine (M2M) communication, which allows direct interaction between devices, utilizing wired or wireless channels without human intervention. The primary objective of M2M communication is to collect data, transmit it over the network, and trigger actions based on events. Industries favor M2M communication for its efficiency, cost-effectiveness, and faster data processing capabilities.

IoT is an alternative way to enable machine communication. It aims to create smart environments to simplify and innovate the interactions between the real world and the digital one by capturing real-time data.

The main difference between the two technologies is that IoT requires M2M, but M2M does not require IoT. Depending on company's necessities, one option will be better than the other. [5]

Table 1.1 compares some characteristics of the two techniques, highlighting their differences:

Table 1.1 – Differences between M2M and IoT (source: airtel.in/business)

	M2M	IoT
Scope	Limited to machine-to-machine interactions within a specific (closed) network or system	Beyond M2M interactions with a wider range of devices and applications and a larger network
Communication	Directly between machines	By sensors automation
Connectivity	Specific communication protocols tailored for machine interactions	Variety of Internet protocols, such as HTTP, FTP and Telnet
Data collection	Generated by machines for monitoring and control purposes	From various sensors and devices, including machines, environmental sensors, and user devices, to gather comprehensive information
Data analysis	Real-time analysis	Combination of real-time analysis and cloud-based analytics
Data sharing	Among communicating parties only	Between other applications to improve the end-user experience
Technology	Hardware-based	Hardware and software-based
Internet	No internet connection required	Active internet connection required
Applications	Industrial automation and control systems	Different sectors, including smart homes, healthcare, transportation, and agriculture, to enable connectivity and automation

One of the objectives of MES is to collect, store and analyze data provided by machines; they can be split into two types, direct and indirect.

Direct data regard operations that the machinery directly performs on products - such as number of pieces, production time, setup time, etc. -, on production program and on machine parameters.

Instead, *indirect data* analyze machine status and how the machine is currently behaving. An illustrative example can be the counters of axis' movements during a manufacturing process. They are composed of guides and a motion system. Guides are mounted on the machine frame, and a carriage with rollers is placed on them; they provide the direction of the movement. The motion system is composed of an electrical motor and a gearbox that provide a linear or non-linear motion, depending on the axis purpose. As a more detailed example, rack and pinion mechanism is shown in *Figure 1.1*; it allows the movement of the axis through an electric motor that rotates the pinion in a rotary motion (CD), generating a uniform linear motion (AB) to the rack.

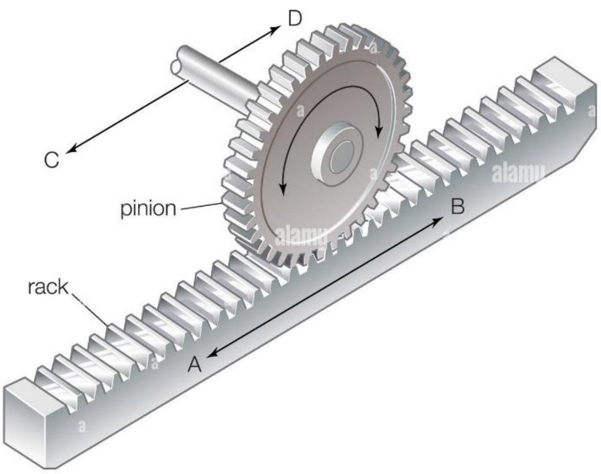

Figure 1.1 – Representation of pinion and rack (source: alamy.com)

The axis are designed to complete a certain number of load cycles, meaning they have a mileage limit before they lose accuracy. In addition to wear, a loss of accuracy can occur due to a dirty environment (e.g., because of the presence of chips), temperature variations, and humidity. In fact, the rollers, by sliding on the linear guides, are subjected to friction, commonly referred to as "gripping", and transfer the error to the machining process. As a result, there is a loss of quality in the final product. For this reason, it is important to keep track of the machines' axis data, considering that it is also possible to identify the correct operating limit of the machine in advance. Therefore, it is necessary to combine data of machines' operating limits and measured data, regarding the number of load cycles; this allows manufacturers to perform predictive and prescriptive maintenance.

1.2. *Combination of machines data and operator measurements*

Data collection is one of the most challenging parts of the manufacturing process for several reasons: a large amount of sensors and a huge computational capacity are needed, and it is quite difficult to have a complete view of the production system. However, the existence of legacy systems allows the manufacturers to have access to the history of all the data stored during the last years. In particular, legacy data provides information regarding the whole manufacturing process from the machineries, with or without the use of sensors.

Consequently, data can be split into two additional categories: the ones given automatically by the machine, and others collected "manually" by the operator. It is crucial to formulate algorithms to combine the two data sources, in order to obtain reasonable and as congruent as possible results.

In fact, quality control is actually performed to reach a well-defined purpose: it aims to identify the process drifts, i.e., eventual deviations from optimal conditions, in advance, before errors occur. To increase the advance, the data collected from measurements may be combined with the data provided by the machine to generate a warning for the user. This way, the operator can intervene on the machine before it can produce out-of-tolerance errors on the workpiece, that would be discarded or reworked with its inevitable time loss. To acquire this knowledge, the combination of predictive and prescriptive analytics is essential for the factory.

1.2.1. *Predictive and prescriptive maintenance*

Different types of maintenance deserve to be mentioned to present the different strategies available; *Figure 1.2* shows them.

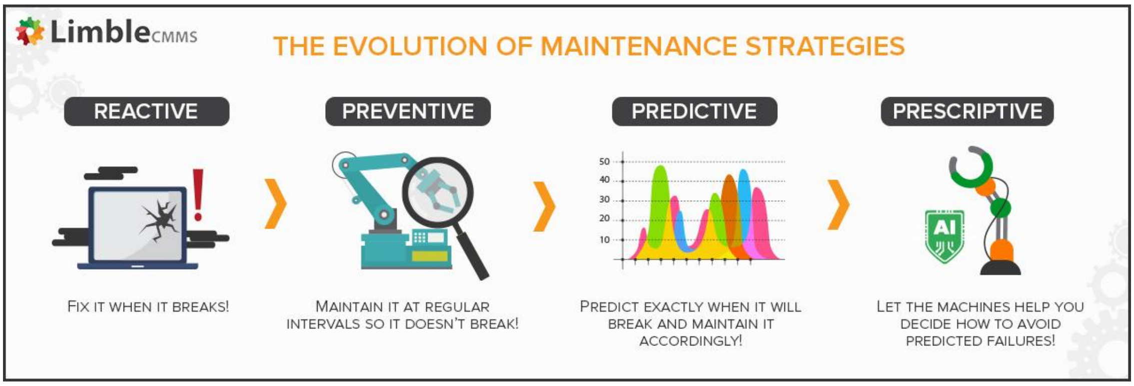

Figure 1.2 – Maintenance strategies (source: https://factech.co.in/blog/machine-learning-in-prescriptive-maintenance/)

Reactive and preventive maintenance does not take into consideration data regarding the machines; in fact, the first one is performed after the failure, and aims to restore the asset to operating condition as soon as possible. Instead, the second one is performed periodically, and can be usage-based, i.e., depending on the actual utilization of the asset, or calendar/time-based, i.e., depending on the scheduled interval of time.

Despite the great advantages of preventive maintenance, like the extension of the asset life, the reduction of maintenance costs, a better organized productivity, and a reduction of idle time, the manufacturing sector is moving toward a more and more innovative industry, where machine learning is one of the main assets. Hence, the collection and interpretation of data is becoming the key to improving the manufacturing sector. According to this, predictive and prescriptive maintenance strategies deserve great attention.

A predictive maintenance strategy may be implemented by using data warehouse and software tools to feed accurate models that can make predictions. It differs from preventive maintenance because it focuses on the actual conditions of the machine, instead of relying on the average or expected life statistics.

Regarding this approach, timing is essential: it is not useful to know the prediction a few minutes or seconds before the event – mainly the actual failure – occurs; more time is needed in order to correct and prevent the failure. To achieve the above-mentioned result, data must be collected continuously or periodically and processed on the basis of maintenance and operational data. Moreover, time-to-failure prediction is a warning about the remaining time before the failure.

However, there are some negative aspects that may generate a loss of precision and need to be mentioned, e.g. the degree of uncertainty, depending on the quantity and quality of data available; the lack of consistency, completeness and presence of data; the inaccurate preparation and manipulation of data; problems with the interpretation and explanation of results [6-9].

Prescriptive maintenance is an alternative strategy with respect to the predictive one. Its main objective is to answer the questions "What should I do now? Why should I do it?". In fact, it is based on the predictions made before, which allow to take strategic decisions. In particular, prescriptive maintenance aims to provide information about how to delay or eliminate equipment failure. In few words, *"where predictive maintenance provides information about a binary decision [...] prescriptive maintenance offers a suite of options and outcomes from which to select"*[1] [10].

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[1] https://www.aspentech.com/en/apm-resources/prescriptive-maintenance#:~:text=Prescriptive%20maintenance%20is%20the%20asset,schedule%20and%20plan%20asset%20maintenance

In order to improve the production performance of the machines and to calculate the amount of malfunctions useful for maintenance, two important indicators define the actual functionalities: the already mentioned Mean Time Between Failure (MTBF) and the Mean Time to Repair (MTTR).

MTBF informs the producer about the average working hours of the equipment between two consecutive failures; it is obtained dividing the total working time of the equipment (*T*) by the number of breakdowns (*N*) during the operation as shown in the formula *[1.1]* below:

$$\mathrm{MTBF} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{t_i} = \frac{\mathrm{T}}{\mathrm{N}} \qquad 1.1$$

MTTR is a parameter which gives information about the time needed to change the equipment status from a failure state to a normal state; it is calculated dividing the time used for maintenance (t_i) by the amount of times that it has been repaired (*n*) as the following formula *[1.2]* shows:

$$\mathrm{MTTR} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\mathrm{t_i}}{\mathrm{n}} \qquad 1.2$$

However, also prescriptive analytics must face some challenges: the inclusion of uncertainty – introduced by predictive analytics –, incomplete data and subjectivity caused by human judgement; the combination of machine and human knowledge; the creation of a general model rather than a specific one; the continuous improvement of decision-making processes; the optimization of the plan choosing among a list of alternatives [11].

1.3. Industry 5.0 paradigm

Manufacturing industries are living through a transition period in which the concept of individual responsibility of a person is becoming more and more important. Humans have responsibilities and qualities that no machine can have. It is true that automation and robotics capabilities are growing, but human activity gives an *added value* to processes.

In Industry 5.0, the creative potential of specialists cooperating with efficient, intelligent and precise machines will increase the quality and decrease the waste in manufacturing processes, optimizing the production solutions in comparison to Industry 4.0. Industry 5.0 will make human-machine communication a reality, where machines will support humans rather than replace them, helping to take decision-making and efficiency to a higher level.

Essentially, Industry 4.0 has interconnected machines; instead, Industry 5.0 will interconnect them to operators. A deeper presentation of this topic will be implemented in the following chapter.

2. State of the art

2.1. About Industry 5.0

Industry 5.0 is the evolution of Industry 4.0: it aims to have a human-centered manufacturing system, where man and machine can perform together combining their cognitive abilities, accuracy and experience to create an innovative way to work.
Industry 5.0 objective is to provide an added value to products, and to try to satisfy customers' requirements with customized items; the collaboration between human intelligence and cognitive computing is the only way to obtain these results.
Obviously, also the world's economy is going to be re-shaped by the fifth industrial revolution; a wide range of technologies will be combined. In fact, compared with the past industrial revolutions, whose main purpose was the economic sphere, Industry 5.0 focuses also on *social needs*.
Since 2017, the research trend on this topic has increased as a consequence of the EU White Paper publication.

The EU White Paper is an official document which contains projects proposals about a specific economic sector. In particular, the "*White Paper on the future of Europe – Reflections and scenarios for the EU27 by 2025*" focuses on five scenarios that have been discussed to find the best combination to achieve the projects proposed. The scenarios are:

1. *Carrying on:* «By 2025 the EU27 continues to focus on jobs, growth and investment by strengthening the single market and by stepping up investment in digital, transport and energy infrastructure. […] Further steps are taken to strengthen financial supervision, to ensure the sustainability of public finances and to develop capital markets to finance the real economy»[2].
2. *Nothing but the single market:* «By 2025 the functioning of the single market becomes the main "raison d'être" of the EU27. […] Given the strong focus on reducing regulation at EU level, differences persist or increase in areas such as consumer, social and environmental standards, as well as in taxation and in the use of public subsidies»[2].
3. *Those who want more do more:* «By 2025 a group of Member States decides to cooperate much closer on defense matters, making use of the existing legal possibilities. This includes a strong common research and industrial base, joint procurement, more integrated

[2] Source: https://commission.europa.eu/system/files/2017-03/white_paper_on_the_future_of_europe_en.pdf

capabilities and enhanced military readiness for joint missions abroad. Several countries move ahead in security and justice matters. […] They decide to go further in creating a common justice area in civil matters»[2].

4. *Doing less more efficiently:* «By 2025 the EU27 steps up its work in fields such as innovation, trade, security, migration, the management of borders and defense. It develops new rules and enforcement tools to deepen the single market in key new areas. It focuses on excellence in R&D and invests in new EU-wide projects to support decarbonization and digitization»[2].
5. *Doing much more together:* «By 2025 the EU27 continues to lead the global fight against climate change and strengthens its role as the world's largest humanitarian and development aid donor. […] Closer partnerships and increased investment in Europe's neighborhood and beyond help to create economic opportunities, manage regular migration and tackle irregular channels»[2]. [12]

2.2. The industrial revolutions

The industrial revolutions have significantly changed the production processes since the 18th Century. Before that, for centuries the production of food, clothing, houses, and other goods was manual or made with the assistance of animals. *Figure 2.1* shows the evolution of the five industrial revolutions through the centuries.

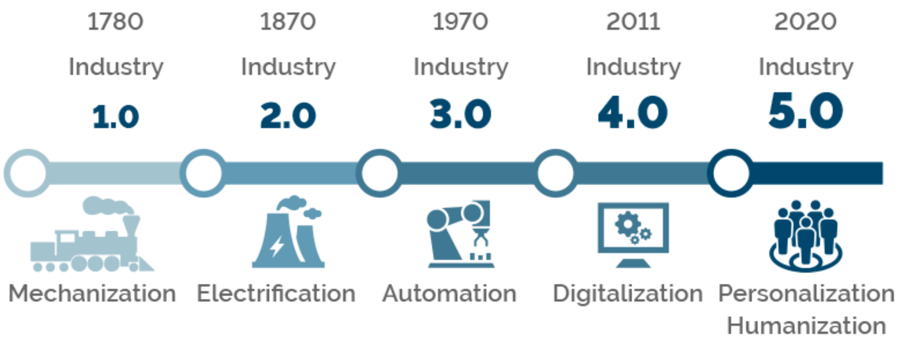

Figure 2.1 – Industrial revolutions' evolution (source: https://blog.proactioninternational.com/en/industry-5.0-the-next-industrial-revolution-is-people-centric)

2.2.1. The First Industrial Revolution: Mechanical production

In the 18th Century, with the spread of production mechanization generated by the use of steam power, the First Industrial Revolution took place. The use of machineries increased the production rate eight times compared to manual manufacturing. This huge technological and economic improvement generated by IR 1.0 has led to a significant sociocultural change.

At the beginning, it seemed to increase employers' poverty, with lack of security, protections, and regulations on workplace, as this meant many working hours for miserable salaries, continuous exposure to danger, and exploitation and abuse at work. However, as problems arose, also advantages did: since steam power started to be used also for electricity and locomotives, people could produce more, travel faster and communicate more rapidly. [13]

2.2.2. The Second Industrial Revolution: Mass production

In the 19th Century, the main source of power became electricity: it was easier to use compared to water and steam, and it was useful to focus power supply on specific machines. In this period, the most innovative machinery was conceived to be easily transportable – because each had its own power sources –, and production systems were improved to increase efficiency and production facilities.

Several innovations were introduced, like the division of labor, which increased productivity, or the assembly lines, which allowed producers to start the mass manufacturing era. The main purpose of IR 2.0 was optimizing work and methods trying to keep high quality standards of the outputs. [13-14]

2.2.3. The Third Industrial Revolution: Automated production

The IR 3.0 is also known as *Digital Revolution* and began in the second half of the 20th Century with the introduction of digital computers and electronic technologies. The innovations brought to the implementation of manufacturing automations in factories: for instance, machineries could substitute the employees in the most complex tasks, and convert technologies from analog to digital, so that it became possible to make copies identical to the original.

A very important point for IR 3.0 is the invention of the Internet: it helped computers to communicate with a central device. In general, ICT – information and communication technologies – have contributed to the technological evolution and the creation of a "new economy", initiating *globalization* and *outsourcing* concepts. Moreover, the digital revolution has changed the way individuals and companies interact; small companies could now have access to larger markets, technology costs had decreased significantly and had made possible investments in manufacturing industry innovations, and finally, digital technologies had strongly increased productivity and business performances. [15]

2.2.4. The Fourth Industrial Revolution: Digital transformation

The IR 4.0 is a transformation of IR 3.0. In the 2010s, an improvement of interconnections and automation led to a change in industries processes and technologies – e.g., artificial intelligence, cloud computing, Internet of Things and robotics have been introduced. Manufacturing systems that already had computer technology with IR 3.0, now have been expanded by network connectivity.

The use of modern smart technologies, machine-to-machine communication and the IoT allowed the mechanization of traditional production and industrial practices. This caused an increase in automation, communication and self-monitoring of smart machines that did not need human intervention. Therefore, smart factories and the manufacturing sector have almost become independent.

IR 4.0 represents a shift from the digital age of the late 1990s and early 2000s to an era of *connectivity* and *information* from the social, political and economic point of view. Other important implementations that Industry 4.0 aimed to start achieving were the concepts of circular economy and sustainable business models. *Figure 2.2* shows the architecture of Industry 4.0.

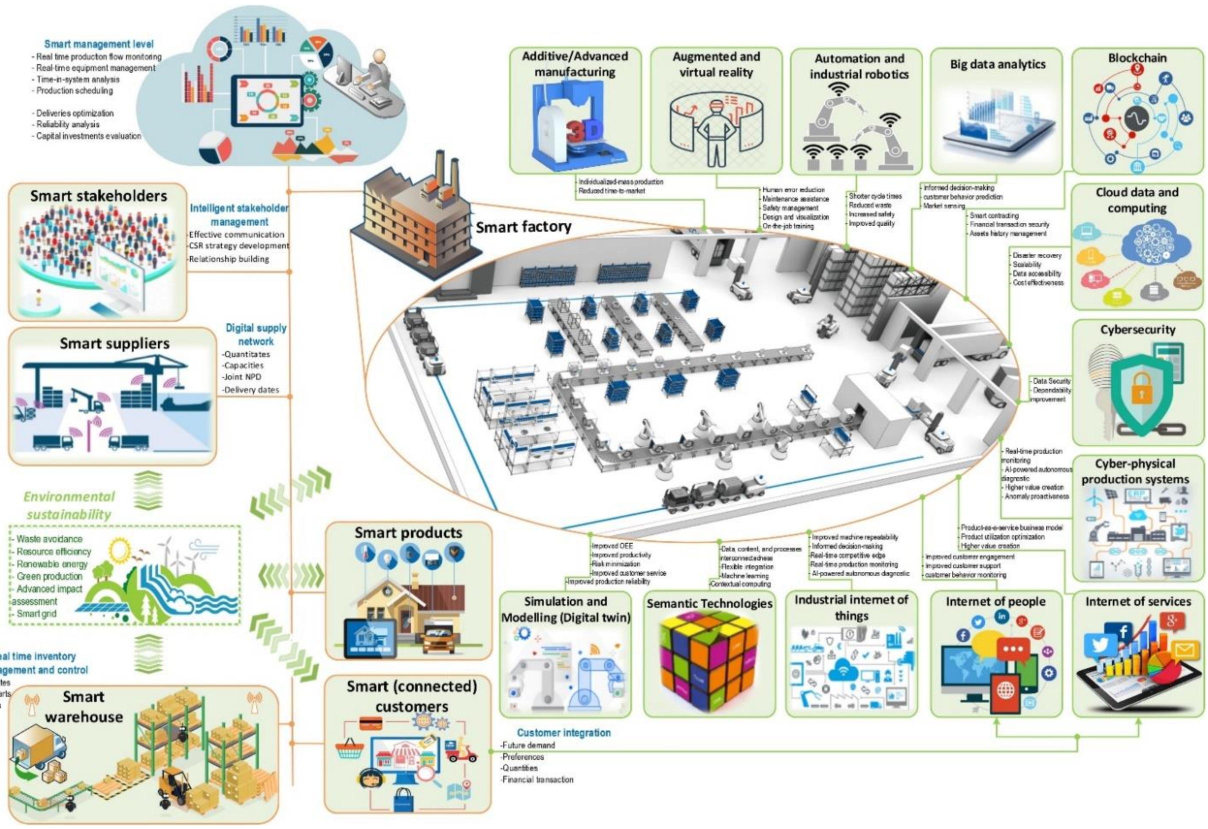

Figure 2.2 – Architecture Industry 4.0 (source: Ghobakhloo, M. (2020), "Industry 4.0, digitization, and opportunities for sustainability", Journal of Cleaner Production, Vol. 252)

The end of Industry 4.0 era has been accelerated by the Operator 4.0 paradigm, which uses smart sensors and wearable devices as support tools. Operator 4.0 is not replaced by machines but enhances his skills. The concepts of Human-Cyber-Physical systems and adaptive automation allow to move toward a socially sustainable workface in a human-centric smart factory. Therefore, the transition from IR 4.0 to IR 5.0 is due to a greater focus on human manufacturers co-working with machines. [16-17]

2.2.5. The fifth Industrial Revolution

Industry 5.0 can be considered as the industry of the future; born in the last few years, it has emerged as a more visionary alternative to the management concept. It is the natural evolution of Industry 4.0 and aims to implement technologies like artificial intelligence, cloud computing, Internet of Things and robotics.
The main social difference between Industry 4.0 and 5.0 is that the popularity of Industry 4.0 has stabilized after a growth. Instead, Industry 5.0 is becoming more and more popular, and its supporters' number is increasing rapidly. [18]

The main characteristics of Industry 5.0 are the three pillars it relies on: human-centricity, resilience and sustainability.

A ***human-centric*** strategy, following the European Commission, is one that *"promotes talents, diversity and empowerment"*[3]. This means that the industry shifts from people serving organizations, to organizations serving people. It can be considered as a radical change and an actual challenge: finding, serving and keeping talents has become a specific purpose of Industry 5.0. Nowadays, strategy consists of creating a *competitive advantage* and a unique *added value* for customers. But to make organizations become truly human-centric, these competitive advantages and unique added value must be *addressed to employees*.

A ***resilient*** strategy is *"agile and resilient with flexible and adaptable technologies"*[3] against external shocks, as the European Commission defines. Indeed, in the last few years resilience has become the heart of the socio-economic sphere after Covid-19 crisis and war in Ukraine. Until now, the key points have been growth, efficiency and profits, which rely on organizations' agility and flexibility. But if resilience must become one of the pillars of Industry 5.0, the focus cannot be on growth, efficiency and profits anymore, but on *anti-fragility* and *strength*, which means that an organization must be able to *anticipate*, *react* and *learn* from any crisis, ensuring meanwhile stable and sustainable performances.

[3] https://www.forbes.com/sites/jeroenkraaijenbrink/2022/05/24/what-is-industry-50-and-how-it-will-radically-change-your-business-strategy/?sh=386360fa20bd

A ***sustainable*** strategy, following the European Commission, *"leads action on sustainability and respects planetary boundaries"*[3]. Essentially, organizations should pay attention to the three Ps of the Triple Bottom Line (TBL) and to all Sustainable Development Goals, that will be explained later. To adopt a sustainable strategy, a company should not focus on reducing its negative impact, but on increasing its positive impact. Polman and Winston – respectively the Unilever ex-CEO and an expert in sustainable business management – in their publication *"Net Positive: How courageous companies thrive by giving more than they take"* talk about Net Positive emissions. They claim that not to generate emissions is impossible, but companies can try to put more into the environment than take out from it – e.g. if you go for a walk in a park, you can bring a small bag with you, and pick up small pieces of trash to clean up the trail, to leave it cleaner than it was before your walk. This can be intended as a company *"becoming part of the solution, rather of part of the problem"*[3]. [19-20]

The TBL approach consists in taking decisions about Profit, People and Planet (3Ps):

- *Profit:* it is intended as an economic profit, which includes economic impacts that a company can face, like new positions, innovation, tax expenses, etc. In fact, "profit" is often replaced with "*prosperity*" which has a wider meaning.
- *People:* it means stakeholders; a company can have positive or negative effects on them. Stakeholders include employees, customers, suppliers and every category which influences or is influenced by a company decision. Clear and honest communication between managers, employees and society is essential to positively affect sustainability and performance of that organization.
- *Planet:* it is the concept about environmental defense. An environment-friendly enterprise must be careful to take sustainable actions as using renewable energy sources, minimizing energy use, using recyclable materials, disposing toxic waste safely, reducing waste and carbon footprint, etc.

A company is doing well if it generates large profits and limits its damage to people and the planet. [21-22]

Instead, the Sustainable Development Goals (SDG) consist of seventeen challenges that aim to achieve a better and more sustainable future; they talk about poverty, green energy, climate change, and responsibilities that every human has in these and many other areas. *Figure 2.3* shows all of them.

In particular, goal 8 is about “promoting sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all”[4]. Since from 2007 to 2012 the unemployment rate has increased by 19%, and almost 2,2 million people earn less than 2 dollars per day, the United Nations Organization has decided that the situation must change. The main goals are supporting economic growth, achieving higher standards of economic productivity through diversification, technological progress and innovation, promoting development, creating new workplaces, decreasing young people unemployment rate by 2030, protecting the right to work and promoting a healthy and safe working environment for all workers. [23]

Figure 2.3 – 17 Sustainable development goals (source: https://unric.org/it/agenda-2030/)

Since machines are more and more intelligent and connected, Industry 5.0 wants to combine their abilities with humans’ knowledge and skills.

For example, cobots are not simple industrial robots, which are designed to work independently without human intervention. They are robots designed to *co-work* and *physically interact* with people in a shared workplace; the collaboration between cobots and people improves processes, efficiency, accuracy, speed, and final products precision.
Cobots can be equipped with sensor technology like AI, lidar/radar, and GPS to execute sophisticated but repetitive tasks, and with other integrated sensors that allow them to control the

[4] https://unric.org/it/obiettivo-8-incentivare-una-crescita-economica-duratura-inclusiva-e-sostenibile-unoccupazione-piena-e-produttiva-ed-un-lavoro-dignitoso-per-tutti/

surroundings, in order to ensure safety and prevent injuries. Artificial Intelligence stimulates human intelligence; the technology is able to give suggestions that people find reliable, becoming a tool rather than a collaborator.

In the future, cobots will be smart enough to comprehend the operators' questions, understand whether they need assistance, and assist them. They will also be beneficial because will give operators the possibility to acquire new information improving their skills.
Therefore, factories will focus less on mass production, automation and digitalization, which were the main topic of Industry 4.0. Industry 5.0 is introducing logic, curiosity, empathy, creativity, ensuring a balance between humans and technology; the way to work is going to change radically. [14, 20]

Industry 5.0 has innovative benefits that previous industrial revolution did not consider.
Firstly, it is *environment-friendly*: a greater sensitivity to the environment has allowed to decrease the amount of waste and the environmental impact due to emissions. This transition is aligned with international institutions, governmental regulations and customers' requirements.
Secondly, Industry 5.0 *optimizes costs*: it aims to use the minimum resources to achieve the highest incomes. In this case, the collaboration between man and machine is the best financial choice for a company.
Lastly, *customization and innovation* are important characteristics of Industry 5.0; technical innovations allow to custom and personalize items to satisfy customers' demand.

Figures 2.4 and *2.5* represent how information flows during a production process in Industry 4.0 and 5.0 respectively. Instead, *Figure 2.6* highlights the differences between the two industries' working methods.

Figure 2.4 – Industry 4.0 connections (source: lecture notes)

Figure 2.6 – Industry 5.0 connections (source: lecture notes)

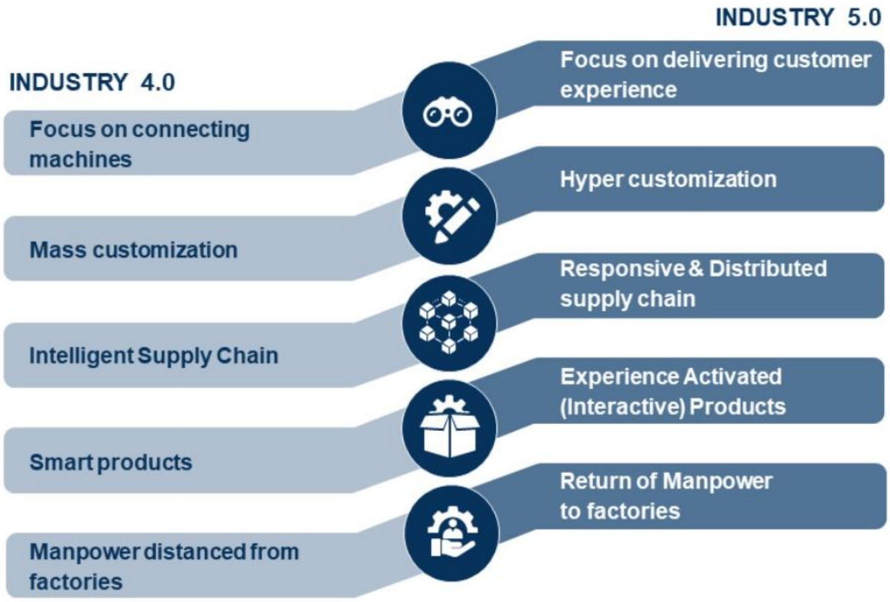

Figure 2.5 – Comparison between Industry 4.0 and 5.0 (source: lecture notes)

The EU wants to encourage companies to face progress and innovation, but nowadays most of the industries are just exploring the world of Industry 5.0; they are still focused on Industry 4.0 or even previous versions. Also, sustainability concept is one of the latest. Once organizations become more human-centric, resilient and sustainable, Industry 5.0 solution will emerge.

The joining link between Industry 4.0 and 5.0 for quality control consists in automated control. It is carried out by measuring machines, which are devices that precisely measure the geometry of the physical object and compare it with the designed one.

There are different types of measuring machines, e.g., they can have a single rotary axis, up to five or six axis with touch probes at the ends. This method of automated control can give signals in case of tolerance errors and can make them available directly on the MES. [20]

2.3. Innovative quality control methods in terms of Industry 5.0

Since I5.0 incoming is led by emerging technologies and digital solutions, the latter may be useful in quality assurance processes, which determine whether a process or a service satisfy specific requirements.

Before presenting innovative techniques, ISO 9001:2015 deserves to be mentioned since it is a prerequisite for all the companies that need to control their processes. As the BSI's (British Standards Institution) official document says:

"*This International Standard specifies requirements for a quality management system when an organization:*

a) needs to demonstrate its ability to consistently provide products and services that meet customer and applicable statutory and regulatory requirements, and

b) aims to enhance customer satisfaction through the effective application of the system, including processes for improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements.

All the requirements of this International Standard are generic and are intended to be applicable to any organization, regardless of its type or size, or the products and services it provides"[5].

This standard is internationally recognized and gives a competitive advantage to the companies since quality is assured to customers. Its structure is composed of ten sections, three of which are an introduction, while the last seven contain the requirements related to the Quality Management System. The latter are:

Section 4: *Context of the organization* – This section presents the requirements to understand the organization and its context, understand the needs and expectations of interested parties, and determine the scope of the QMS in order to implement it.

[5] BS EN ISO 9001:2015 Quality management systems — Requirements

Section 5: *Leadership* – It must be demonstrated by top management with respect to the QMS and the customer focus by establishing a quality policy and assigning roles and responsibilities within the company.

Section 6: *Planning* – Top management must take actions to address risks and opportunities of QMS and must identify objectives to increase quality and plans to achieve them.

Section 7: *Support* – This section regards the management and the control of all resources, including human resources, buildings and infrastructure, workplaces, monitoring resources, etc. and all the competences, consciousness, communication and control of documented information.

Section 8: *Operation* – Operational requirements regard all the aspects of products or services planning, review, design, control of external providers, production and delivery, and control of nonconforming process outputs.

Section 9: *Performance evaluation* – It allows to monitor the proper functioning of the QMS, including measurement of processes, evaluation of customers satisfaction, internal audits and top management analysis and review of QMS.

Section 10: *Improvement* – This section determines the opportunities for improvement and implementation of QMS, including the evaluation of process nonconformities and consequently the adoption of corrective actions on it. [24-25]

These sections are based on a PDCA cycle (Plan-Do-Check-Act), whose purpose is to drive and sustain improvements within the processes.

So, quality control is carried out in measurement, monitoring and verification activities of processes and final products or services that can be performed before, during and after the production process. In the *preliminary* phase industries check inputs, i.e. raw material, in the *intermediate* phase they control the semi-finished product, and in the *testing* phase the finished product before delivery. These activities are facilitated and optimized by adopting IoT solutions.

Quality control requires well-defined standards to be verified, both in terms of characteristics to be checked and in terms of expected performance; in case of non-compliance with the standards, tolerance thresholds must be considered. In addition to "*what*" to check, it is important to define also "*when*", "*where*" (checkpoints), "*how often*" (frequency of checks) and to respect the *punctuality* of the scheduled deadlines.

Traditionally, the characteristics to be checked are divided into three levels, related to the damage caused in case of non-compliance: they can be *critical* if they seriously compromise functionality, *important* if they compromise optimal functionality, *secondary* if they do not compromise functionality.

Industry 5.0 allows industries to use new systems of quality control by combining operators work and innovative technologies and devices; the adoption of IIoT solutions permits to optimize quality control activities thanks to real-time monitoring of the production flows: specific software processes the data provided by sensors placed at strategic points in the production line, improving traceability.

A Quality Control System with IIoT solutions can be designed individually or developed within a MES. The system monitors control parameters throughout the entire production process and detects any non-compliance based on data sent by sensors placed on the plant line.
In fact, the analysis of big data – generated by the connected network of devices enabled to the Internet – processes, compares, monitors and achieves data in real-time and transforms them into useful information for decision-making. More specifically, in quality control field, IoT Analytics allows measuring detailed data about production costs of each individual item or service, resource consumption involved in processes, conditions of the machines used, raw material quantities and workloads. [26]

To achieve innovative methods, the lates tools and technologies are starting to be used. Some of them will be introduced in the following sub-paragraphs.

2.3.1. Vocal software for quality control

Traditionally, the control operation is carried out manually by evaluating the processing performance and recording the measurement made on paper modules. Corrections to machinery settings are then made manually by copying the annotated parameters on machine's computer.

A significant innovation is the use of voice commands to confirm machinery settings or to record corrections. Each quality control station is equipped with a computer, where the operators, wearing a cordless headset through which they receive instructions regarding the verification of machinery operation, *communicate* any correction by displaying the measurement results on the PC monitor.

This innovative solution is able to recognize operators' commands even in noisy environments and offers operators the possibility of working hands-free, without having to record result on paper, with a consequent speeding up of quality control procedures and a reduction in transcription and machine settings errors.

2.3.2. Computer Vision Systems for quality control

Computer vision is the automatic extraction of information from the processing of digital images using proximity sensors for monitoring and control in difficult conditions.

For example, in a textile industry, sensors can be installed in the production line to measure yarn tension, to count its twists and the meters of thread collected in individual bobbins, and to analyze anomalies during machines preparation; these sensors are then connected to a terminal and send an alert in case of anomalies during production, allowing a timely intervention and a process optimization before waste occurs.

In recent years, computer vision has been more and more adopted in the industrial and manufacturing world thanks to the availability of solutions that can be integrated directly into production lines and factory environments. The solution can be useful not only for analysis and control of defectiveness, but also for predictive maintenance, scanning and reading of barcodes, and workplace safety.

In order to guarantee the highest level of customer satisfaction and reduce the post-sales problems as much as possible, inspections of products during production and quality checks are crucial activities that cannot be ignored. Manual execution of these activities is expensive and risks not being sufficiently accurate, especially where defects may not be visible or evident to the human eye. With artificial vision systems, manufacturing companies can optimize and simplify automatic product inspection and quality control processes, through accurate and precise measurements of components or parts used during product assembly. Artificial vision systems capture images of products or goods along the line, sending them to the cloud for processing: information or alerts on any defects are sent to the relevant personnel. [27]

2.3.3. Augmented Reality and wearable devices

Augmented reality is an interactive technology that enhances the real world with perceptual information generated by computers, i.e., it connects the real and digital world. Using software, applications and hardware such as wearable AR glasses, augmented reality overlays digital content onto real environment and objects. In Industry 5.0, it allows industrial users to become one with the systems and machines they work with, and to optimize and enhance technology and IoT networks with human ingenuity, observation and creativity. AR true value lies in being part of an Industry 5.0 ecosystem connected to the cloud that incorporates everything, from big data to automated robots. [28]

The integration of AR into quality control and QA can help prevent defects during production, optimize the production process, and reduce time-to-market. For example, technicians wearing smart glasses can frame a product and obtain information from IoT sensors integrated into product components.

Smart glasses are one of the most innovative forms of wearable technology for the industry. They have integrated software that supports Bluetooth, Wi-Fi and GPS, and have already started to replace traditional tools and methods of inspection processes of companies in the last years. They have an optical display, which can be monocular or binocular, and a microphone, so users can interact with the glasses through voice commands; usually they have also manual commands, e.g., to consult the settings page, to select a language, etc. or even in case of malfunction of the tool. Moreover, industrial devices must offer resilience to harsh conditions, great ability to withstand damage, compatibility with safety equipment, and full mobility. [29-30]

A practical application of industrial smart glasses in the manufacturing industry consists in taking measurements on board machine, through an operator wearing the device, to check that the final products meet the required standards, verifying both quantitative and qualitative parameters. They do not need to write down measurements on paper, interrupting their work, but can enter data directly into the cloud with voice commands; in fact, as *Figure 2.7* shows, the operator is communicating the measurements hands-free and can measure the products without wasting time. To make this possible, the environment must be in ideal conditions: NTP, Normal Temperature and Pressure, avoid expansion or contraction of the final products, in order to obtain optimal results and to reduce errors. Temperature must be equal to 20°C, and Pressure to 1 atm.

Remote support platforms integrated with smart glasses provide great potential in terms of quality, timing, productivity and transparency.

Figure 2.7 – Operator wearing smart glasses and taking measurements (source: https://headapp.eu/it/industries/industria/)

2.4. Industrial AR applications

Augmented Reality applications are an essential step towards Industry 5.0, and manufacturers are investing more and more in this technology to make possible human and machine interaction. The Greek University of Patras conducted research on human and machine collaboration with the aid of AR and found that AR interfaces can blend in the working environment and enrich it, making the interaction natural and intuitive*, Lotsaris K. et al. (2021)*.

There are a lot of applications of AR in manufacturing that are leading to operational efficiency. It has been successfully integrated in assembly guidance, assembly training and assembly planning & design, *Wang, X. et al. (2016)*; *Figure 2.8* shows the major applications of AR technologies in assembly tasks.

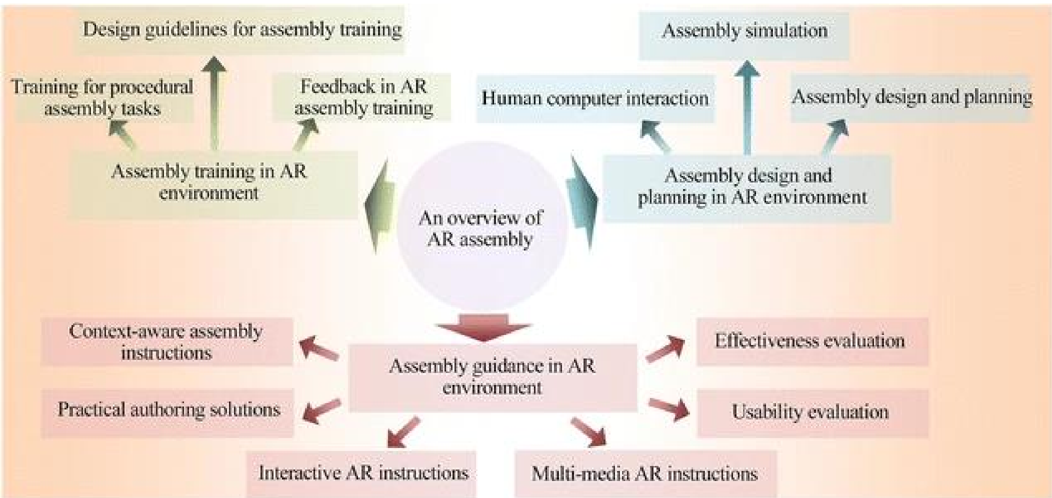

Figure 2.8 – Applications of AR technologies in assembly tasks (source: Wang, X. et al. (2016))

In manufacturing, training and updating courses can be performed with the support of digital AR work instructions. Just a click can allow individuals to switch programs that easily adapt to any skill level. This way, training is standardized; otherwise, oral training would depend on the instructor's skills, and a written paper would contain information dating back to the last update. AR gives the possibility to ensure the same information to all the workstations, with the last updated version.

Similarly, AR work assembly instructions guide the operators step by step, i.e., describing one action at a time; they are led by instructions directly onto the surface, instead of reading instructions and interpreting pictures without any support. This approach allows operators to focus on the quality of the single step, significantly reducing time, errors, and cognitive load on the worker.

The same functionality of guidance can be applied to products variation. Work instructions are written on an index of programs available on every AR system, and one barcode scan is enough to allow AR software – connected to an enterprise MES or PLC – to recognize and call the instructions related to that specific work.

AR could also incorporate quick inspections to work instructions; the American company LightGuide Inc. developed an AR software that allows producers to verify the products quality step by step, without hindering the workflow. It is possible to integrate 3D vision cameras and machine learning with AR software that identifies errors and suggests indications and actions. Moreover, this software includes a structure which prevents from moving to the next step if the current one is not correctly completed.

In order to raise available process data, AR helps to integrate automation into manual processes – that are still relevant in the manufacturing industry. This way, producers can have access to manual processes and automated data at the same time, leading to more detailed points of reference.

Since AR can be used to solve any challenge providing benefits, several types of industry all around the world are investing in it. [31-32]

Automotive industry is one of the most open to AR. For example, Ford uses augmented reality for the design phase where designers, with the support of holographic goggles, can overlay 3D elements onto a clay model of a vehicle, then quickly evaluate and create new car designs. However, the overall design is still done through clay modelling. Designers work simultaneously with engineers to optimize the process; in fact, it becomes more efficient and allows for much more creativity for designers and engineers on the team. Ford also uses AR for maintenance: it helps technicians to identify problems on vehicles and repair them quickly. [33]

Similarly, the car manufacturer BMW uses AR with integrated remote rendering at its Munich headquarters. This remote technology allows the streaming of the AR application. Engineers can see a true-to-scale model of the prototype created in CAD programs and can evaluate and generate different variants of a concept in a few minutes. Moreover, thanks to the remote transmission, people at different locations can review design together and identify errors by employing multi-user mode. [34]

Aerospace and defense manufacturing require very high-quality levels, most of all in assembly phase. AR applications ensure quality and standardize and digitalize work instructions; thanks to this, workers view the step instructions right where they need them and are confirmed in each step of the process, preventing and eliminating errors. Since 2011, Airbus has used AR to project data, information and design details to simplify construction and inspection processes saving time. Engineers and operators have used devices that displayed 3D models on top of the real environment, providing valuable insight into size and positioning. [35]

Instead, Boeing wanted to simplify the electrical and electronic components deployment and wiring; to obtain this simplification, the company has been using augmented reality to provide technicians with real-time, hands-free, immersive 3D wiring diagrams projections. According to Boeing's declarations, this increased wiring speed and accuracy by 33%, saving millions of dollars per jet and allowing the company to manufacture more aircraft at a faster rate. [36]

Electronics manufacturing is constantly innovating, so work instructions need to be updated at the same time frame. AR can have a training function, it can project work instructions, making them easier and faster to comprehend, and standardize assembly processes for enhanced quality control. [32]

Medical and pharmaceutical manufacturing need strict standard procedures and verification methods: every process needs to ensure the safety of the operator and end-user. AR, with the support of 3D sensors, confirms if a step is correctly performed. Moreover, it is used for virtual training to work on lab machineries and remote assistance for medical devices, reducing training and guidance times by 40%. [37]

Finally, since the thesis is about application of AR support to MES, the study conducted by *Blaga A. et al. (2021)* about AR applications on the MES needs to be briefly mentioned in order to present that this "collaboration" is feasible. Their aim was improving day-to-day manufacturing operations by developing human-robot collaboration systems with augmented reality. One of their main goals was the 3D vision enhancement of industrial operators with the help of head-mounted display (HMD) equipment, which eased instantaneous perception of the scenario. [38]

3. Orchestra and QA methods

Orchestra is a Turin-based company founded in 2016 with the aim of designing and providing its own technologies and solutions for Industry 4.0. The company focuses on the needs of manufacturing SMEs interested in real-time monitoring and control of their production assets and the advancement of production orders; Orchestra enables its customers to access these features through a Web application called MiniMES, used to *"plan, advance, track and control production in real time"*[6].

In 2015, the company was selected and hosted by I3P, the incubator of Innovative Companies of the Politecnico di Torino. It has been chosen as one of sixteen innovative projects among hundreds of candidates, with the benefit of being hosted and supported within the university campus.

Thanks to the specific technological know-how of its team and to the knowledge of production process and organization of a company, Orchestra is able to offer constantly updated solutions to the SMEs market and to develop with large and medium enterprises Open Innovation and R&D financed projects.

At the beginning of 2020, Orchestra launched the new brand of RETUNER products for smart factories perfectly tuned to Industry 4.0. As the company says, *"In Industry 4.0, the machines, plants, devices, and products of a company must harmonize on the same score"*. The core concept is to *"tune the various components of the factory as if they were musical instruments that are preparing to play together in a concert"*[6]*;* i.e., to create intelligent connections and integrations between machineries and business management systems, trying to fill a gap that is often present in factories and that can be filled with the use of digital technologies.

In particular, RETUNER is focused on a Cloud Driven Edge Computing architecture to support Industry 4.0. The Edge component bidirectionally connects any new or existing plant or machine through industrial protocols, and merges and integrates data with algorithms, transforming them from raw data into information already on board the machine. The information is then exchanged with the RETUNER software platform, that acts as a *hinge* to share production information in real-time with any new or existing application, local or cloud-based.

Among other solutions, Orchestra also provides support services on its products to end customers and partners: it supports remotely feasibility studies, requirement analysis, definition of project

[6] https://www.retuner.eu/

performance indicators, installation, and training. And its customer base embraces various sectors, including mechanical machining, glass, plastic and stone processing, automotive, chemical, pharmaceutical, food, nautical, and manufacturing. [39]

3.1. RETUNER suite architecture

RETUNER is the brand launched by Orchestra in 2020. It has been designed and developed following a Cloud Driven Edge Computing architecture, which interconnects devices and their data including IoT devices, smartphones, sensors and other internet-connected devices, as shown in *Figure 3.1*. [39]

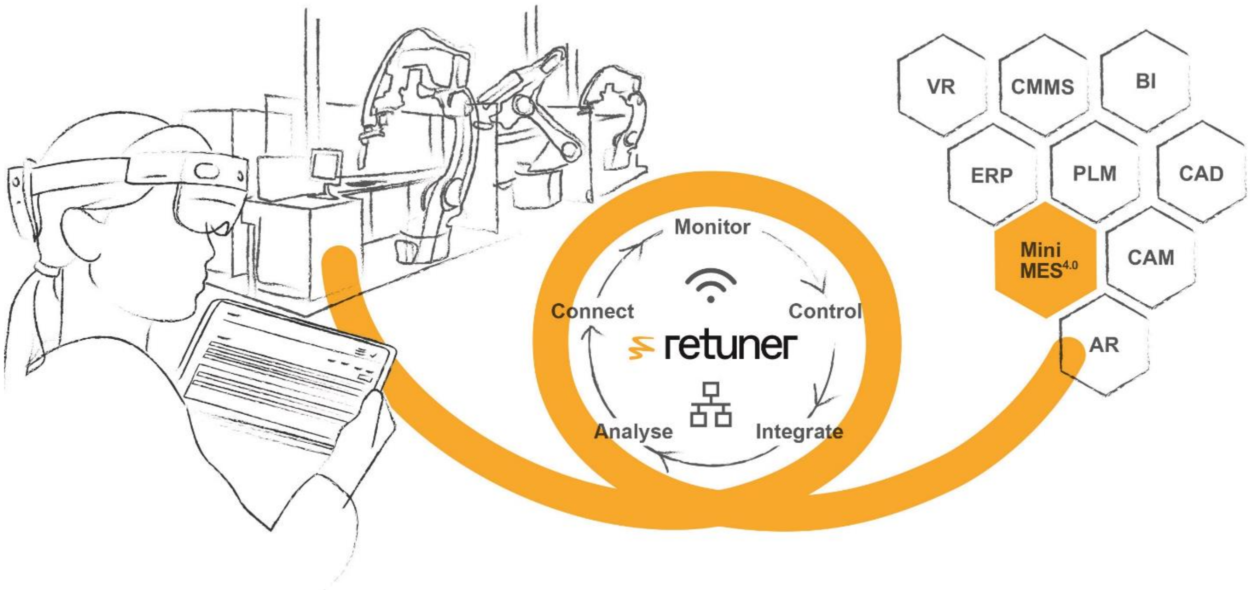

Figure 3.1 – RETUNER suite

Edge computing is evolving and becoming more popular thanks to its adaptability to multiple use cases, helping IoT to solve critical issues and improving performance. *Table 3.1* shows the comparison between IoT, Edge and Cloud, highlighting the advantages – and in certain cases the limits – of using Edge computing instead or as support to the other techniques.

Table 3.1 – Characteristics of IoT, Edge and Cloud Computing (source: https://ieeexplore.ieee.org/abstract/document/8123913)

	IoT	Edge	Cloud
Deployment	Distributed	Distributed	Centralized
Components	Physical devices	Edge notes	Virtual resources
Computational	Limited	Limited	Unlimited
Storage	Small	Limited	Unlimited
Response Time	NA	Fast	Slow
Big Data	Source	Process	Process

In fact, despite the limited capacity and storage of Edge Computing, it satisfies IoT requirements more rapidly and offers it enough computational capacity and storage space. On the other hand, IoT supports Edge Computing by extending its structure and making it more dynamic.
It can be proved that Edge Computing-assisted IoT is a crucial factor in enhancing performance: it allows to reach important achievements like a significant reduction of response time and traffic flows, *decrease of latency* and consequently of total costs, optimization of the scheduling, high saving of power consumption, important improvement in quality of transmitted data and in response time, etc. [40]

The subsequent diagram (*Figure 3.2*) synthetically explains the architecture of the company's products suite:

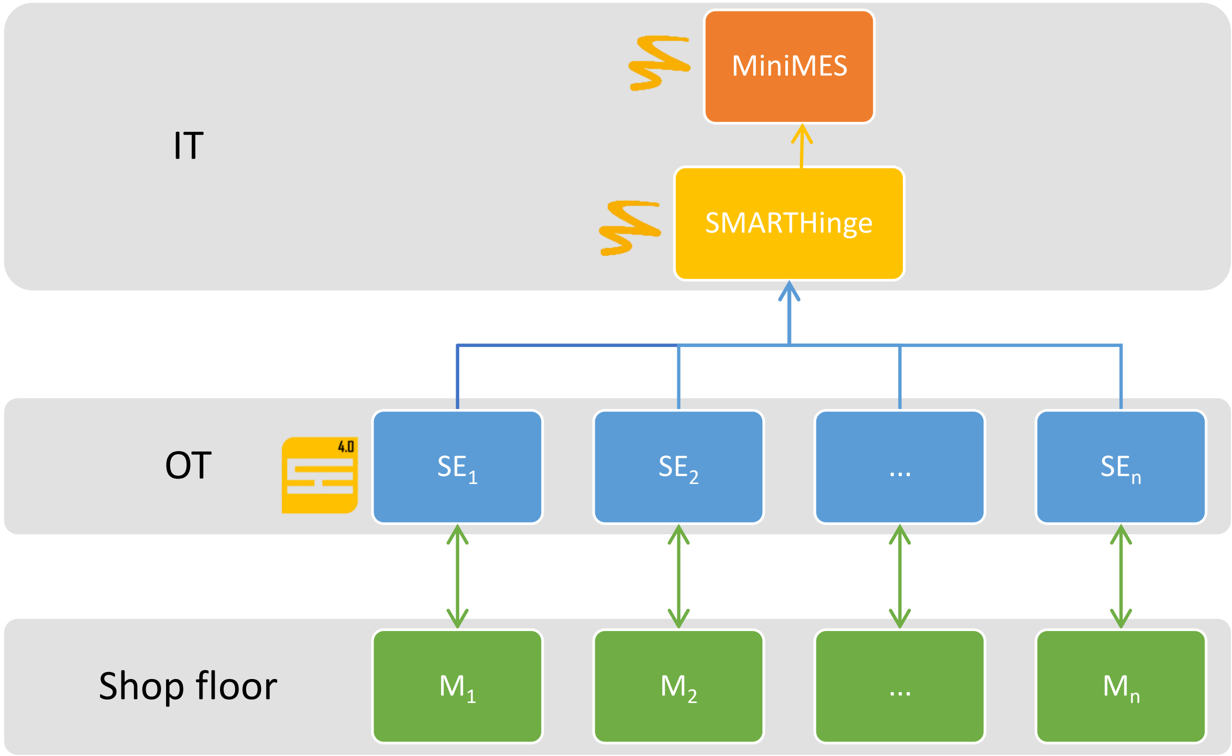

Figure 3.2 – RETUNER's architecture

The Shop floor represents the production level and SEs are the SMARTEdges interconnected; SMARTHinge and MiniMES are RETUNER's Web Platforms, respectively the IIoT platform and MES.

Focusing on the company, Orchestra proposes the SMARTEdge 5.0 NextGeneration device. It is either hardware or software component, depending on the type of machine, and it communicates bidirectionally with the machines by using several types of protocols, depending on their communication semantics.

Bidirectional communication consists of sending and receiving data to and from machineries. Sent data are about the machining program and parameters to be performed, i.e., what to do and how to do it. Received data regard actual programs and variables made available by the machine, i.e., what has been done and how.

In the case of machines that cannot communicate through local network, the hardware version is connected to the machine's PLCs and shares data using high level communication protocols, such as OPC-UA, with the IIoT gateway and/or management platforms.

Other machines, that already have integrated communication protocols, use the software version of SMARTEdge, which is installed directly on the machine's PC or on the server.

There is a distinction between protocols: they can be low-level, intended as hardware, or high-level, to which field protocols belong. The first ones are communication protocols designed for industrial purposes, like Profinet and Profibus. SMARTEdge takes data using low-level protocols, like RS485, RS232, UART, Canbus, and sends them using high-level ones, like the already cited Modbus TCP, OPC-UA, MTConnect, etc.

The hardware version of SMARTEdge is also endowed with a Linux-based operating system on which proximity digital services can be installed for the use and consumption of the on-board machine operator. Its primary role is to interpret and transform machine data into ready-for-use information for new AR and AI-based digital proximity services.

SMARTEdge is an extension that provides communication between the machine and the IIoT gateway installed on customers' local server, i.e., SMARTHinge 5.0. The reason why a dedicated component as SMARTEdge is necessary to each machine is that each machine communicates with its own semantic and communication protocol, and SMARTEdge must be parametrized in different ways depending on the particular machine.

The exchange of data and information may be wired or wireless; SMARTHinge collects, parametrizes and stores real-time production data from the shop floor, i.e., from machines. It also exchanges data with company systems, like ERP, MES, CAD/CAM, CMMS, BI, via Restful JSON API. SMARTHinge role is to serve as a database and make data available on MiniMES, but it can also be replaced by IIoT platforms of third parties.

The MiniMES 5.0 is a complete MES in the form of a Web Application so that it can be used from any device connected to the company network. Its function is to plan, advance, track and control production in real-time.

Through MiniMES, the monitoring of several essential functions for company's production processes takes place. On the WebApp Dashboard, customers can find and select functions about products, planning, calendar, jobs, customization, and plugins.

3.1.1. MiniMES description

Products

Information about the products could be entered either automatically or manually by the customer and allow the definition and configuration of its catalog, from design to production approval. They include all the specifics like dimensions, manufacturing process, raw material, parameters, part programs, etc.

A part program is a sequence of instructions given to the machine to produce a piece according to the required parameters. In case the machinery does not support the part program, the machining parameters are provided to the machine through a file called recipe.

Planning

The planning page contains a list of all the working phases of the products in progress, starting from production orders. It also includes details about assignments, operators, cycle time, etc. The various processes are programmed on one or more manual machines or workstations, based on the times and resources available in the company.

Calendar

The calendar is a tool for assisting the scheduling of the various processing operations, based on current resource availability. It highlights processes status, delays, and the connection between different phases. It is represented by a Gantt chart with machines on the Y-axis and processing time on the X-axis.

Stations

Through this service, each single process on the machines is tracked, summarizing the times, the number and type of pieces produced, and any non-conformities in real-time. The operator can check the whole list of machineries and operations and can control them by activating, pausing – if ended – and closing the operation processes. After the quality control, data from machines are checked and stored inside that particular work phase for future reference.

Customization

Settings can be customized based on specific needs from the system settings tab. It is useful in situations in which units of measurements vary depending on the country, or to set measurements different from default ones, like internal diameter, external diameter, length, etc.

Plugin

Plugin allows integrating external machines, tools and functionalities with Business Intelligence Models and interconnections. BI allows customers to have a comprehensive view of their data and use them to improve production, eliminate inefficiencies, and quickly adapt to special requirements.

At this stage, Orchestra needs to implement a new function, the *quality control metrics*, to verify if the production process is in statistical control and to support the producers in case of process drifts. The next chapter will present the development of this section. [39]

3.2. Machineries interconnections in Industry 4.0

Automation and digitalization are the main focus not only for RETUNER, but also for all the smart factories which are rapidly becoming more and more numerous thanks to the implementation of Industry 4.0.

Until now, this thesis has highlighted the benefits of the Industry 4.0 and consequently of interconnections; to sum up, they are:

- *Production efficiency*, thanks to the data sharing by intelligent systems; this leads to the optimization and control increase, and consequently to higher quality and quantity, and lower production time, costs and resources (i.e., environmental impact).
- *Data analysis,* used for predictive analytics and decision-making processes; it occurs after data are collected, processed and transformed, and allows instantaneous access to digital information.
- *Predictive maintenance,* which allows maintenance interventions before the failure occurs; this avoids machine breakdowns that would cause additional costs and downtime.
- *Production flexibility*, through new technologies that can suit different production environments; this makes customization faster and more efficient, reducing human errors, and generates a new dimension of business competitiveness.
- *Safety at work*, with the reduction of accidents; it also contributes to the company's sensitive data protection. [41-42]

Nevertheless, Industry 4.0 must also face some limitations because of the introduction of AI and other digital technologies which are part of everyday life: as they are becoming cheaper, they are easily accessible, influencing every aspect of the social sphere. Moreover, I4.0 has increased the risk of cyberattacks, data breaches and violation of privacy. Its main disadvantages are:

- *Geographical division*, because technologies are expensive and there is a huge difference between developed and developing countries' possibilities and resources. In this situation, only the wealthiest countries may take advantage of Industry 4.0 benefits.
- *Cybersecurity risks*, caused by interconnections; this could lead to compromised data, financial loss, and damage to critical infrastructure. In fact, cybersecurity must be a priority in the technology field.
- *Confidentiality of data*, as Company data; they may be collected and used inappropriately.
- *Dependency on technology*, that may cause the loss of skills, knowledge and stimulus; this could lead to a drop in the ability to think critically and to solve problems over time.
- *Need of human decision making;* since data is collected by the machine, there are no systems capable of making decisions based on raw data, so a human analysis is always needed.
- *Environmental impact*, because of the increasing use of devices that need energy to be powered; this causes a rise in GHG emissions.
- *Unequal distribution of wealth*, caused by the higher possibility of richest countries to invest in new technologies; consequently, there will be a much consistent income gap, that may lead to negative implications in the economic and social spheres. [43]

The above-mentioned limits are quite general, as they are related to social and environmental aspects and do not mention what would be the negative consequences in the more specific case of the industry, from the economic point of view. These are listed below:

- *Large initial investment*, as purchasing new devices and technologies is expensive.
- *New business models creation*, as new strategies must be pursued in order to have a competitive advantage.
- *Continuous updates*, because of the constant progress of technology; this may be economically unsustainable to many companies.
- *Economic gap between industries* that have adapted and those that have not to the Industry 4.0 model.
- *The presence of specialized personnel*, which is required to analyze and monitor automated processes; this happens as the staff requires training because of a lack of skills.
- *Go through the change*, as workers may not be ready, may be resistant, unwilling or unable to adapt. Top management must help the staff to reach consciousness of the utility and importance of the change. [44]

A deeper analysis about cybersecurity needs to be done, since it is a very current topic. In the past, Operation Technology (OT) systems, which provide control over the inputs and outputs of key elements in a process, were separated from traditional Information Technology (IT) systems; but their gradual integration started increasing operational efficiency and reducing the total cost of ownership. "As a result, cybersecurity threats increased, becoming more integrated into the internet-connected components of the enterprise IT environment", *SmartEDGE4.0 N.G. Cybersecurity: a new level of security between OT and Machines* article says.

Obviously, different devices require different approaches to increase security, and potential impacts and risks are different. The greatest risks are about the safety of people and property, followed by availability and integrity. AI and Machine Learning algorithms may protect machines from cyber-attacks since they can produce smart alerts. This means that the implementation of Cybersecurity algorithms directly on-board the machine produces an *additional security level* that can provide all the protection needed. [45]

3.3. Limits of Industry 4.0: real cases

As already mentioned in the previous paragraph, the fourth industrial revolution has brought with it several criticalities which may affect the industry environment. However, there are also limits that particularly affect the production processes at the technical level, influencing in a negative way the efficiency of the work or the quality of final products.

3.3.1. Reduction of efficiency

The production process consists in a procedure with different steps: before starting to work there is a setup time in which the settings are configured; then there is the effective time in which the machine works; and finally, it must be unloaded and prepared for a new work cycle.

It is evident that the whole process counts a lot of downtime, and this is showered on the performance of the process calculation, where η is obtained by dividing the working time by the total time, including the idle time, as the following formula *(3.1)* shows:

$$\eta = \frac{t_w}{t_{tot}} \tag{3.1}$$

Industry 5.0 may be useful since the operator is available to support the machine in the calculation of cycle time. His function should be starting the time count during the processes that give an added value to the final product and stop it for downtime. Thanks to this intervention, data will not be underestimated.

3.3.2. Utility of data

The dataset exchanged by machine may not be exhaustive because of the quantity of data and their quality. Some data can be useless or even redundant, it depends on the context which is not always clear/exploited/usable. For example, the operating time of a machine is useless at the production level but is useful for maintenance or for the relation between temperature and time, where operators can see if there are suspicious fluctuations which may indicate an error in heating/cooling rate. Also in this case, the intervention of the operator is necessary to improve the production process, according to Industry 5.0 criteria.

3.3.3. Machine functionalities

If the machine does not present any particular functionalities, two alternatives may be provided: to implement the functionality with the support of tools like sensors or electronic devices, or to introduce a human operator to afford the tasks that the machines cannot. For example, the Nadella iAXNR circular system, shown in *Figure 3.3*, does not have the equipment necessary to perform quality control, and to equip it with sensors would be uneconomical. For this reason, the operator becomes an “additional sensor” of the machine, a supervisor, relying on the Industry 5.0 model once again.

Figure 3.3 – Nadella iAXNR machine (source: https://www.meccanicanews.com/2022/12/06/sistemi-di-movimentazione-sempre-piu-intelligenti/)

3.4. Why does quality matter?

According to ISO 9000 family definition, quality of a product, process, or service refers to the degree to which it is able to satisfy stated – declared, e.g. products' specification – or implied – implicit, e.g. customers' expectations – needs.

Quality can be split into three dimensions: offered, expected, and perceived.

Offered Quality (Q_o) is the quality assured by an organization through its design and manufacturing system; it is evaluated from the organization's technical and objective point of view.

Expected Quality (Q_e) is the customer's subjective expectations based on a reference model that compares different products and services, and that is subjected to pressure of competitors. It is based on ex-ante evaluations and changes over time.

Perceived Quality (Q_p) is the sum of the attributes that customers perception of a new product or service, according to its quality; it is based on ex-post evaluations and does not necessarily rely on real data, since it is subjective.

Often, it happens that the expected quality does not coincide with the offered one; this way, a quality gap is generated, as the formula *(3.2)* below shows:

$$\Delta Q = Q_e - Q_o \tag{3.2}$$

Two possible alternatives may be faced:

1. $\Delta Q < 0$, i.e., $Q_e < Q_o$. It happens when the company offers more than what customers expect. Since the market could not be mature enough, this situation is led by marketing, which generates customer needs for new products or services. In fact, communication and persuasion channels are the keys to influence and convince the potential customer.
2. $\Delta Q > 0$, i.e., $Q_e > Q_o$. In this case, customers are disappointed as they do not receive what they expected. This solution offers products and services with new functions and is based on new technologies that need to be improved to reach customers' standards. It focuses on engineering, technical and organizational contents, since Q_e constantly evolves.

Hence, marketing and technology drive the innovation process to increase the sales and improve the customer perception of the product or service of the company.

To obtain engineering, technical and organizational innovation improvements, the company can rely on the Lean and Integrated System (LIS), which is a management system able to implement some operational/organizational approaches. LIS differs from the traditional organizational structure for several aspects; some of them are represented in the *Table 3.2:*

Table 3.2 – Traditional organization vs. Lean and Integrated System

	Traditional	LIS
Structure	Vertical: no horizontal communication between functions at low levels (only at high)	Horizontal: collaboration and interaction between functions, facilitated by the presence of cross-functional teams[7]
Hierarchical organization	Strict: each stage reports to the stage above	Flat: no intermediaries between staff and executives
Information	Reported with possible distortions	Reported without filters nor distortions
Divisions	Isolated (even physically) and in negative competition; disincentive to collaboration and interactions	Collaborative and with positive interactions

Figures 3.4 and *3.5* respectively represent traditional and LIS organizations.

[7] A *cross-functional team* is a group of people with different functional expertise, working to a common goal.

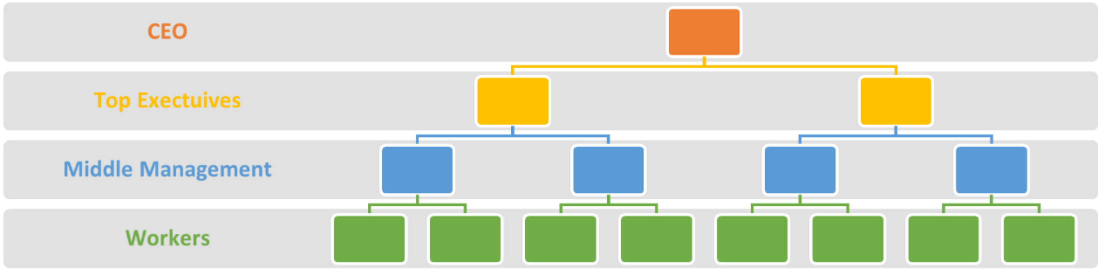

Figure 3.4 – Traditional organization

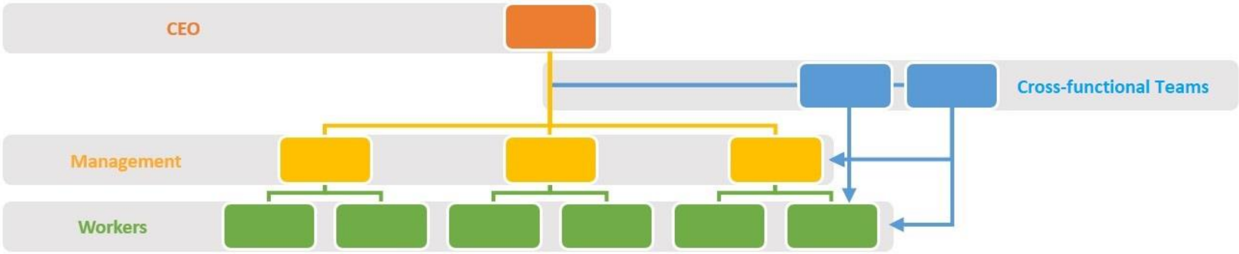

Figure 3.5 – Lean and Integrated Systems model organization

3.4.1. Introduction to Lean and Integrated Systems

The last structure shows that a LIS is characterized by an adaptive and flexible structure, with a great synergy between the divisions of the organization and good interaction with customers.

This model is characterized by several organizational models, but the most important are Concurrent Engineering (CE) and Lean Production (LP).

CE is an approach used to develop products dealing with all the aspects relevant for their design, combining this with engineering, production, distribution and maintenance processes. QFD (Quality Function Deployment) is a very useful tool at this stage.

CE improves the design phase taking into consideration the production cost, the product appearance, and technical aspects like producibility, fitting capability, maintainability, etc.

A Concurrent Engineering product life-cycle approach can be represented on a GANTT chart which relates the time (x-axis) and each phase (y-axis). This model is often used when a company is under time constraints to deliver a project. In fact, it allows to optimize the process by overlapping the project phases. However, as it reduces the production time, it also increases the risk, and the uncertainty of interpretation of the exact status of the project.

Lean Production is a manufacturing method implemented in 1950s-60s by the Japanese company Toyota with the aim of "*getting the right things, to the right place, at the right time, in the right* *quantity to achieve perfect workflow while minimizing waste and being flexible and able to change*"[8]. [46]

In particular, the reduction of waste, *muda* in Japanese, must be applied to seven types of waste:

- *Overproduction*: producing more products than needed.
- *Waiting*: inactive working periods not necessary to the production process.
- *Transportation*: movement of products into different areas and departments.
- *Processing*: all inefficiencies leading to delays, defectiveness or scraps, costs increase, variability and instability of the results.
- *Overproduction*: producing more than what is needed generates a "trapped value".
- *Motion*: moving equipment into a workstation more than necessary.
- *Defective products*: need to be discarded or remanufactured.

Lean manufacturing relies on the *Kaizen* – "continuous improvement" from the Japanese – method, which introduces the concept of continuous improvement to perform better.

The main aspects of this methods are quality, communication, involvement and inclusion; In fact, it is based on teamwork, self-discipline, improvement of employees' morale (workplace atmosphere), Quality Circles (which consists in a group of workers collaborating on the identification, analysis and solution to same problem), and improvement suggestions.

Another approach used by lean production is the *just-in-time* method; it focuses on realizing the right product based on the demand, in the accorded amount, in the right time, following customer's requirements.

It aims to improve the ability to economically respond to market change by eliminating constraints and bringing out problems with an impact on quality and production costs, through the increase of the workflow speed.

The development of lean model is obtained with the use of tools; the most common are Value Stream Mapping (VSM), 5Whys, and 5s.

The VSM is a layout representing the current state map and defining a future state map of a process. The current state map is not about showing activities and flows, but it focuses on creating value

[8] Kosky, P. et al. (2021), "Manufacturing Engineering", *Exploring Engineering: An Introduction to Engineering and Design*, Fifth Ed., Chapter 12, pp. 259-291
https://www.sciencedirect.com/science/article/abs/pii/B9780128150733000120?via%3Dihub

for the customer. Starting from this, the future state map aims at reducing times and costs at non-added value and identifying every possible loss of value in each process phase.

The 5 Whys technique aims to find the root cause of a problem. It consists in repeating five times the question "Why?" to intermediate solutions to the problem; however, five is just an indicative number of necessary steps to reach the root cause.

The 5s approach consists in applying five rules to organize a workplace. They are:

- *Seiri*, i.e., *separate* what is necessary from what is not into the workplace; it consists in cleaning it and rationally classifying the objects present.
- *Seiton*, i.e., *set in order* materials and items, reducing the number of objects in the workplace without causing stop or delay of the production.
- *Seiso*, i.e., *clean* and inspect machines and tools, and verify and eliminate problems.
- *Seiketzu*, i.e., standardize the process to clean and order the workplace.
- *Shitsuke*, i.e., *sustain* the self-discipline of workers, verifying periodically the results obtained.

3.4.2. The importance of Quality

Quality control, and consequently the production of high-quality goods, in manufacturing is essential to protect manufacturers from risks and costs, also providing benefits. The most important are:

- *Improve products*, reaching the highest possible quality. A better product will lead to customers' satisfaction, that are conscious of the quality of the product.
- *Brand loyalty*, as the products are trustworthy, high-quality and unique; this means that customers will certainly prefer the company to the competitors. Even if the product undergoes a modification, they will trust.
- *Comply with regulations*, that the company already knows. In fact, this will not become an extra task, but an integral part of the operation. Following the regulations, sanctions and delays are avoided.
- *Become confident and consistent* about the level of quality achieved. Thanks to this, the company feels confident about the product it is selling.
- *Conserve resources* to avoid waste and loss of money. Quality control allows to reduce the quantity of material and resources used, since mistakes are diminished.

- *Reduce the level of risk*, as the product may be defective, break soon, customers may dislike it and will not buy it anymore in the future, etc. Quality control drastically reduces these risks, generating benefits.

In addition to quality, *quantity* is also important for a company; in fact, production must meet the customer's demand. However, there are some aspects that highlight the more crucial rose of quality rather than quantity:

- Negative reputation: the company may produce large quantities of mediocre products. They will probably cost less, but reliability and durability are sacrificed, and many customers may not be willing to invest money in that company's products.
- More competition: since lower-quality products are more affordable to customers than others, this sector is subjected to great competition.
- Risk of legal actions: if the low-quality product breaks and harms customers, legal actions may be taken against the producer, with negative consequences for the company's reputation.
- Difficulties to growth: because of low-quality, customers will not purchase products of that company; hence, it does not have the possibility to grow and expand. [47]

However, there are some tips that may be useful for the improvement of quality control; following Jospeh Juran ideas – the author of "Quality control handbook", (1951) – the company, should start wonder:

1. How do customers see the company? (Customer perspective)
2. What must it excel at? (Internal perspective)
3. Can it continue to improve and create value? (Innovation and learning perspective)
4. How does it look to shareholders? (Financial perspective) [48]

It could be useful for the company to compile a report that reflects the results of improvement efforts and provide guidance for future improvement efforts; they require an investment of resources in the so-called "quality costs". The long-term effect of the costs of poor-quality concept is represented in *Figure 3.6*. The benefits of an improvement effort involve both reductions in cost and increases in sales revenue.

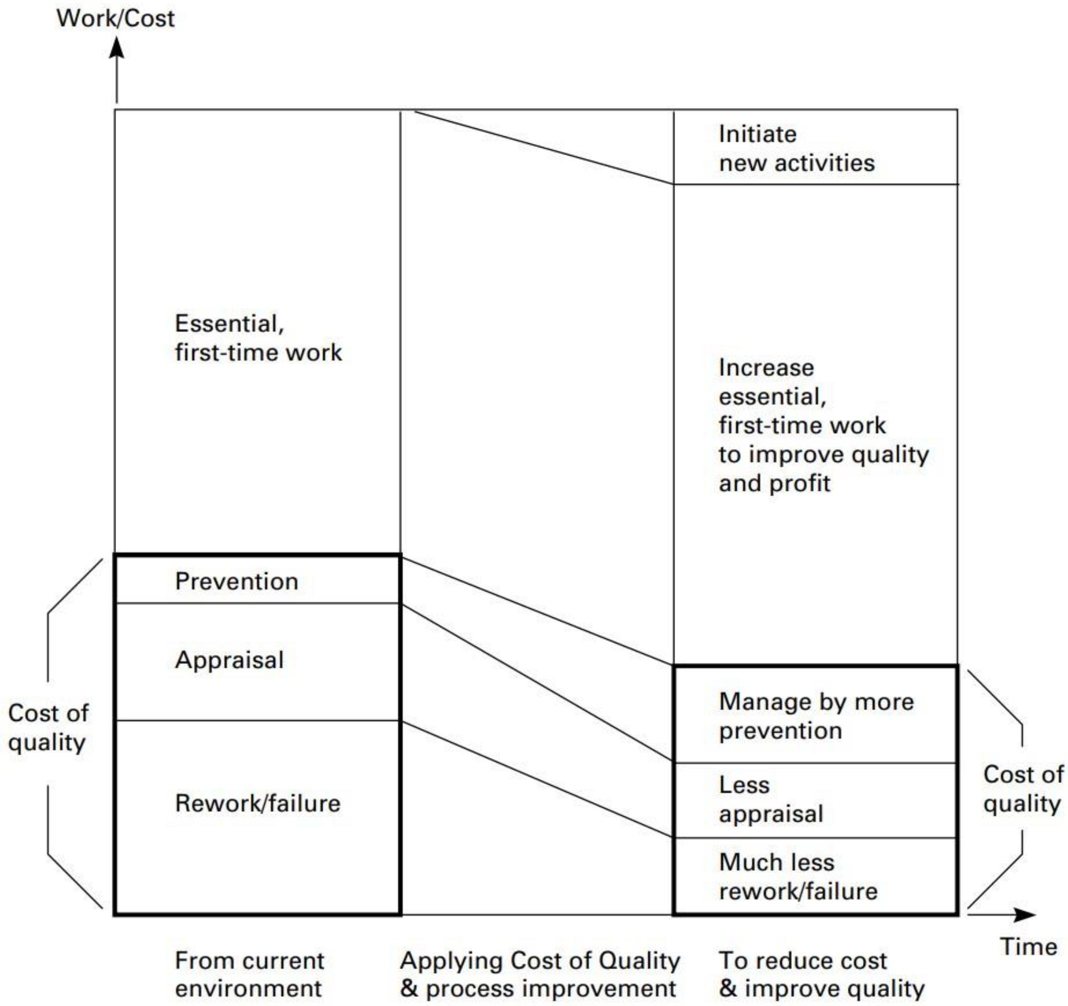

Figure 3.6 – Effects of quality costs
(source: https://www.academia.edu/9378072/JURAN_S_QUALITY_HANDBOOK_JURAN_S_QUALITY_HANDBOOK)

These benefits allow to reach a competitive advantage in the market. And this is done to prevent "non-quality costs", which are related to inefficiencies and low quality. A higher quality allows greater production, which leads to a bigger competitive advantage in the long term. This proves that increasing the quality of the products reduces the costs: reduction of reworks, less mistakes and delays, a more efficient use of time and resources.

The first one talking about non-quality costs concept was the same Juran, but Feigenbaum and later H. James Harrington have been the very first ones to identify and classify the non-quality costs. They can be defined as "hidden costs" because they cannot be measured easily; the main are costs of nonconformities, costs of inefficient processes, and costs of lost opportunities for sales revenue.

The costs of nonconformities depend on internal defects, i.e. production errors that have caused an expense for a product that cannot be sold; they may occur because of several reasons like equipment malfunction or bad supplies of materials. These failures are discovered before the products leave the company. They will affect the expense in two different ways based on the possibility to rework or not the part. Additionally, an evaluation cost is paid to find the error.

The costs of inefficient properties are the expenses for products in compliance to the output but are inefficient, i.e., they are out of control, their processes are redundant, or they do not have added-value steps. As with the previous costs, they are related to internal factors and cause the same types of expenses.

The costs of lost opportunities for sales revenue are generated by customers' dissatisfaction, that leads to a loss of trust in the customers and an inability to attract new ones. They are defined as external failure costs because are found after the product leaves the company and reaches the customer. Consistent consequences of these failures are the loss of image and all the negative impacts that will persist over time. [49-51]

4. *Determination and analysis of functional requirements*

The analysis of functional requirements is the first step to define a new product feature. It gives the possibility to determine the final user's needs and the best possible way to satisfy them. To obtain this information, market and, more specifically, customers' requirements are analyzed from a simple and effective quality management point of view.

This achievement is obtained as a result of several steps; first of all, there is the definition of the possible ways identified in order to implement the quality control module into the MiniMES: quality control phase or control during the phase – with or without metrics; the further step is about the definition of quality control metrics and their defining interface; subsequently, the definition of the control board is defined depending on the type of control (in phase or as a phase); then, there is the definition of the summary dashboard of the process status; and finally, the development of the criteria for OCAP generation, in order to prevent, or at least correct, eventual non-conformities.

The analysis has been applied to the Planoplast case study, of which needs and problems have been evaluated, and the control phase without pre-defined metrics has been introduced. This type of control is the most common one that will be applied to clients that need a quality control management system, based on an analysis of the customers' needs.

The final purpose of the study is to avoid an out-of-control process and data, with a consequent non-compliant or low-quality product; to make this happen, the development of quality analysis must be performed. It consists in collecting and analyzing data of an out-of-control process and understanding how to correct it with an OCAP template that guides the producer.

To obtain these results, there are different steps to deal with: going backwards, there is the development at UI/UX level, i.e., interface and experience offered that must be user-friendly and intuitive; this phase depends on the development of capabilities, that in turn require an analysis of functional requirements. It is a deep analysis thar make possible to understand what the *customer's needs* – and not requirements – are, since it is important to know what the real useful result is, and not what the customer wishes to obtain. The analysis is performed following the subsequent steps:

1. Identifying and describing the problem.
2. Backward tracing the necessary requirements, useful for problem resolution.
3. Determining the best method to evaluate them.
4. Developing or integrating the equations and algorithms to obtain the result required by the customer.

5. Generating suggestions or reports with possible corrective actions.

All of these steps have been applied in a real case study after the study and analysis of the company.

4.1. Planoplast case study: problems and requirements

Planoplast is a company of the Adviplast group, leader in the distribution of plastic materials and engineering thermoplastics in bars and sheets for more than 10 years. In particular, they are national leader in the supply of colored methacrylate sheets (*Figure 4.1*), useful mainly in design applications, and in semi-worked plastic materials sector, which includes PMMA, PETG, transparent PVC, and other products for visual communication like expanded PVC, anti-shock polystyrene, mirrored acrylic, of which a possible application is represented in *Figure 4.2*, and many more [52-53].

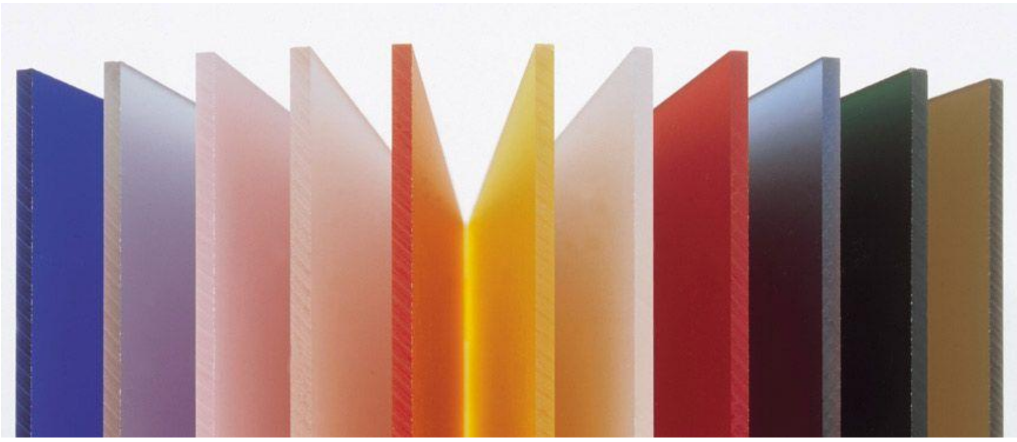

Figure 4.1 – Colored methacrylate sheets (source: https://www.adviplast.eu/lastre-acrilico-colato-trasparente)

Figure 4.2 – Application of mirrored acrylic (source: https://www.adviplast.eu/lastre-in-acrilico-specchiato)

Since the company started to offer a service of processing materials, it needed to digitize the flows and the processes that were manually managed before. This way, Planoplast could control the production processes and define rapidly and precisely the costs of the orders. The next step that the company wants to take is an improvement of the quality control branch. [52].

According to the 5 Whys model, it can be stated that the starting point is digitization: *Why* does the company need it?

1. It wants everything to be integrated into a single platform. *Why?*
2. Because the customers want to simplify production management. *Why?*
3. Because they want to prevent errors from occurring. *Why?*
4. Because they need to minimize wasting time and resources. *Why?*
5. Because they want to maximize the marginality on each order.

So, the *maximization of the marginality* on each order, minimizing the waste, is the final problem of the company.

In addition, another important point is the *identification of the process drifts before* the production is out of tolerance. During data drift monitoring, real data changes must necessarily be distinguished by random fluctuations, that may naturally occur.

In case non-conformities occur, the customer's needs consist of locating the origin of them and identifying the root causes in order to have the possibility to correct them and avoid them being repeated in the future.

Also waste of time and resources is a relevant feature; in addition to the limits regarding the technical drawings noticed by Orchestra: they should be present on the screen, but they cannot be overwritten with notes, need a specific visualizer for files with a .dxf or .dvg format, and must be large enough and have a good resolution to be seen clearly. A unique solution may be useful to solve these problems.

4.2. Resolution methods

4.2.1. Maximization of marginality: Digitization

Following the method explained before, the next step consists in the implementation of the possible solutions to the problem.

Digitization of quality control is the first step that brings to the resolution to the problem. It is the key to achieving other important goals like the reduction of risk of errors during quality control, the integration of the quality control procedure with other processes, and the introduction of

Industry 4.0 paradigm. This helps the company to accelerate the quality control phase, reducing the cycle time and the production lead time. The increase in speed is allowed by the automatic generation of certified reports (e.g., ISO 9001) that include technical drawings, quality tabs, and photographic documentation. The latter is essential to demonstrate to the customer the compliance of processing with regulations. Moreover, digitization improves the efficiency in the same order's information collection and recovery, allowing easier access to data thanks to databases, rather than printed copies.

4.2.2. Identification of the process drifts: Statistics and control charts

To identify the process drifts before the production is out of tolerance, the solution proposed is the use of control charts, in particular $\bar{x}$-*MR* charts to run a quantitative control with individual measurements, and *np* charts to run a qualitative control considering the number of non-compliant units. The operation requires several calculations, that are presented after a statistical and quality engineering reminder.

Obviously, two products must have the same quality characteristics but cannot be identical; in fact, variability takes over. The most common sources of variability are the 3Ms: differences in Materials, in the performance of the Manufacturing equipment, and in the way Men (operators) perform their tasks.

Quality characteristics are evaluated on specifications, which allow to understand if a product or a performance is acceptable or not. A measurement value that corresponds to the desired one is called Natural Value (NV) or Target value (T). It falls inside a range that is included between the Upper Specification Limit (USL) and the Lower Specification Limit (LSL), respectively the largest and the lowest allowable values to be conforming. A quality characteristic can be conforming or non-conforming whether it falls within or beyond the specification limits. However, specifications can also be one-sided, i.e., must be below a certain USL or over a LSL.

Natural Variability is the tendency towards producing products in regular conditions, with quality characteristics different from Target values, where the process is governed by random sources – and causes – of variability, and which do not include anomalies, failures or accidents. The presence of non-natural variability is provided by the presence of non-random patterns, like outliers, increasing/decreasing trends, or cyclic/periodic trend; in this case, the process must be defined out of control.

Natural variability is quantitatively measured by Natural Tolerance (NT) range; it indicates the expectation regarding deviations of technical/quality characteristics of interest. This probability is conventionally set at 99.73%.

The process variability is usually measured with standard deviation σ, which is useful to define the upper and lower natural tolerance limits, UNTL and LNTL, as 3·σ above and below the mean. NT and the two NT limits can be obtained by using the following formulas *(4.1 and 4.2):*

$$\mathrm{NT} \equiv 6 \cdot \sigma \tag{4.1}$$

$$\begin{cases} \mathrm{UNTL} = \mu + 3 \cdot \sigma \\ \mathrm{LNTL} = \mu - 3 \cdot \sigma \end{cases} \tag{4.2}$$

They are valid only upon the assumption that the process follows a normal distribution $x \sim \mathbb{N}(\mu, \sigma^2)$. For other distributions, the 6·σ interval does not necessarily include 99.73% of the process output.

Control charts are tools that monitor the evolution of production processes and evaluate if they meet their specifications, i.e. they represent a reference of the natural variability of a process. They need to be periodically updated, whenever something changes in the process.

QA categories present different levels that can be defined as low, middle, and high level.

The medium level regards QA during the phase, i.e., measurements taken in the traditional way or with the support of AR according to industry 5.0 while the machine is working; they are tested with the $\bar{x}$-MR chart. In particular, the $\bar{x}$-chart is used to monitor the central tendency of the process, and the $\overline{MR}$-chart to observe the dispersion of the process using a moving range (MR) of two or more consecutive observations that generate an artificial sample of size n. The two systems are given by the formulas (*4.3 – 4.5*):

$$\bar{x} - \text{chart} \begin{cases} \mathrm{UCL_x} = \bar{x} + \mathrm{L_x} \cdot \dfrac{\overline{MR}}{\mathrm{d_2}} \\ \mathrm{CL_x} = \bar{x} \\ \mathrm{LCL_x} = \bar{x} - \mathrm{L}_x \cdot \dfrac{\overline{MR}}{d_2} \end{cases} \tag{4.3}$$

where, if n = 2:

$$\mathrm{MR_i} = |\mathrm{x_i} - \mathrm{x_{i-1}}| \tag{4.4}$$

$d_2 = 1.128$ is a function of the MR with n=2 (tabulated factor);

$L_x = 3$ is defined as the "distance" of the control limit from the center line; usually a ± 3·σ control limit is used, i.e., L=3.

$$\overline{MR} - \text{chart} \begin{cases} \mathrm{UCL_{MR}} = \mathrm{D_4} \cdot \overline{MR} \\ \mathrm{CL_{MR}} = \overline{MR} \\ \mathrm{LCL_{MR}} = \mathrm{D_3} \cdot \overline{MR} \end{cases} \tag{4.5}$$

where D_4 = 3,267 and D_3 = 0 are a function of the MR with n=2 (tabulated factor).

Instead, the higher-level category regards measurements taken by measuring machines; as the previous level are estimated with the $\bar{x}$-*MR* chart. This type of measurement is done once the production is completed, i.e., during the QA phase.

Finally, the lower level is about the number of non-compliant pieces, i.e., that are defective, scraps, or non-conforming. As in the previous case, it is performed during the QA phase. This type of features is evaluated with the *np*-chart, where p represents the percentage of defective units on the total number of units inspected and n is the constant sample size, and the control limits are calculated as (*4.6 – 4.7*):

$$\mathrm{np} - \text{chart} \begin{cases} \mathrm{UCL_{np}} = \mathrm{n} \cdot \mathrm{p} + \mathrm{L}_{np} \cdot \sqrt{n \cdot \mathrm{p} \cdot (1-\mathrm{p})} \\ \mathrm{CL_{np}} = n \cdot \mathrm{p} \\ \mathrm{LCL_{np}} = n \cdot \mathrm{p} - \mathrm{L}_{np} \cdot \sqrt{n \cdot \mathrm{p} \cdot (1-\mathrm{p})} \end{cases} \tag{4.6}$$

where:

$$\mathrm{LCL}_{np} = \max\left(0, n \cdot p - L_{np} \cdot \sqrt{n \cdot p \cdot (1-p)}\right) \tag{4.7}$$

$L_{np} = 3$ is defined as the "distance" of the control limit from the center line; usually a ± 3·σ control limit is used, i.e., L=3.

Process Capability is the ability of a process to manufacture product units complying with specifications. It can be expressed with the Process Capability Ratios (PCRs) with the following formula *(4.8)*:

$$C_p = \frac{USL - LSL}{NT} \tag{4.8}$$

This indicator is calculated under the assumption of a normal distribution. In general, it is required that $C_p > 1$, i.e., that the process gives products that satisfy the specifications, with the typical reference value of $C_p \approx {}^{4}/_{3} \approx 1.33$.

While it is related to variability, another PCR is related to centering; it is presented in the formula below *(4.9):*

$$C_{pk} = \min(C_{pu}, C_{pl}) = \min\left(\frac{USL - \mu}{3 \cdot \sigma}, \frac{\mu - LSL}{3 \cdot \sigma}\right) \tag{4.9}$$

While C_p measures the potential capacity of the process, C_{pk} measures its effective capacity. The latter could be both positive and negative; if $C_{pk} \geq 1$ NT limits are within specification limits, and if $C_p = C_{pk}$ the process is centered; if $C_{pk} < C_p$ it is not, and if $C_{pk} \leq 0$ the process average μ is beyond specification limits. [54]

4.2.3. Identification of the process drifts: Statistical tests

Moreover, the turning points test and other statistical tests are useful as an additional procedure to predict eventual process drifts. They are essential to determine whether the changes are due to chance or they are systemic and need to be analyzed. Some of them are:

- The Mann-Whitney test, a non-parametric[9] test used to compare two independent samples. Even in the case of not-normally distributed data or outliers, it allows to detect differences in the distribution between two groups or time periods. However, it is not very efficient as it can only detect differences in the median without determining the direction nor the magnitude of changes.
- The Chi-square test, used to compare categorical data[10] between two or more groups. Changes in the distribution of categorical data are identified over time without assumptions

[9] "Parametric tests are those that make assumptions about the parameters of the population distribution from which the sample is drawn. This is often the assumption that the population data are normally distributed. Non-parametric tests are "distribution-free" and, as such, can be used for non-Normal variables." [55]
[10] "Categorical data refers to a form of information that can be stored and identified based on their names or labels. It is a type of qualitative data that can be grouped into categories instead of being measured numerically". They can be nominal or ordinal data: the first ones cannot be ranked or measured, while the other ones can. Some examples are birthdate, favorite sport, hair color, height, etc. [56]

regarding the distribution of data. However, it requires a large sample size, it is difficult to interpret in the case of numerous categories and cannot determine the direction or magnitude of changes. Moreover, it may not be appropriate for types of data that are not categorical.

- ANOVA, i.e., the Analysis of Variance, used to compare three or more groups' means. It is useful for detecting mean variations of a continuous variable over time or between groups. However, it cannot determine the direction or magnitude of the changes and assumes normality and equal variances of the groups. It is more suitable for large sample sizes and data without outliers.
- The t-test, used to compare the means of two groups. It detects changes in the mean of a continuous variable between two periods or groups; in fact, it is an ANOVA test limited to two groups comparison. Its main advantage is the simplicity and ability to handle normally distributed data. However, it assumes normality, can be sensitive to outliers and can only compare two groups.
- Fisher's exact test, based on the hypergeometric distribution and used to determine whether the proportions of data described by two or more categorical variables is random. It is defined "exact" because it does not rely on approximation but calculates exactly the results.

It is important to mention that tests for data drifts cannot be perfect: they could be more or less suitable depending on the use case and data. In fact, the statistical tests fit to the features taking into consideration several aspects like the correlation between the feature and the model performance, the feature type and distribution, the size of the samples to be compared, the size of drift to detect, and the cost of the model performance drop. [57-58]

In this specific case, the *one sample t-test* is the best alternative because it examines if the mean of a population is statistically different from a known or theoretical value. To perform this test, the data must satisfy some requirements:

- Test variable that is continuous, i.e., interval or ratio level.
- Scores on the test variable are independent, i.e., there is no relationship between scores on the test variable.
- Random sample of data from the population.
- Normal distribution (approximately) of the sample and population on the test variable.
- Homogeneity of variances (i.e., variances approximately equal in both the sample and population).
- No outliers.

- Measurements reported in working sequence.

Kendall's turning points test has been performed to evaluate whether a set of random variables are independent and identically distributed. Under the null hypothesis (H_0) that the sequence is random, it can be demonstrated that T_p is a random variable, following a normal distribution with: (formulas *4.10 - 4.12*):

$$\mathrm{T_p} \sim \mathbb{N}\left(\mu_{\mathrm{Tp}},\ \sigma_{\mathrm{Tp}}{}^2\right) \tag{4.10}$$

$$\mu_{\mathrm{Tp}} = \frac{2}{3}(\mathrm{n} - 2) \tag{4.11}$$

$$\sigma_{\mathrm{Tp}} = \sqrt{\frac{16\mathrm{n} - 29}{90}} \tag{4.12}$$

where *n* is the total number of observations and the value of 2 subtracted is about the first and the last points of the sequence that must be excluded from counting peaks and valleys.

For a generic sequence of n points, t_p, i.e., turning points, and the Confidence Interval (CI) must be determined, and an eventual anomaly must be checked:

- If t_p is included within the 95% CI, H_0 cannot be rejected, i.e. sequence is random.
- If t_p is out of the 95% CI, H_0 must be rejected.

This means that with a 95% CI, upper and lower limits are calculated as follow (*formula 4.13*):

$$\begin{cases} \mathrm{UCIL} = \mu_{\mathrm{Tp}} + \mathrm{Z}_{1-\frac{\alpha}{2}} \cdot \sigma_{\mathrm{Tp}} \\ \mathrm{LCIL} = \mu_{\mathrm{Tp}} - Z_{1-\frac{\alpha}{2}} \cdot \sigma_{\mathrm{Tp}} \end{cases} \tag{4.13}$$

where α = 5% and $Z_{1-\alpha/2}$ = 1,96, as a given data from tables *(Figure 4.3)*.

Substituting α = 5% into $Z_{1-\alpha/2}$, the value of Z obtained is $Z_{1-0,05/2} = Z_{0,975}$. Searching for an approximation of the value 0,975, the correspondent column and row highlights that 1,96 is the value that Z assumes.

$$\Phi(z) = P(Z \le z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2}\, du$$

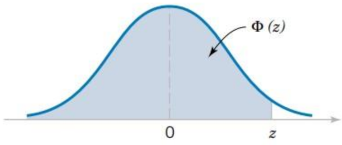

Table II Cumulative Standard Normal Distribution (*continued*)

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.500000	0.503989	0.507978	0.511967	0.515953	0.519939	0.532922	0.527903	0.531881	0.535856
0.1	0.539828	0.543795	0.547758	0.551717	0.555760	0.559618	0.563559	0.567495	0.571424	0.575345
0.2	0.579260	0.583166	0.587064	0.590954	0.594835	0.598706	0.602568	0.606420	0.610261	0.614092
0.3	0.617911	0.621719	0.625516	0.629300	0.633072	0.636831	0.640576	0.644309	0.648027	0.651732
0.4	0.655422	0.659097	0.662757	0.666402	0.670031	0.673645	0.677242	0.680822	0.684386	0.687933
0.5	0.691462	0.694974	0.698468	0.701944	0.705401	0.708840	0.712260	0.715661	0.719043	0.722405
0.6	0.725747	0.729069	0.732371	0.735653	0.738914	0.742154	0.745373	0.748571	0.751748	0.754903
0.7	0.758036	0.761148	0.764238	0.767305	0.770350	0.773373	0.776373	0.779350	0.782305	0.785236
0.8	0.788145	0.791030	0.793892	0.796731	0.799546	0.802338	0.805106	0.807850	0.810570	0.813267
0.9	0.815940	0.818589	0.821214	0.823815	0.826391	0.828944	0.831472	0.833977	0.836457	0.838913
1.0	0.841345	0.843752	0.846136	0.848495	0.850830	0.853141	0.855428	0.857690	0.859929	0.862143
1.1	0.864334	0.866500	0.868643	0.870762	0.872857	0.874928	0.876976	0.878999	0.881000	0.882977
1.2	0.884930	0.886860	0.888767	0.890651	0.892512	0.894350	0.896165	0.897958	0.899727	0.901475
1.3	0.903199	0.904902	0.906582	0.908241	0.909877	0.911492	0.913085	0.914657	0.916207	0.917736
1.4	0.919243	0.920730	0.922196	0.923641	0.925066	0.926471	0.927855	0.929219	0.930563	0.931888
1.5	0.933193	0.934478	0.935744	0.936992	0.938220	0.939429	0.940620	0.941792	0.942947	0.944083
1.6	0.945201	0.946301	0.947384	0.948449	0.949497	0.950529	0.951543	0.952540	0.953521	0.954486
1.7	0.955435	0.956367	0.957284	0.958185	0.959071	0.959941	0.960796	0.961636	0.962462	0.963273
1.8	0.964070	0.964852	0.965621	0.966375	0.967116	0.967843	0.968557	0.969258	0.969946	0.970621
1.9	0.971283	0.971933	0.972571	0.973197	0.973810	0.974412	0.975002	0.975581	0.976148	0.976705
2.0	0.977250	0.977784	0.978308	0.978822	0.979325	0.979818	0.980301	0.980774	0.981237	0.981691
2.1	0.982136	0.982571	0.982997	0.983414	0.983823	0.984222	0.984614	0.984997	0.985371	0.985738
2.2	0.986097	0.986447	0.986791	0.987126	0.987455	0.987776	0.988089	0.988396	0.988696	0.988989
2.3	0.989276	0.989556	0.989830	0.990097	0.990358	0.990613	0.990863	0.991106	0.991344	0.991576
2.4	0.991802	0.992024	0.992240	0.992451	0.992656	0.992857	0.993053	0.993244	0.993431	0.993613

Figure 4.3 – Statistical table for the Cumulative Standard Normal Distribution

That is, if t_p is included within the {LCIL, UCIL} interval, H_0 cannot be rejected, i.e., sequence is random.

The algorithm is implemented as follows:

```
for(i=0; i<n; i++)
        Δi=δyi/δxi
        if(sign(Δi)!= sign(Δi-1))
                tp++
print(tp)
```

The cycle "for" indicates that, for each point i respecting the indication i < n, where n is the total number of points, the number of turning points is incremented by one every time that the slope Δ_i of each function change in sign. This is performed by comparing two consecutive points starting from point 0 (i = 0) up to the second last (i < n), e.g., i_0 and i_1, followed by i_1 and i_2, etc. up to i_{n-1}

and i_n. The final step consists of receiving the number of turning points present through "print" function.

Once the requirements have been verified, the null hypothesis (H_0) and the alternative hypothesis (H_1) of the one sample t-test can be expressed as:

H_0: $\mu = \mu_0$, "the population mean is equal to the proposed population mean"

H_1: $\mu \neq \mu_0$, "the population mean is not equal to the proposed population mean"

where μ is the "true" population mean and μ_0 is the proposed value of the population mean.

The statistical test for one sample t-test is denoted t, which is calculated with the following formula *(4.14 - 4.15)*:

$$t = \frac{\bar{x} - \mu_0}{s_{\bar{x}}} \tag{4.14}$$

where:

$$s_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \tag{4.15}$$

μ_0 is the test value, i.e., the proposed constant for the population mean;

$\bar{x}$ is the sample mean;

n is the sample size, i.e., the number of observations;

σ is the sample standard deviation;

$s_{\bar{x}}$ is the estimated standard error of the mean.

The calculated t value is then compared to the critical t value from the t distribution table *(Figure 4.4)* with a chosen confidence level and degrees of freedom depending on the subsequent formula *(4.16)*:

$$D_f = n - 1 \tag{4.16}$$

In the case of one sample t-test, the degrees of freedom depend on the total number of observations minus one.

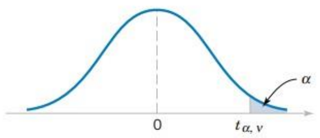

Table IV Percentage Points $t_{\alpha,\nu}$ of the *t*-Distribution

ν \ α	.40	.25	.10	.05	.025	.01	.005	.0025	.001	.0005
1	.325	1.000	3.078	6.314	12.706	31.821	63.657	127.32	318.31	636.62
2	.289	.816	1.886	2.920	4.303	6.965	9.925	14.089	23.326	31.598
3	.277	.765	1.638	2.353	3.182	4.541	5.841	7.453	10.213	12.924
4	.271	.741	1.533	2.132	2.776	3.747	4.604	5.598	7.173	8.610
5	.267	.727	1.476	2.015	2.571	3.365	4.032	4.773	5.893	6.869
6	.265	.718	1.440	1.943	2.447	3.143	3.707	4.317	5.208	5.959
7	.263	.711	1.415	1.895	2.365	2.998	3.499	4.029	4.785	5.408
8	.262	.706	1.397	1.860	2.306	2.896	3.355	3.833	4.501	5.041
9	.261	.703	1.383	1.833	2.262	2.821	3.250	3.690	4.297	4.781
10	.260	.700	1.372	1.812	2.228	2.764	3.169	3.581	4.144	4.587
11	.260	.697	1.363	1.796	2.201	2.718	3.106	3.497	4.025	4.437
12	.259	.695	1.356	1.782	2.179	2.681	3.055	3.428	3.930	4.318
13	.259	.694	1.350	1.771	2.160	2.650	3.012	3.372	3.852	4.221
14	.258	.692	1.345	1.761	2.145	2.624	2.977	3.326	3.787	4.140
15	.258	.691	1.341	1.753	2.131	2.602	2.947	3.286	3.733	4.073
16	.258	.690	1.337	1.746	2.120	2.583	2.921	3.252	3.686	4.015
17	.257	.689	1.333	1.740	2.110	2.567	2.898	3.222	3.646	3.965
18	.257	.688	1.330	1.734	2.101	2.552	2.878	3.197	3.610	3.922
19	.257	.688	1.328	1.729	2.093	2.539	2.861	3.174	3.579	3.883
20	.257	.687	1.325	1.725	2.086	2.528	2.845	3.153	3.552	3.850
21	.257	.686	1.323	1.721	2.080	2.518	2.831	3.135	3.527	3.819
22	.256	.686	1.321	1.717	2.074	2.508	2.819	3.119	3.505	3.792
23	.256	.685	1.319	1.714	2.069	2.500	2.807	3.104	3.485	3.767
24	.256	.685	1.318	1.711	2.064	2.492	2.797	3.091	3.467	3.745
25	.256	.684	1.316	1.708	2.060	2.485	2.787	3.078	3.450	3.725
26	.256	.684	1.315	1.706	2.056	2.479	2.779	3.067	3.435	3.707
27	.256	.684	1.314	1.703	2.052	2.473	2.771	3.057	3.421	3.690
28	.256	.683	1.313	1.701	2.048	2.467	2.763	3.047	3.408	3.674
29	.256	.683	1.311	1.699	2.045	2.462	2.756	3.038	3.396	3.659
30	.256	.683	1.310	1.697	2.042	2.457	2.750	3.030	3.385	3.646
40	.255	.681	1.303	1.684	2.021	2.423	2.704	2.971	3.307	3.551
60	.254	.679	1.296	1.671	2.000	2.390	2.660	2.915	3.232	3.460

Figure 4.4 – Table for the t distribution

Considering α = 5% column, the t value is the one to the correspondent degree of freedom (indicated as *v* in the table) row. If the calculated t value > critical t value, then we reject the null hypothesis. [59]

In the case the sample does not follow a normal distribution, the Mann-Whitney parametric test is the best solution as statistical test; anyway, as said before, it is not very efficient, since it includes outliers and compares the median instead of the mean.

4.2.4. Waste and visual limits: UI/UX interface

One of the most important topics of predictive and smart quality control in an Industry 5.0 approach is the *reduction of waste*, since it has numerous consequences that the industry may benefit from. Referring to the waste and technical drawings problems, the solution is the development of an easy, intuitive and responsive interface is enough (UX/UI design). This leads to the great advantage of reducing the time of quality control operations and simplifying it with the introduction of the Poka-yoke method – form the Japanese, meaning "mistake-proofing" or "error prevention". The method helps the operators to avoid (*yokeru*) mistakes (*poka*) and defects by preventing and correcting human errors. Some of the features offered by the poka-yoke method is a user-friendly and adaptable interface, essential to simplify the process and help the user to achieve these needs. [60]

First, this has a positive economic impact: it reduces direct costs, like wasted raw materials, their transportation and processing, and the lost gain caused by the lost sale. Also indirect costs are reduced: labor cost, energy and other utilities use is decreased since less processes are carried out. In addition, according to lean manufacturing principles, reducing waste raises efficiency: real-time production monitoring is simplified, less time is needed to perform the tasks and consequently production becomes faster. It has benefits also from the environmental point of view, as a waste reduction can reduce the energy consumption and its emissions; this increases the plant reputation, considering that customers and potential business partners are becoming more and more aware of sustainability themes, leading to customers loyalty and improving the employees' morale. [64]

4.3. Resolution of problems

4.3.1. Digitization and UI/UX interface

The solution to the maximization of marginality is digitization. The introduction of Orchestra technology helps the company to interconnect machines, according to Industry 4.0 and 5.0, equipping them with MES, to collect raw data and turn them into information to control machines' efficiency and monitor each process progress, and finally to have correct and certified data on which to base their business analysis. [61]

The passage to a universal digitization is made possible thanks to the development of a user-friendly and intuitive interface that guides the user through the choice of better solutions in the easiest possible way.

4.3.2. Control charts and statistical tests

The first study to identify the process drifts before the production goes out-of-tolerance are the control charts; the most useful identified are the $\overline{x}$-*MR* charts for a quantitative control, and *np* charts to run a qualitative control. The study has been performed by applying the previous formulas

(4.1 - 4.9) to real data collected by Planoplast during the production of two different products; only the most important measurements from a mechanical point of view have been analyzed. This solution can be implemented with statistical tests that give additional information about the prediction and definition of process drifts before they occur. The turning point test and the t-test have been performed on the same data used before, and the outcome is the following.

Sample 1:

The first analyzed sample is the part of a carriage shown in *Figure 4.5*; the written measurements[11] have been taken into consideration on the basis of 21 samples measured for every 50 units produced. They have been applied to the x-MR charts because in this case study a quantitative analysis was necessary; obviously, in the case of qualitative analysis the p-chart would have been the most appropriate method.

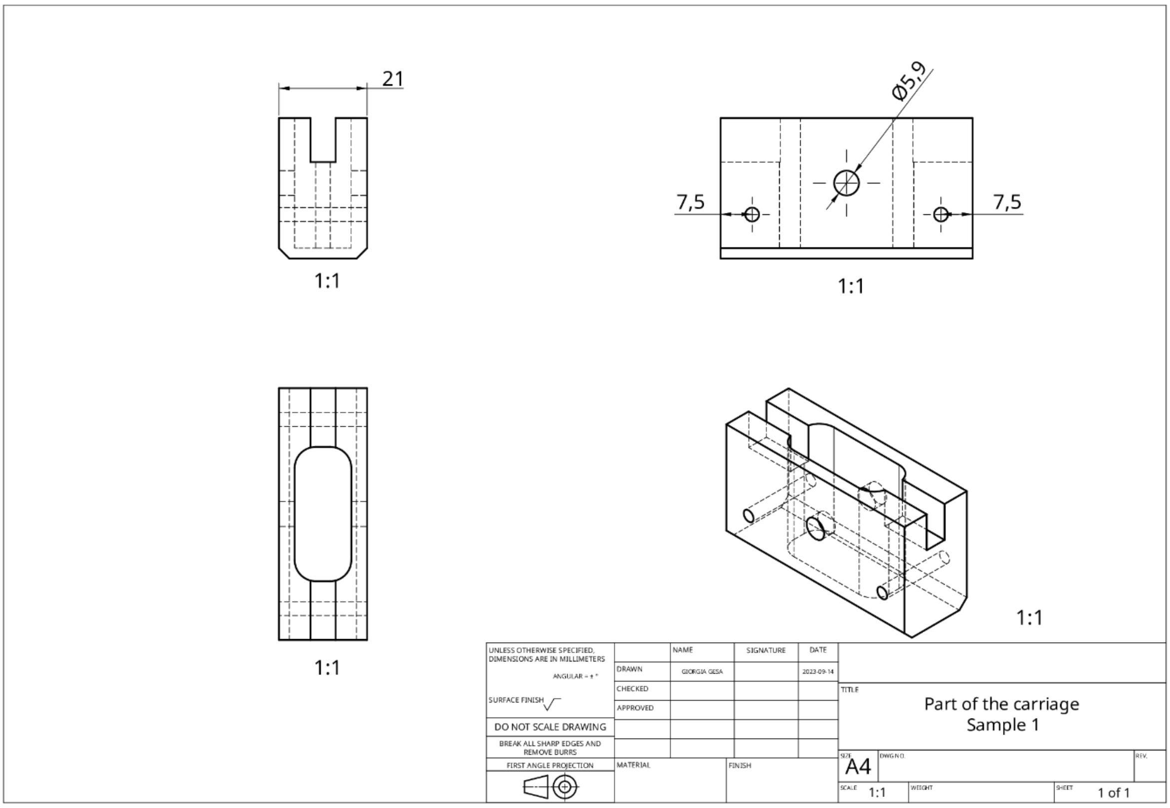

Figure 4.5 – Sample 1 drawing

- ***Measurement 1***: the total height of the unit must theoretically be μ=21mm. The following *Table (4.1)* shows the data collected by the operators with the support of a caliber and the consequent mobile range:

Table 4.1 – Sample 1, measurement 1 data and MR

[11] Not all of the measurements have been reported on the drawing for privacy reasons.

n	*Measurement*	*Moving Range (MR)*	t_p
1	20,86	-	-
2	20,88	0,02	1
3	20,86	0,02	1
4	20,88	0,02	0
5	20,88	0	0
6	20,9	0,02	1
7	20,88	0,02	1
8	20,89	0,01	1
9	20,88	0,01	0
10	20,86	0,02	1
11	20,9	0,04	1
12	20,88	0,02	1
13	20,89	0,01	0
14	20,89	0	0
15	20,88	0,01	1
16	20,9	0,02	1
17	20,88	0,02	1
18	20,89	0,01	1
19	20,88	0,01	1
20	20,89	0,01	1
21	20,88	0,01	-
Avg	20,882	0,015	*Tot* 14

According to equations *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.6 - 4.7* show the x-chart and MR-chart obtained with these data.

$$\bar{\text{x}} - \text{chart} \begin{cases} \text{UCL}_\text{x} = 20{,}922 \\ \text{CL}_\text{x} = 20{,}882 \\ \text{LCL}_\text{x} = 20{,}442 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} \text{UCL}_\text{MR} = 0{,}049 \\ \text{CL}_\text{MR} = 0{,}015 \\ \text{LCL}_\text{MR} = 0 \end{cases}$$

C_p= 1 and C_{pk}=1; being these values equal, we start to assume that the process is centered, i.e., it is accurate and precise.[12]

[12] "Accuracy and precision are both ways to measure results. Accuracy measures how close results are to the true or known value. Precision, on the other hand, measures how close results are to one another. They're both useful ways to track and report on project results. […] While accuracy can be used in one instance, precision will be measured over time. This is because precision requires repeatability to determine the degree of closeness between each set of measurements." – source: https://asana.com/it/resources/accuracy-vs-precision [62]

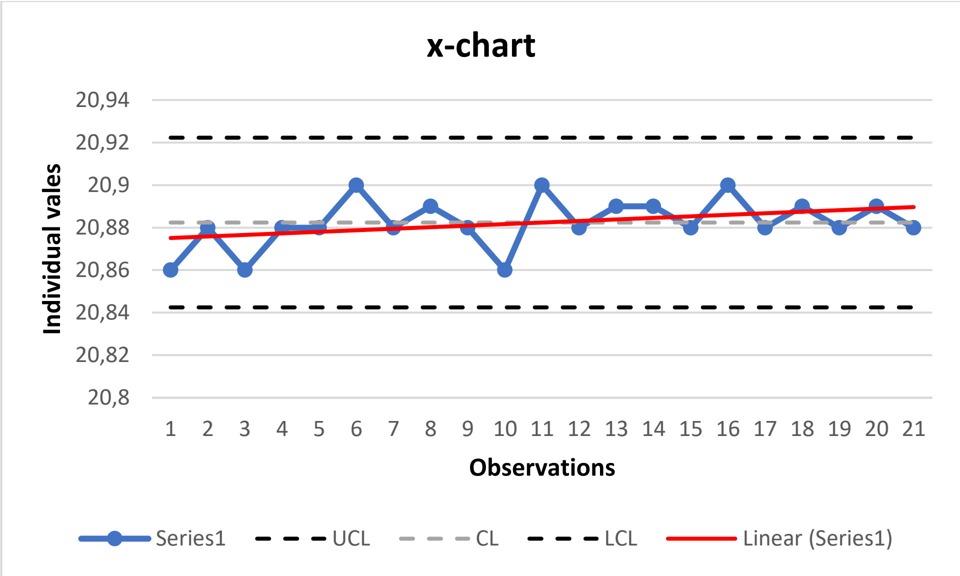

Figure 4.6 – Sample 1, measurement 1 x-chart

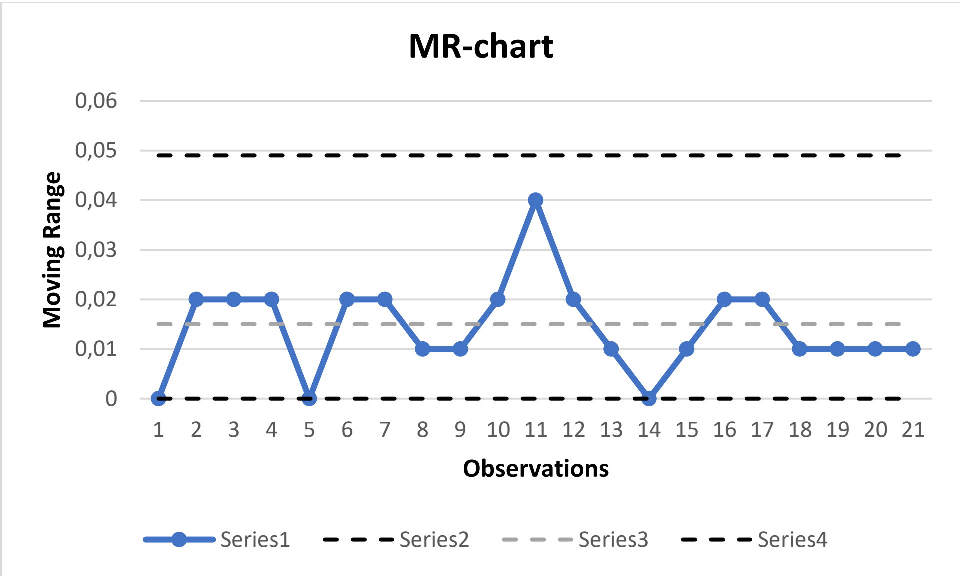

Figure 4.7 – Sample 1, measurement 1 MR-chart

The x-chart evidences the presence of a slight rising trend, indicated by the red line, and both the x and MR-chart do not present any outlier.

It is possible to count on x-chart 14 turning points t_p. By using formulas *(4.11)* and *(4.12)*, the values $\mu_{tp} = 12{,}67$ and $\sigma_{tp} = 1{,}85$ have been obtained and put into the formula *(4.13)*, obtaining:

$$\begin{cases} \text{UCIL} = 16{,}29 \\ \text{LCIL} = 9{,}05 \end{cases}$$

Being t_p included in the interval, the sequence follows a normal distribution, i.e., it is random; since it respects the hypothesis of normality, it is possible to perform the t-test.

According to the equations *(4.15)* and *(4.14)*, $s_{\bar{x}}$ = 0,40 and t = - 0,29. The critical value has been obtained by consulting the table for the t-distribution *(Fig. 4.4)* with a value of $t_{0,05;20}$ = 1,725. So, the null hypothesis H_0 must be rejected, and it must be declared that the actual average of the population *($t_{0,05;20}$)* is statistically different from the theoretical one *(t)*, i.e., the difference between the two averages is *statistically significant*. This means that there is a very low probability that the two values are not equal because of casual fluctuations. A deeper analysis is done in the next paragraph.

- ***Measurement 2***: the diameter of the untapped hole must theoretically be μ=5,9mm. *Table 4.2* shows the data collected by the operators with the support of a caliber and the MR:

Table 4.2 – Sample 1, measurement 2 data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	5,93	-	-
2	5,93	0	0
3	5,93	0	0
4	5,93	0	0
5	5,9	0,03	1
6	5,92	0,02	0
7	5,93	0,01	0
8	5,93	0	0
9	5,93	0	0
10	5,93	0	0
11	5,93	0	0
12	5,92	0,01	0
13	5,92	0	0
14	5,93	0,01	1
15	5,92	0,01	0
16	5,92	0	0
17	5,93	0,01	1
18	5,92	0,01	0
19	5,92	0	0
20	5,92	0	0
21	5,92	0	-
Avg	5,924	0,0055	*Tot* 3

According to formulas *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.8 - 4.9* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 5{,}939 \\ CL_x = 5{,}924 \\ LCL_x = 5{,}909 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} \text{UCL}_{\text{MR}} = 0{,}018 \\ \text{CL}_{\text{MR}} = 0{,}005 \\ \text{LCL}_{\text{MR}} = \ 0 \end{cases}$$

C_p= 2 and C_{pk}=1; being $C_{pk} < C_p$, we start assuming that the process is not centered, i.e. the actual μ does not match to the theoretical one. Even if the process is not accurate, it can be considered precise since $C_{pk} \geq 1$.

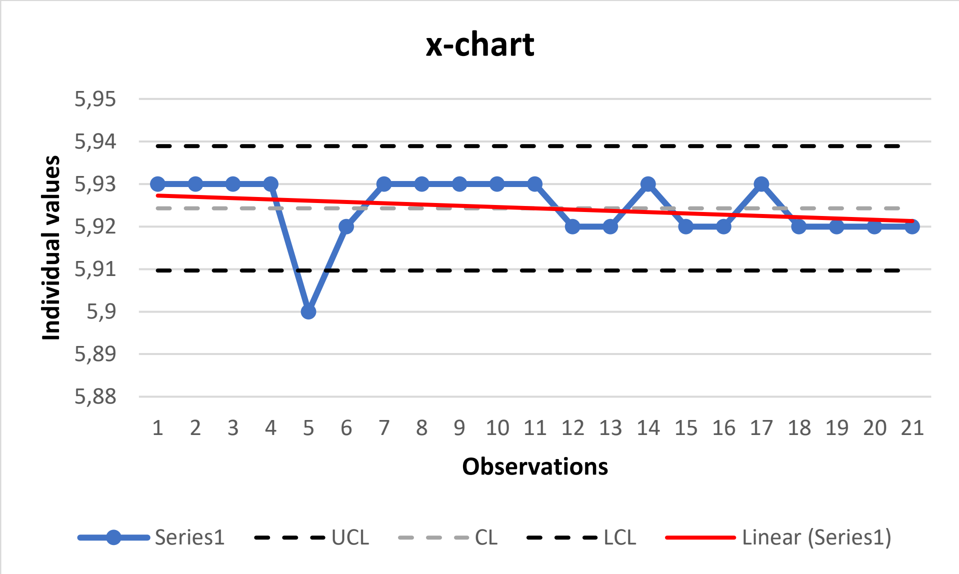

Figure 4.8 – Sample 1, measurement 2 x-chart

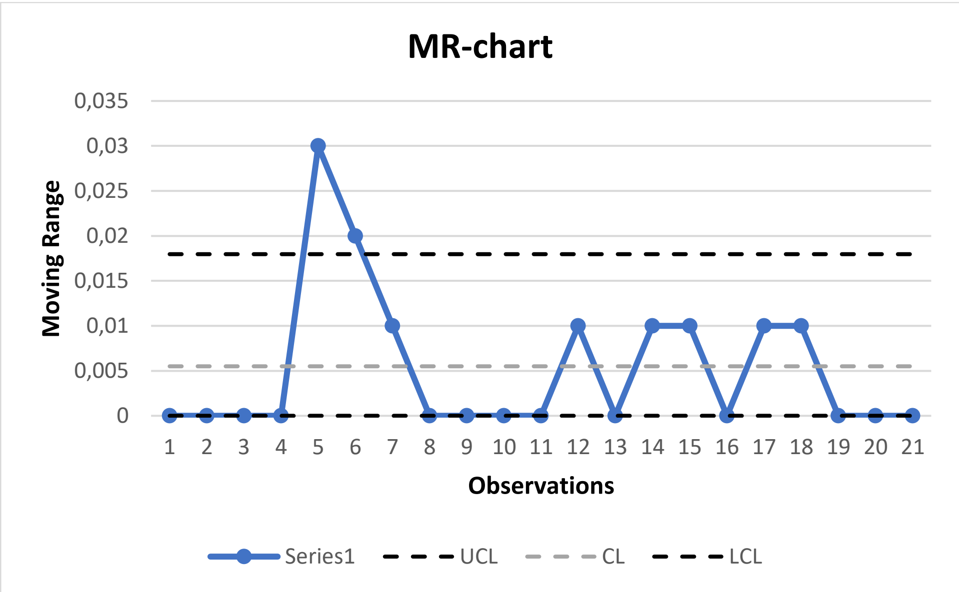

Figure 4.9 – Sample 1, measurement 2 MR-chart

The x-chart evidences the presence of a slight downward trend, indicated by the red line, and both the x and MR-chart present outliers.

Since the performance of t-test requires the absence of outliers, the procedure can be repeated with 20 observations, removing the n.5. *Table 4.3* shows the updated data:

Table 4.3 – Sample 1, measurement 2 updated data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	5,93	-	-
2	5,93	0	0
3	5,93	0	0
4	5,93	0	0
5	5,92	0,01	1
6	5,93	0,01	0
7	5,93	0	0
8	5,93	0	0
9	5,93	0	0
10	5,93	0	0
11	5,92	0,01	0
12	5,92	0	0
13	5,93	0,01	1
14	5,92	0,01	0
15	5,92	0	0
16	5,93	0,01	1
17	5,92	0,01	0
18	5,92	0	0
19	5,92	0	0
20	5,92	0	-
Avg	5,926	0,00368	*Tot* 3

According to eq. *(4.3)* and *(4.5)* the limits remain unchanged; *Figure 4.10 - 4.11* show the x-chart and MR-chart obtained.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 5{,}940 \\ CL_x = 5{,}926 \\ LCL_x = 5{,}911 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}012 \\ CL_{MR} = 0{,}003 \\ LCL_{MR} = 0 \end{cases}$$

In this case, $C_p = C_{pk} = 1{,}493$; since they assume the same value, the process turns out precise and accurate.

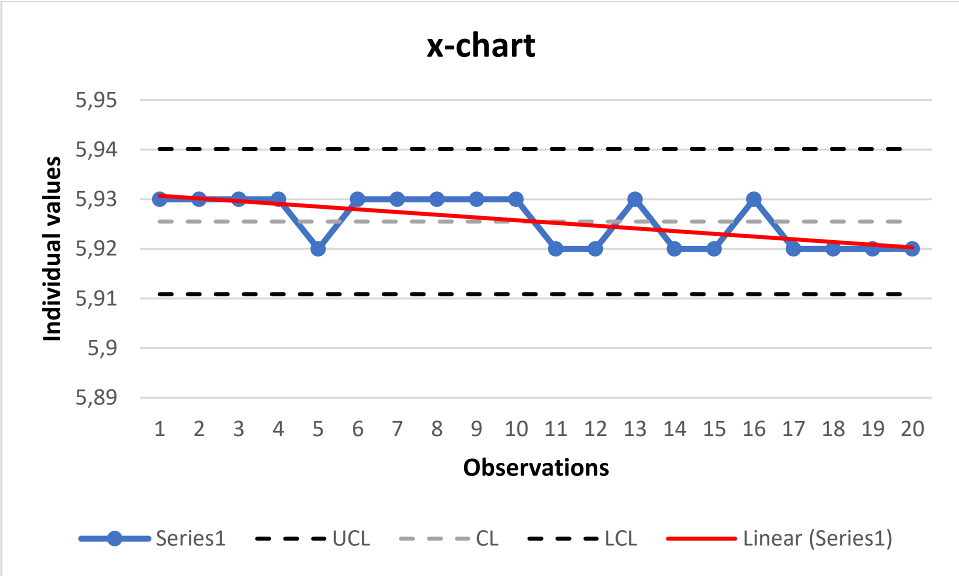

Figure 4.10 – Sample 1, measurement 2 x-chart excluding outlier (obs.5)

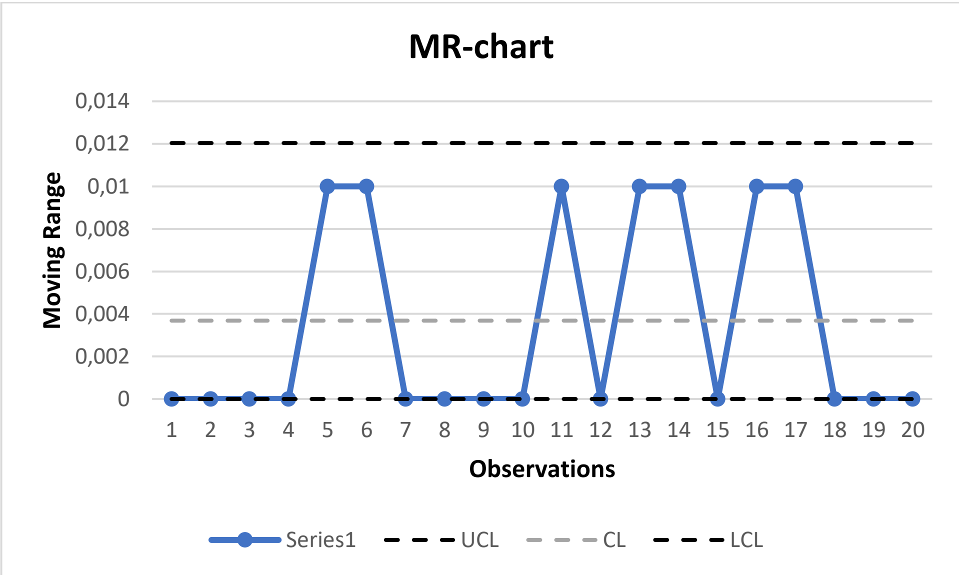

Figure 4.11 - Sample 1, measurement 2 MR-chart excluding outlier (obs.5)

The presence of a slight downward trend, indicated by the red line, persists; anyway, both the x and MR-chart do not present outliers anymore, i.e., the process is under statistical control.

Now, it is possible to count the presence of 3 turning points on x-chart. By using formulas *(4.11)* and *(4.12)*, the values $\mu_{tp} = 12$ and $\sigma_{tp} = 1{,}79$ have been obtained and put into the formula *(4.13)* giving the interval:

$$\begin{cases} UCIL = 15{,}52 \\ LCIL = 8{,}48 \end{cases}$$

Being t_p not included in the interval, the sequence does not follow a normal distribution, i.e., it is not random once again and the t-test cannot be performed.

- ***Measurement 3***: the distance of the first of the two threads center to the side edge must theoretically be μ=7,5mm. *Table 4.4* shows the data collected by the operators with the support of a caliber and the MR:

Table 4.4 - Sample 1, measurement 3 data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	7,43	-	-
2	7,44	0,01	0
3	7,46	0,02	0
4	7,47	0,01	1
5	7,4	0,07	1
6	7,49	0,09	0
7	7,49	0	0
8	7,48	0,01	0
9	7,48	0	0
10	7,49	0,01	1
11	7,46	0,03	1
12	7,48	0,02	0
13	7,5	0,02	0
14	7,5	0	0
15	7,5	0	0
16	7,5	0	0
17	7,5	0	0
18	7,48	0,02	1
19	7,5	0,02	0
20	7,5	0	0
21	7,5	0	-
Avg	7,479	0,0165	*Tot* 5

According to formulas *(4.3)* and *(4.5)* the limits have been calculated; *Figure 4.12 - 4.13* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 7{,}522 \\ CL_x = 7{,}4785 \\ LCL_x = 7{,}435 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}054 \\ CL_{MR} = 0{,}017 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1$; having them the same value, the process results precise and accurate.

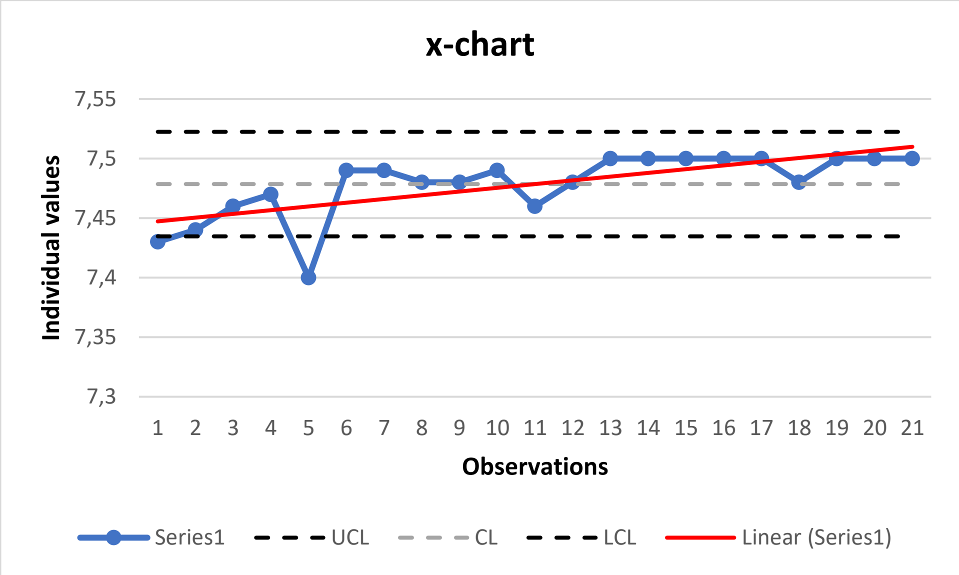

Figure 4.12 – Sample 1, measurement 3 x-chart

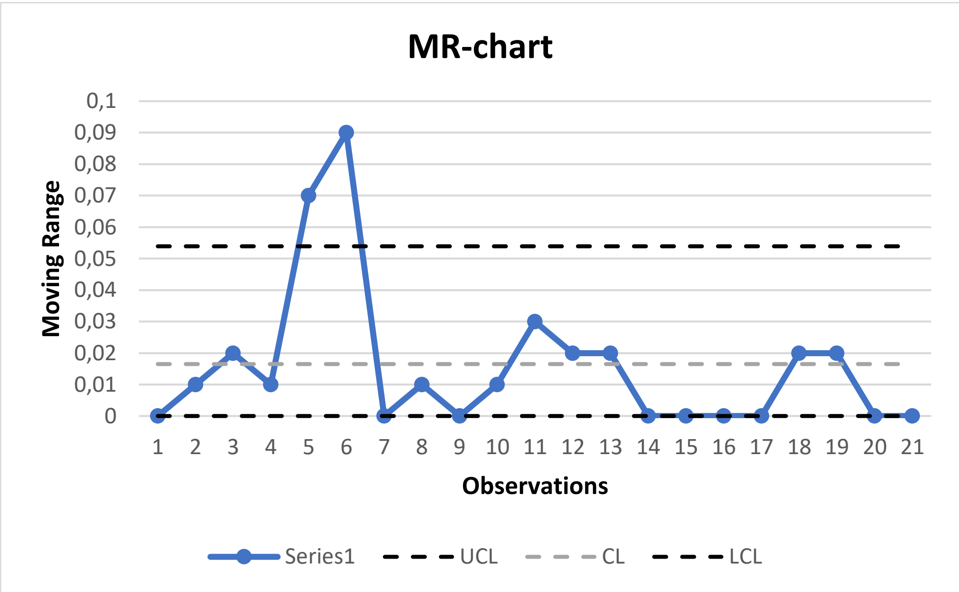

Figure 4.13 – Sample 1, measurement 3 MR-chart

The x-chart evidences the presence of an upward trend, indicated by the red line, and both the x and MR-chart present outliers that do not allow to perform the t-test. The removal of observation n.5 and repetition of the same procedure on the remaining 20 observations is done. *Table 4.5* shows the updated data:

Table 4.5 – Sample 1, measurement3 updated data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	7,43	-	-
2	7,44	0,01	0
3	7,46	0,02	0
4	7,47	0,01	0
5	7,49	0,02	0

6	7,49	0	0
7	7,48	0,01	0
8	7,48	0	0
9	7,49	0,01	1
10	7,46	0,03	1
11	7,48	0,02	0
12	7,5	0,02	0
13	7,5	0	0
14	7,5	0	0
15	7,5	0	0
16	7,5	0	0
17	7,48	0,02	1
18	7,5	0,02	0
19	7,5	0	0
20	7,5	0	-
Avg	7,4825	0,01	*Tot* 3

According to *(4.3)* and *(4.5)* the limits are calculated; *Figures 4.14 - 4.15* show the x-chart and MR-chart obtained.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 7{,}526 \\ CL_x = 7{,}483 \\ LCL_x = 7{,}439 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}033 \\ CL_{MR} = 0{,}010 \\ LCL_{MR} = 0 \end{cases}$$

In this case, $C_p = C_{pk} = 1{,}65$; since they assume the same value, the process turns out to be precise and accurate.

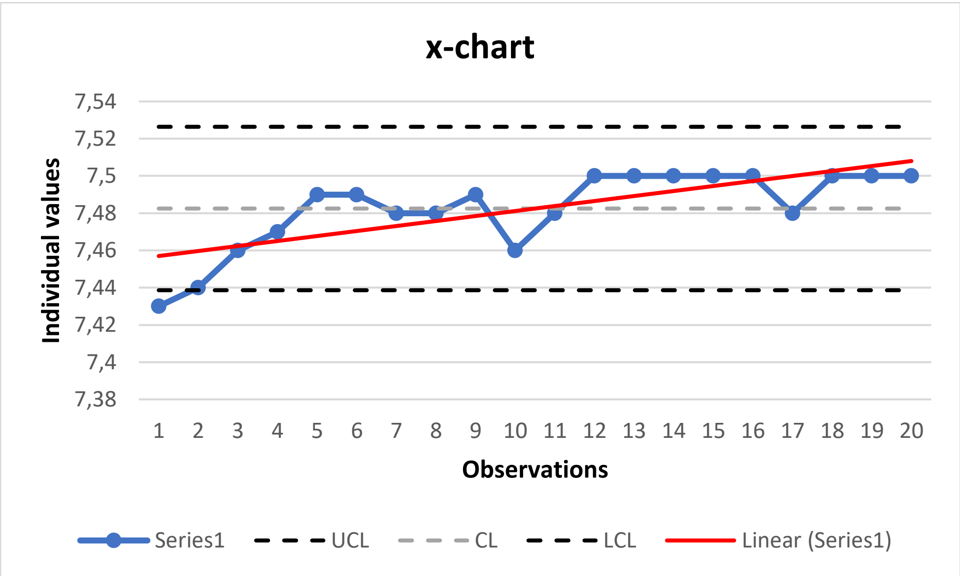

Figure 4.14 - Sample 1, measurement 3 x-chart excluding outlier (obs.5)

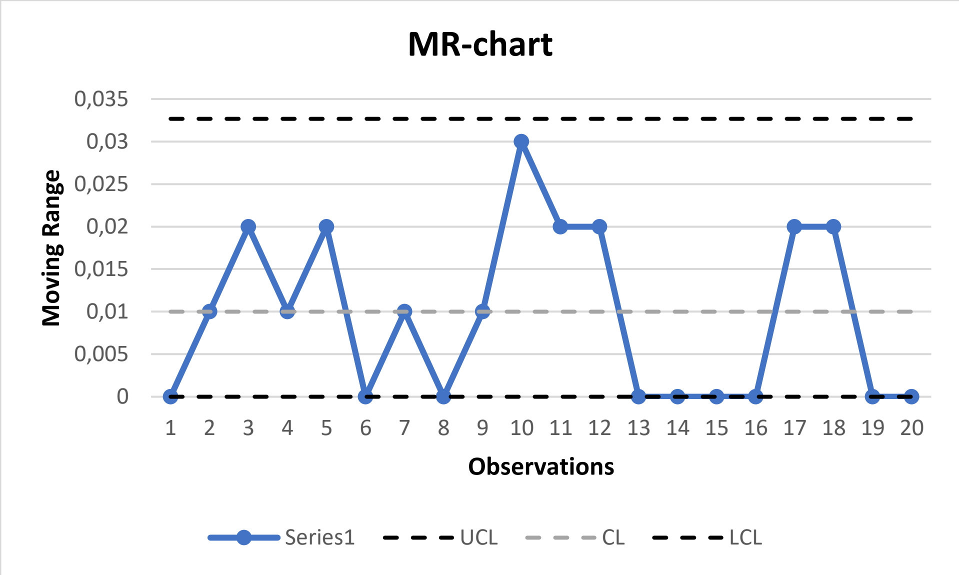

Figure 4.15 – Sample 1, measurement 3 MR-chart excluding outlier (obs.5)

The presence of a slight upward trend, indicated by the red line, persists, and so also for an outlier in x-chart. This means that another repetition of the process must be performed with 19 observations, this time removing the n.1, shown in *Table 4.6*.

Table 4.6 – Sample 1, measurement 3 updated data and MR (2)

n	*Measurement*	*Moving Range (MR)*	t_p
1	7,44	-	-
2	7,46	0,02	0
3	7,47	0,01	0
4	7,49	0,02	0
5	7,49	0	0
6	7,48	0,01	0
7	7,48	0	0
8	7,49	0,01	1
9	7,46	0,03	1
10	7,48	0,02	0
11	7,5	0,02	0
12	7,5	0	0
13	7,5	0	0
14	7,5	0	0
15	7,5	0	0
16	7,48	0,02	1
17	7,5	0,02	0
18	7,5	0	0
19	7,5	0	-
Avg	7,485263158	0,01	*Tot* 3

According to *(4.3)* and *(4.5)* the limits become the subsequent; *Figure 4.16 - 4.17* show the newest x-chart and MR-chart obtained. Also, C_p and C_{pk} do not change, so the process turns out to be precise and accurate again.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 7{,}529 \\ CL_x = 7{,}485 \\ LCL_x = 7{,}441 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}033 \\ CL_{MR} = 0{,}010 \\ LCL_{MR} = 0 \end{cases}$$

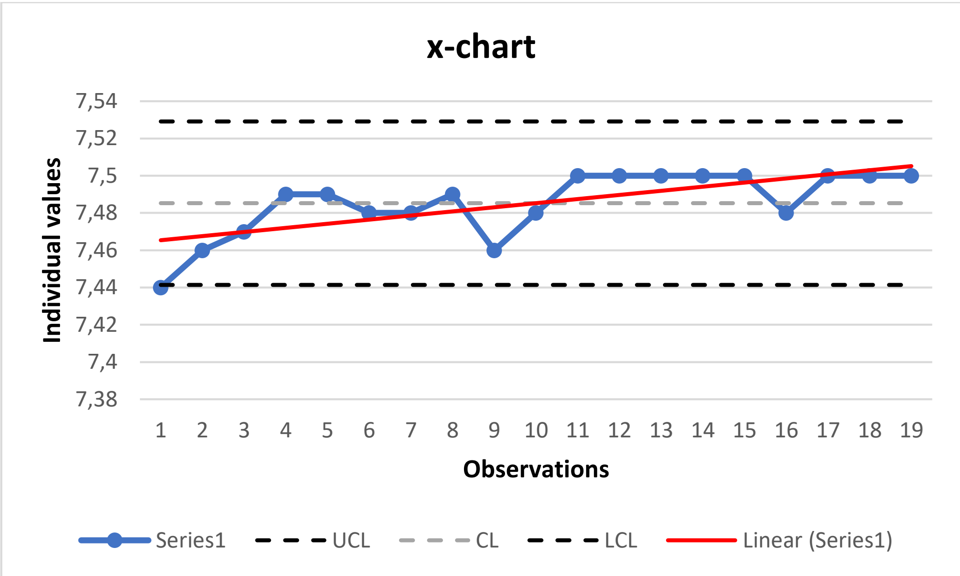

Figure 4.16 – Sample 1, measurement 3 x-chart excluding outlier (obs.1)

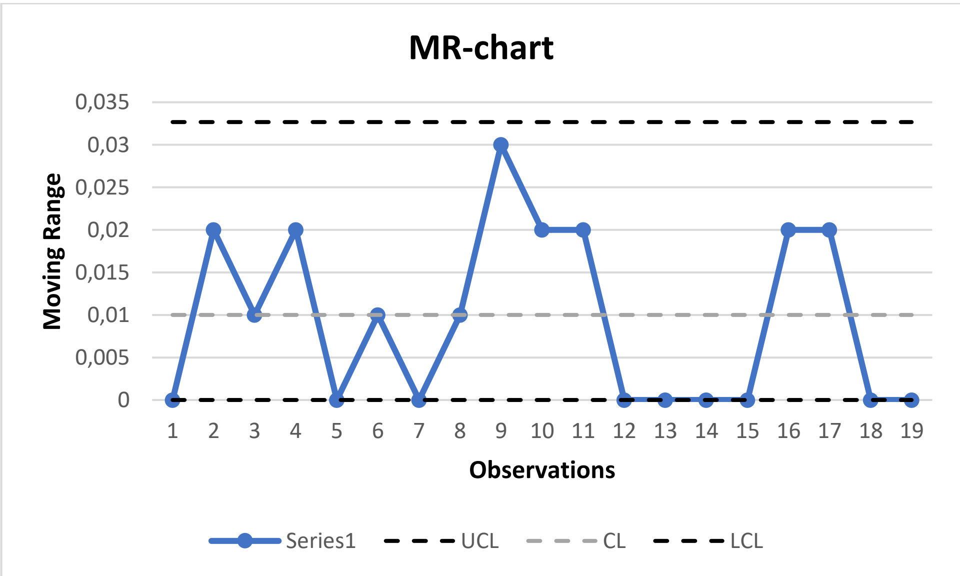

Figure 4.17 – Sample 1, measurement 3 MR-chart excluding outlier (obs.1)

Since there are no outliers, it is possible to verify the normality of the distribution to eventually perform the t-test. The x-chart presents 3 turning points. By using formulas (*4.11)* and (*4.12*), the values $\mu_{tp} = 11{,}33$ and $\sigma_{tp} = 1{,}75$ have been obtained and put into the formula *(4.13)* obtaining the new interval:

$$\begin{cases} \text{UCIL} = 14{,}76 \\ \text{LCIL} = 7{,}91 \end{cases}$$

Since t_p is not included in the interval, the sequence does not follow a normal distribution, i.e., it is not random, and the t-test cannot be performed.

- ***Measurement 4***: the distance of the other thread center to the side edge must theoretically be μ=7,5mm (symmetrical to the first one). *Table 4.7* shows the data collected by the operators with the support of a caliber and the MR:

Table 4.7 – Sample 1, measurement 4 data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	7,52	-	-
2	7,52	0	0
3	7,52	0	0
4	7,52	0	0
5	7,52	0	0
6	7,5	0,02	1
7	7,52	0,02	1
8	7,5	0,02	1
9	7,52	0,02	1
10	7,51	0,01	1
11	7,52	0,01	0
12	7,52	0	0
13	7,5	0,02	1
14	7,52	0,02	1
15	7,5	0,02	1
16	7,52	0,02	1
17	7,5	0,02	1
18	7,52	0,02	0
19	7,52	0	0
20	7,5	0,02	1
21	7,52	0,02	-
Avg	7,514	0,013	*Tot* 11

According to equations *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.18 - 4.19* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 7{,}548 \\ CL_x = 7{,}514 \\ LCL_x = 7{,}479 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}042 \\ CL_{MR} = 0{,}013 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1$; having them the same value, the process results precise and accurate.

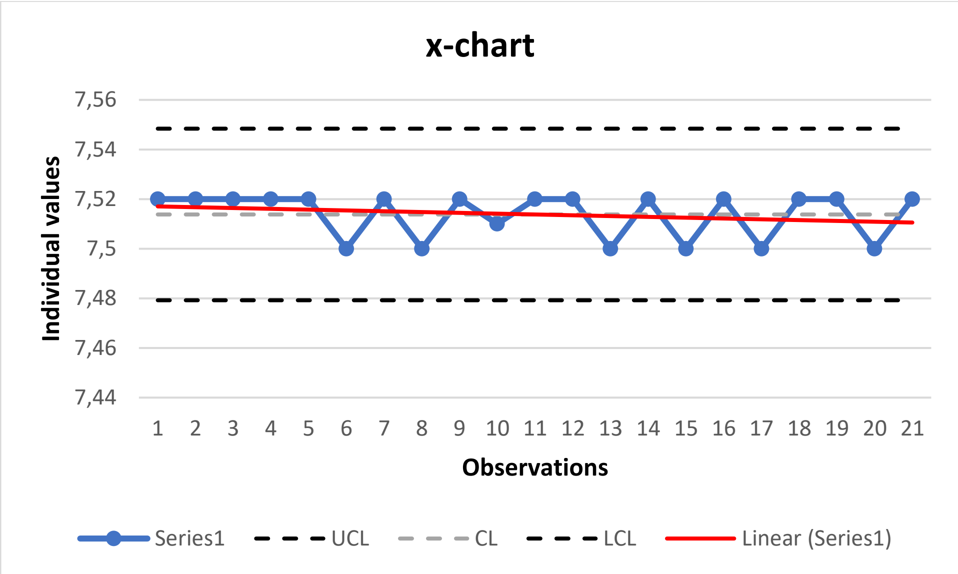

Figure 4.18 – Sample 1, measurement 4 x-chart

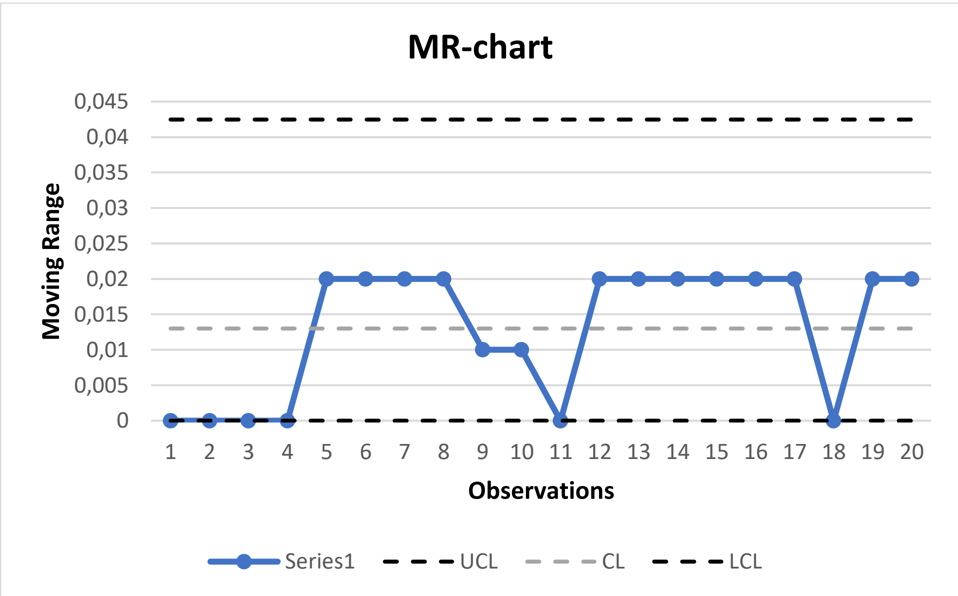

Figure 4.19 – Sample 1, measurement 4 MR-chart

The x-chart evidences the presence of a slight downward trend, indicated by the red line. Since there are no outliers, Kendall's test can be performed to verify the feasibility of the t-test.

It is possible to count 11 turning points on the x-chart. By using formulas *(4.11)* and *(4.12)*, the values $\mu_{tp} = 12{,}67$ and $\sigma_{tp} = 1{,}85$ have been obtained and put into the formula *(4.13)* obtaining:

$$\begin{cases} \text{UCIL} = 16{,}29 \\ \text{LCIL} = 9{,}05 \end{cases}$$

Being t_p included in the interval, the sequence follows a normal distribution, i.e., it is random. This characteristic and the absence of outliers allow to perform the one sample t-test.

According to the formulas *(4.15)* and *(4.14)*, $s_{\bar{x}} = 0{,}40$ and $t = 0{,}034$. The critical value has been obtained by consulting the table for the t-distribution *(Fig. 4.4)* with a value of $t_{0,05;20} = 1{,}725$. So, the null hypothesis H_0 must be rejected, and it must be declared that the actual average of the population *($t_{0,05;20}$)* is *statistically different* from the theoretical one *(t)*, i.e., there is a very low probability that the two values are not equal because of casual fluctuations.

Sample 2:

The second sample taken into consideration is the wheel of a carriage, shown in *Figure 4.20*; 31 samples measured for every 50 units produced have been taken into consideration. The most important measurements from the mechanical point of view have been analyzed. As before, the x-MR charts have been used because this case study required a quantitative analysis.

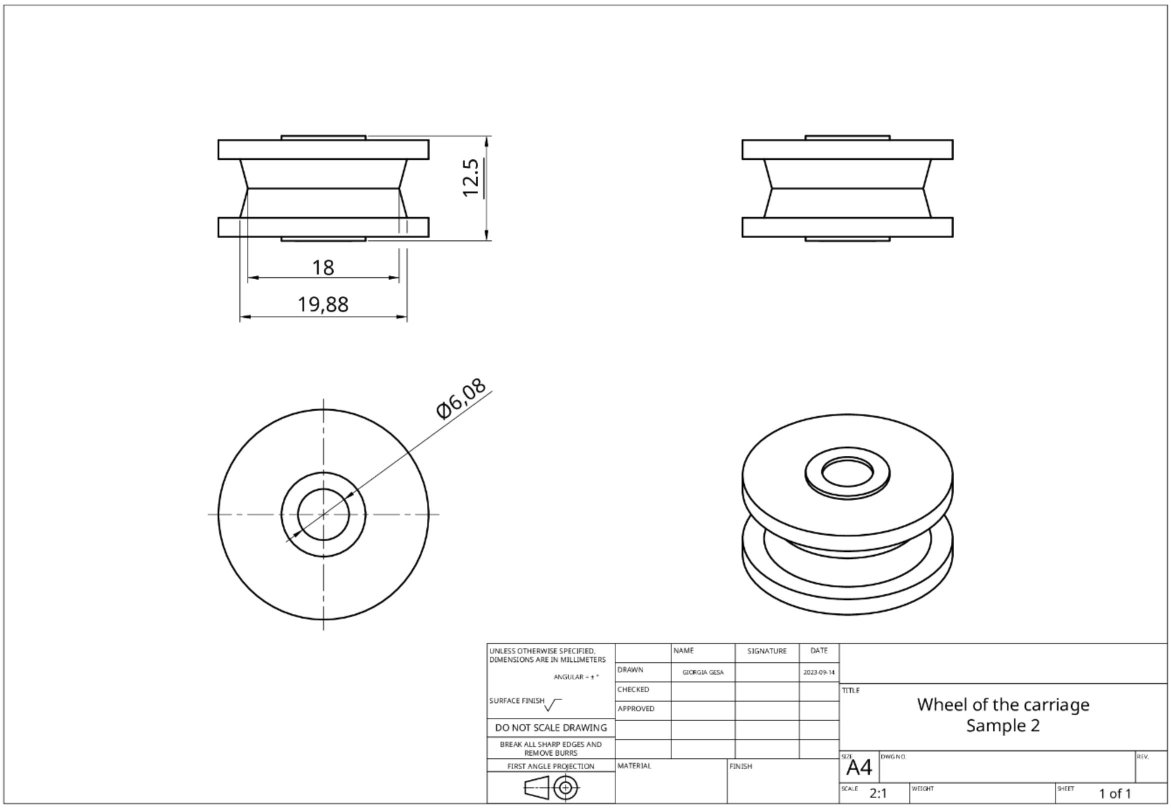

Figure 4.20 – Sample 2 drawing

- ***Measurement 1***: the total thickness of the unit must theoretically be μ=12,5mm. The following *Table (4.8)* shows the data collected by the operators with the support of a caliber and the consequent moving range:

Table 4.8 – Sample 2, measurement 1 data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	12,56	-	-
2	12,53	0,03	0
3	12,47	0,06	1
4	12,51	0,04	0
5	12,55	0,04	1
6	12,54	0,01	0
7	12,43	0,11	1
8	12,48	0,05	1
9	12,47	0,01	1
10	12,51	0,04	1
11	12,47	0,04	1
12	12,48	0,01	0
13	12,48	0	0
14	12,48	0	0
15	12,52	0,04	1
16	12,47	0,05	0
17	12,47	0	0
18	12,48	0,01	0

19	12,53	0,05	1
20	12,52	0,01	0
21	12,47	0,05	1
22	12,51	0,04	1
23	12,49	0,02	0
24	12,48	0,01	1
25	12,51	0,03	0
26	12,53	0,02	1
27	12,47	0,06	0
28	12,47	0	0
29	12,5	0,03	1
30	12,47	0,03	1
31	12,48	0,01	1
32	12,47	0,01	-
Avg	12,494	0,0294	*Tot* 16

According to *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.21 - 4.22* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 12{,}572 \\ CL_x = 12{,}494 \\ LCL_x = 12{,}416 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}096 \\ CL_{MR} = 0{,}029 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1$; being these values equal, we start to assume that the process is centered, i.e., it is accurate and precise.

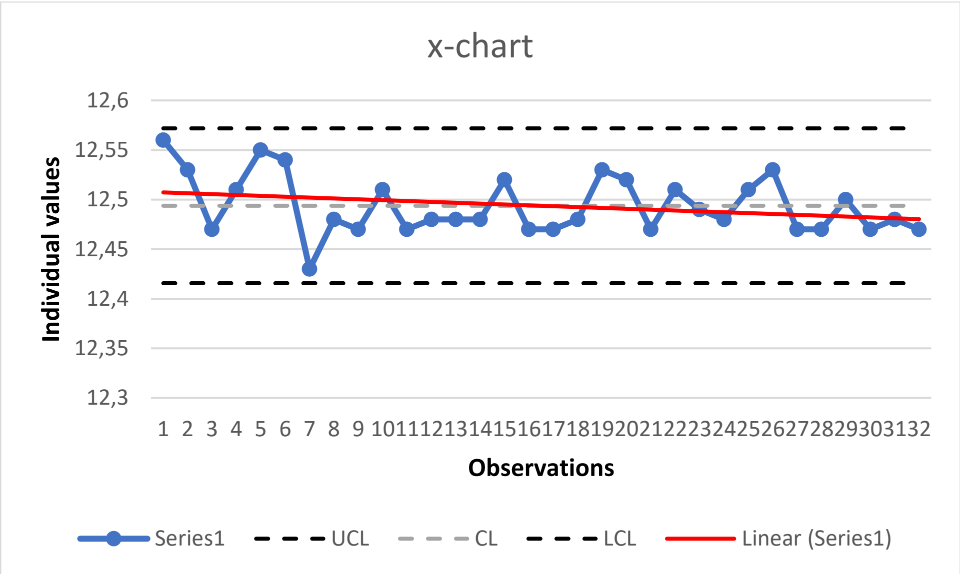

Figure 4.21 – Sample 2, measurement 1 x-chart

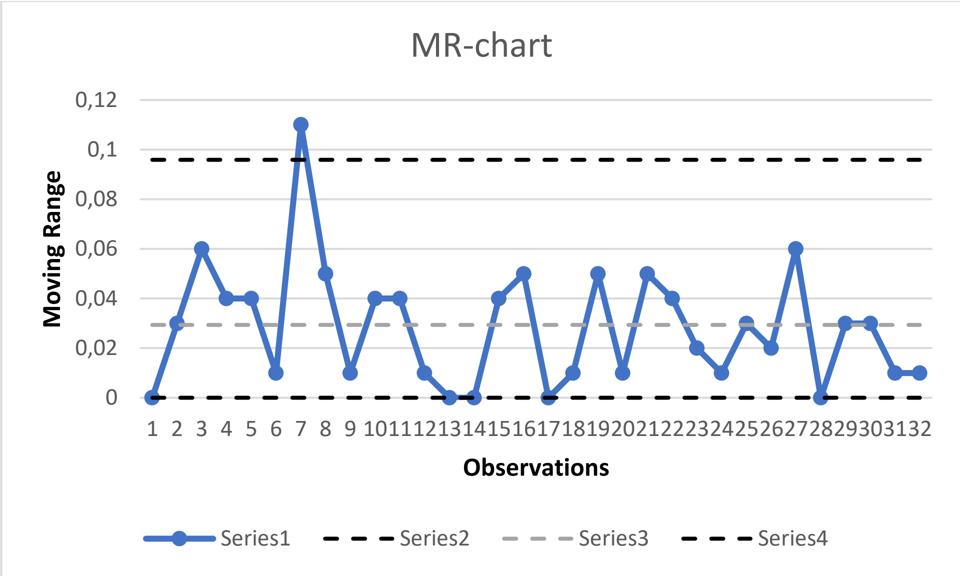

Figure 4.22 – Sample 2, measurement 1 MR-chart

The x-chart follows a downward trend, as the red line indicates, and it has no outliers. MR-chart has instead an outlier, so the procedure must be repeated with 31 observations, removing n.7, before applying the t-test. The new *Table 4.9* of data is the following:

Table 4.9 – Sample 2, measurement 1 updated data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	12,56	-	-
2	12,53	0,03	0
3	12,47	0,06	1
4	12,51	0,04	0
5	12,55	0,04	1
6	12,54	0,01	0
7	12,48	0,06	0
8	12,47	0,01	1
9	12,51	0,04	1
10	12,47	0,04	1
11	12,48	0,01	0
12	12,48	0	0
13	12,48	0	0
14	12,52	0,04	1
15	12,47	0,05	0
16	12,47	0	0
17	12,48	0,01	0
18	12,53	0,05	1
19	12,52	0,01	0
20	12,47	0,05	1
21	12,51	0,04	1
22	12,49	0,02	0
23	12,48	0,01	1
24	12,51	0,03	0

25	12,53	0,02	1
26	12,47	0,06	0
27	12,47	0	0
28	12,5	0,03	1
29	12,47	0,03	1
30	12,48	0,01	1
31	12,47	0,01	-
Avg	12,496	0,027	*Tot* 14

According to *(4.3)* and *(4.5)* the limits are calculated below; *Figures 4.23 - 4.24* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 12{,}574 \\ CL_x = 12{,}496 \\ LCL_x = 12{,}418 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}088 \\ CL_{MR} = 0{,}027 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1{,}087$; being once again these values equal, we assume that the process is centered, i.e., it is accurate and precise, as before.

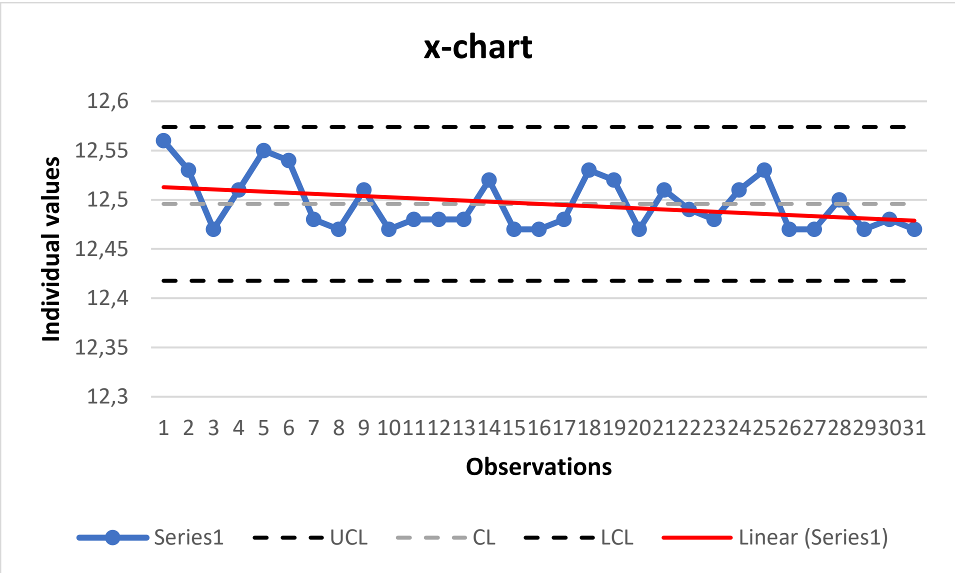

Figure 4.23 – Sample 2, measurement 1 x-chart excluding outlier (obs.7)

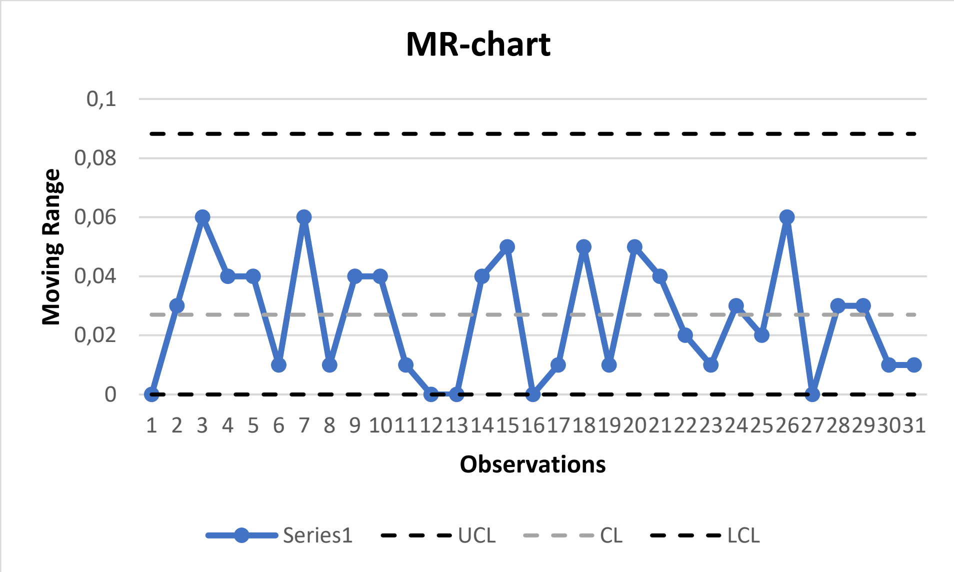

Figure 4.24 – Sample 2, measurement 1 MR-chart excluding outlier (obs.7)

Since there are no outliers anymore, the turning points test can be performed in order to verify the presence of a normal distribution. The x-chart presents 14 turning points.

By using formulas *(4.11)* and *(4.12)*, the values μ_{tp} = 19,33 and σ_{tp} = 2,28 have been obtained and put into the formula *(4.13)* obtaining the new interval:

$$\begin{cases} \text{UCIL} = 23{,}798 \\ \text{LCIL} = 14{,}869 \end{cases}$$

Since t_p is not included in the interval, the sequence does not follow a normal distribution, i.e., it is not random, and the t-test cannot be performed.

- ***Measurement 2***: the smaller diameter of the unit section must theoretically be μ=18mm. The following *Table (4.10)* shows the data collected by the operators with the support of a caliber and the consequent moving range:

Table 4.10 – Sample 2, measurement 2 data and MR

n	*Measurement*	*Moving Range (MR)*	*t_p*
1	17,99	-	-
2	18,02	0,03	0
3	18,02	0	0
4	18,03	0,01	1
5	18,02	0,01	1
6	18,06	0,04	1
7	18,02	0,04	1
8	18,03	0,01	1
9	18,02	0,01	0
10	18,02	0	0
11	18,02	0	0
12	17,98	0,04	1

13	18,03	0,05	0
14	18,06	0,03	1
15	18,03	0,03	0
16	18,03	0	0
17	18,04	0,01	1
18	18,03	0,01	0
19	18	0,03	1
20	18,03	0,03	1
21	18,02	0,01	1
22	18,03	0,01	1
23	18	0,03	1
24	18,07	0,07	1
25	18	0,07	1
26	18,02	0,02	0
27	18,02	0	0
28	17,97	0,05	1
29	18,01	0,04	1
30	17,97	0,04	1
31	18,03	0,06	1
32	18,01	0,02	-
Avg	18,020	0,026	*Tot* 19

According to equations *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.25 - 4.26* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 18{,}088 \\ CL_x = 18{,}020 \\ LCL_x = 17{,}951 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}084 \\ CL_{MR} = 0{,}026 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1$; being these values equal, we start to assume that the process is centered, i.e., it is accurate and precise.

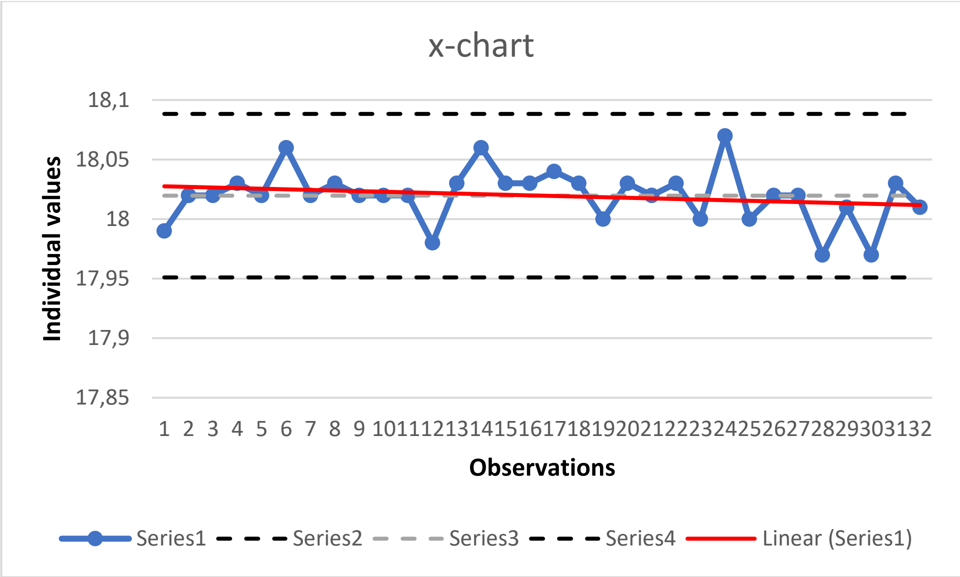

Figure 4.25 – Sample 2, measurement 2 x-chart

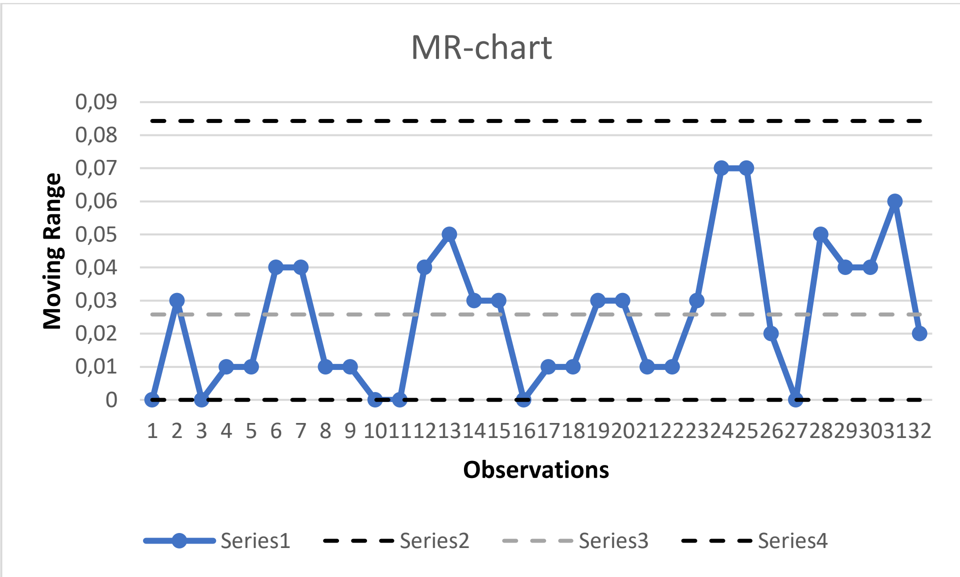

Figure 4.26 – Sample 2, measurement 2 MR-chart

The x-chart evidences the presence of a slight downward trend, indicated by the red line. Since there are no outliers, Kendall's test can be performed to verify the feasibility of the t-test.

It is possible to count 19 turning points. By using formulas *(4.11)* and *(4.12)*, the values $\mu_{tp} = 20$ and $\sigma_{tp} = 2{,}32$ have been obtained and put into the formula *(4.13)* obtaining:

$$\begin{cases} \text{UCIL} = 24{,}54 \\ \text{LCIL} = 15{,}46 \end{cases}$$

Being t_p included into the interval, the sequence follows a normal distribution, i.e., it is random. So, the t-test is performed.

According to the equations *(4.15)* and *(4.14)*, $s_{\bar{x}} = 0{,}41$ and $t = 0{,}048$. The critical value has been obtained by consulting the table for the t-distribution *(Fig. 4.4)* with a value of $t_{0,05;31} \approx 1{,}697$[13]. So, the null hypothesis H_0 must be rejected, and it must be declared that the actual average of the population *($t_{0,05;31}$)* is statistically different from the theoretical one *(t)*, i.e., the difference between the two averages is *statistically significant*.

- ***Measurement 3***: the larger diameter of the unit section must theoretically be 19,88mm. *Table 4.11* shows the data collected by the operators with the support of a caliber and the consequent moving range:

Table 4.11 – Sample 2, measurement 3 data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	19,96	-	-
2	19,9	0,06	1
3	19,92	0,02	0
4	19,96	0,04	1
5	19,92	0,04	1
6	19,93	0,01	1
7	19,9	0,03	1
8	19,96	0,06	1
9	19,93	0,03	0
10	19,93	0	0
11	19,92	0,01	0
12	19,87	0,05	0
13	19,85	0,02	0
14	19,8	0,05	1
15	19,85	0,05	0
16	19,87	0,02	1
17	19,85	0,02	1
18	19,87	0,02	1
19	19,85	0,02	1
20	19,9	0,05	1
21	19,88	0,02	0
22	19,87	0,01	0
23	19,87	0	0
24	19,83	0,04	1
25	19,85	0,02	0
26	19,88	0,03	1
27	19,85	0,03	0
28	19,8	0,05	1
29	19,82	0,02	0
30	19,88	0,06	1

[13] Since the exact value for $t_{0,05;31}$ *is not present in the table, I approximate it with the nearest value corresponding to* $t_{0,05;30}$.

31	19,85	0,03	1
32	19,87	0,02	-
Avg	19,881	0,030	*Tot* 17

According to *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.27 - 4.28* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 19{,}961 \\ CL_x = 19{,}881 \\ LCL_x = 19{,}801 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}098 \\ CL_{MR} = 0{,}003 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1$; being these values equal, we start to assume that the process is centered, i.e., it is accurate and precise.

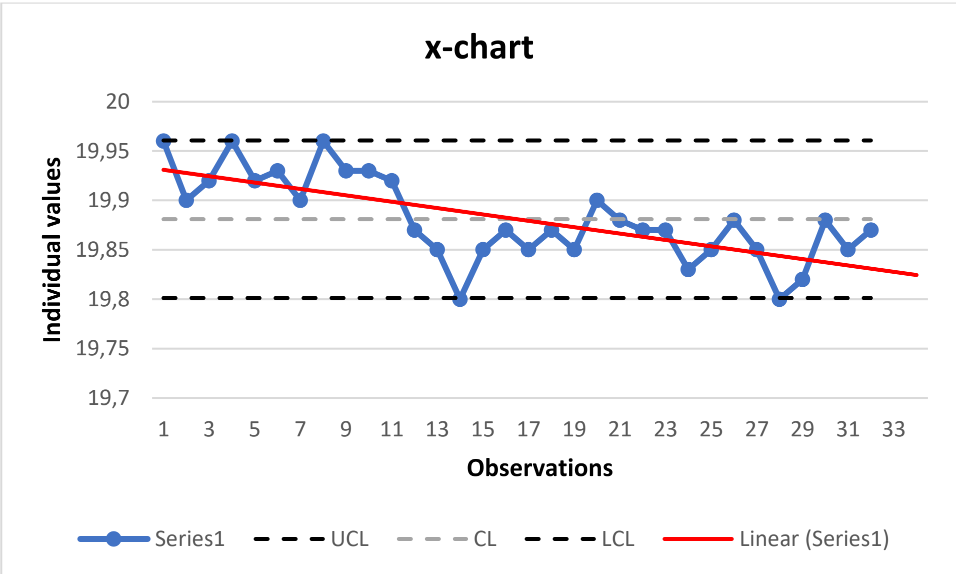

Figure 4.27 – Sample 2, measurement 3 x-chart

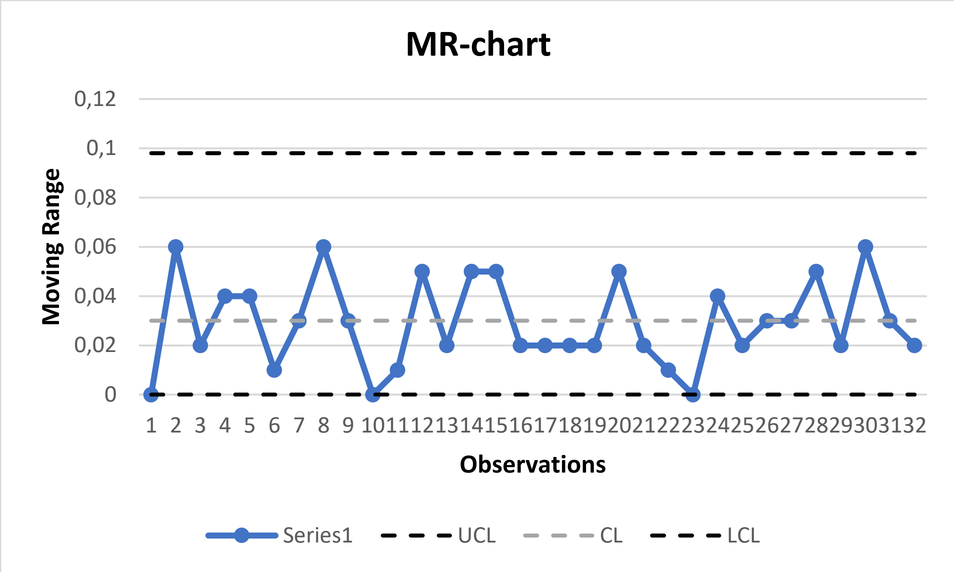

Figure 4.28 – Sample 2, measurement 3 MR-chart

The x-chart evidences the presence of a downward trend, indicated by the red line. Since there are no outliers, Kendall's test can be performed to verify the feasibility of the t-test.

There are 17 turning points, and using formulas *(4.11)* and *(4.12)*, the values $\mu_{tp} = 20$ and $\sigma_{tp} = 2{,}32$ have been obtained and put into the formula *(4.13)* obtaining:

$$\begin{cases} \text{UCIL} = 24{,}54 \\ \text{LCIL} = 15{,}46 \end{cases}$$

Being t_p included into the interval, the sequence follows a normal distribution, i.e., it is random. The performance of the t-test is now allowed.

According to the formulas *(4.15)* and *(4.14)*, $s_{\bar{x}} = 0{,}41$ and $t = 0{,}0023$. The critical value has been obtained by consulting the table for the t-distribution *(Fig. 4.4)* with a value of $t_{0,05;31} \approx 1{,}697$. So, the null hypothesis H_0 must be rejected, and it must be declared that the actual average of the population *($t_{0,05;31}$)* is once again *statistically different* from the theoretical one *(t)*.

- ***Measurement 4***: the through-hold diameter of the cross-section of the unit must theoretically be 6,8mm. The following *Table (4.12)* shows the data collected by the operators with the support of a caliber and the consequent moving range:

Table 4.12 – Sample 2, measurement 4 data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	6,1	-	-
2	6,1	0	0
3	6,1	0	0
4	6,1	0	0

5	6,1	0	0
6	6,07	0,03	0
7	6,07	0	0
8	6,1	0,03	1
9	6,09	0,01	1
10	6,1	0,01	0
11	6,1	0	0
12	6,07	0,03	0
13	6,07	0	0
14	6,1	0,03	1
15	6,09	0,01	0
16	6,05	0,04	1
17	6,06	0,01	0
18	6,08	0,02	0
19	6,1	0,02	1
20	6,07	0,03	1
21	6,09	0,02	1
22	6,08	0,01	0
23	6,05	0,03	0
24	6	0,05	1
25	6,06	0,06	0
26	6,1	0,04	1
27	6,06	0,04	1
28	6,08	0,02	1
29	6,07	0,01	0
30	6,05	0,02	0
31	6,05	0	0
32	6,1	0,05	-
Avg	6,078	0,020	*Tot* 11

According to *(4.3)* and *(4.5)* the limits have been calculated; *Figures 4.29 - 4.30* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} \text{UCL}_x = 6{,}132 \\ \text{CL}_x = 6{,}078 \\ \text{LCL}_x = 6{,}025 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} \text{UCL}_{MR} = 0{,}065 \\ \text{CL}_{MR} = 0{,}020 \\ \text{LCL}_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1$; being these values equal, we start to assume that the process is centered, i.e., it is accurate and precise.

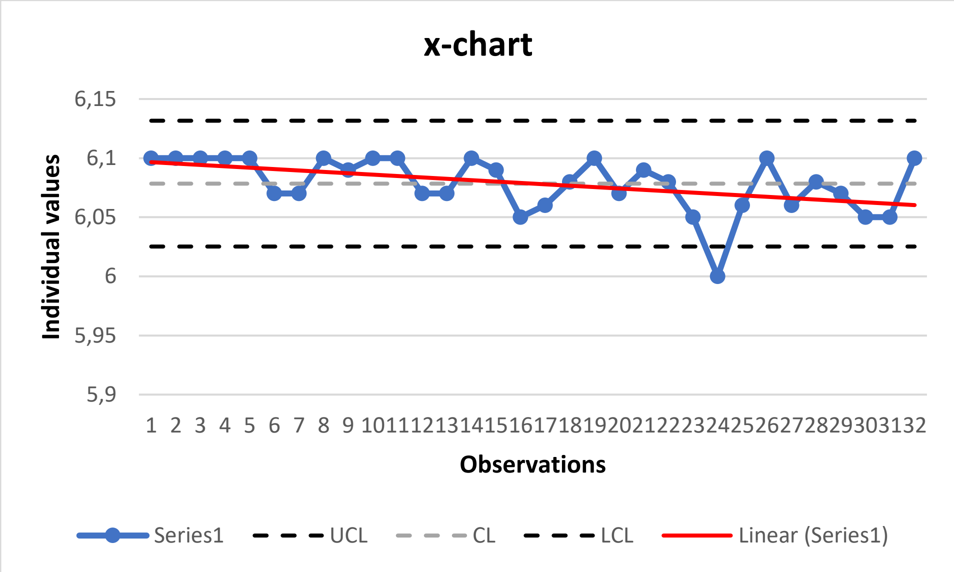

Figure 4.29 – Sample 2, measurement 4 x-chart

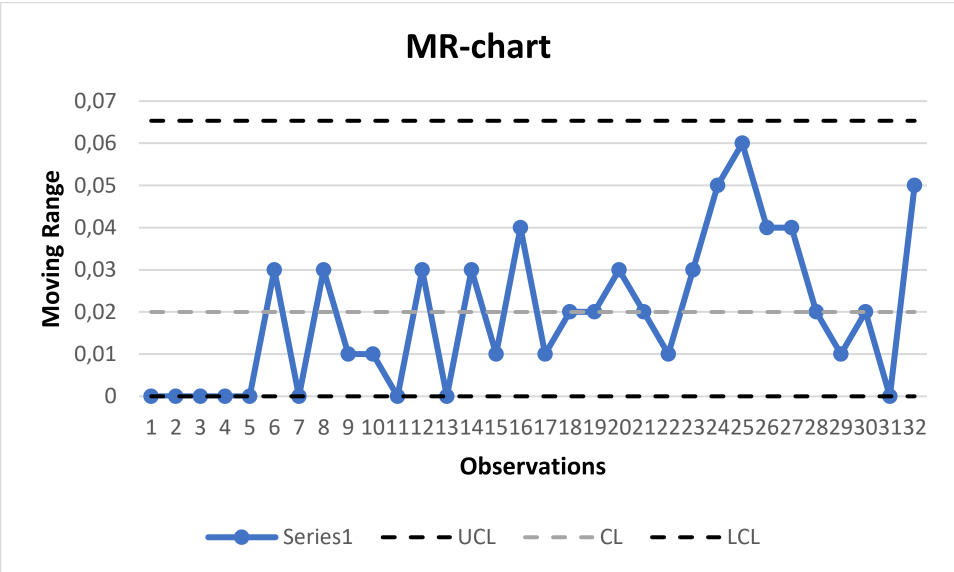

Figure 4.30 – Sample 2, measurement 4 MR-chart

The x-chart evidences the presence of a downward trend, indicated by the red line, and it also presents an outlier. The presence of the latter does not allow to perform the t-test.

The removal of observation n.24 and repetition of the same procedure on the remaining 31 observations is done. *Table 4.13* shows the updated data:

Table 4.13 – Sample 2, measurement 4 updated data and MR

n	*Measurement*	*Moving Range (MR)*	t_p
1	6,1	-	-
2	6,1	0	0
3	6,1	0	0
4	6,1	0	0
5	6,1	0	0

6	6,07	0,03	0
7	6,07	0	0
8	6,1	0,03	1
9	6,09	0,01	1
10	6,1	0,01	0
11	6,1	0	0
12	6,07	0,03	0
13	6,07	0	0
14	6,1	0,03	1
15	6,09	0,01	0
16	6,05	0,04	1
17	6,06	0,01	0
18	6,08	0,02	0
19	6,1	0,02	1
20	6,07	0,03	1
21	6,09	0,02	1
22	6,08	0,01	0
23	6,05	0,03	1
24	6,06	0,01	0
25	6,1	0,04	1
26	6,06	0,04	1
27	6,08	0,02	1
28	6,07	0,01	0
29	6,05	0,02	0
30	6,05	0	0
31	6,1	0,05	-
Avg	6,081	0,0173	*Tot* 11

According to *(4.3)* and *(4.5)* the limits have remained the same as before; *Figures 4.31 – 4.32* show the x-chart and MR-chart obtained with these data.

$$\bar{x} - \text{chart} \begin{cases} UCL_x = 6{,}134 \\ CL_x = 6{,}081 \\ LCL_x = 6{,}028 \end{cases}$$

$$\overline{MR} - \text{chart} \begin{cases} UCL_{MR} = 0{,}057 \\ CL_{MR} = 0{,}017 \\ LCL_{MR} = 0 \end{cases}$$

$C_p = C_{pk} = 1{,}15$; being these values equal, we start to assume that the process is centered, i.e., it is accurate and precise.

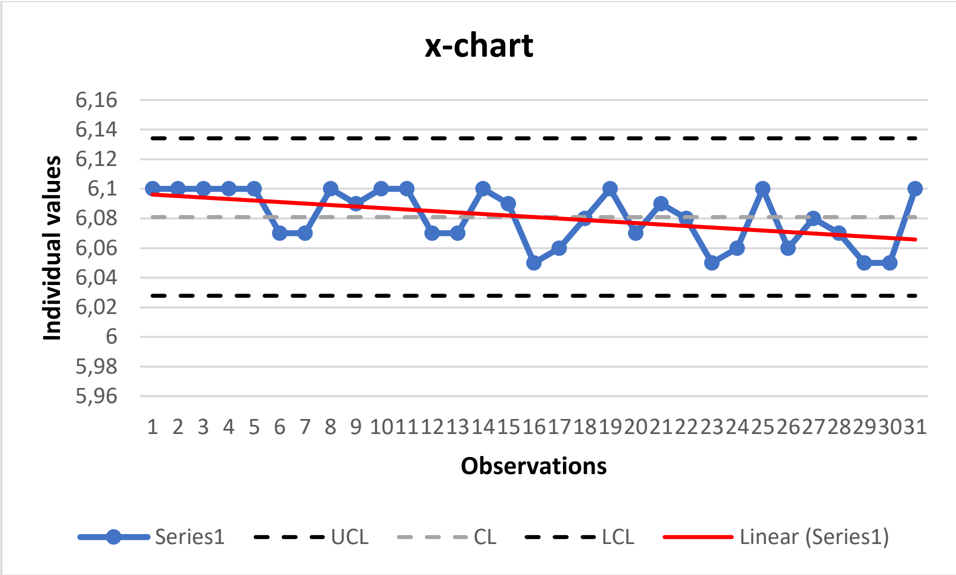

Figure 4.31 – Sample 2, measurement 4 x-chart excluding outlier (obs.24)

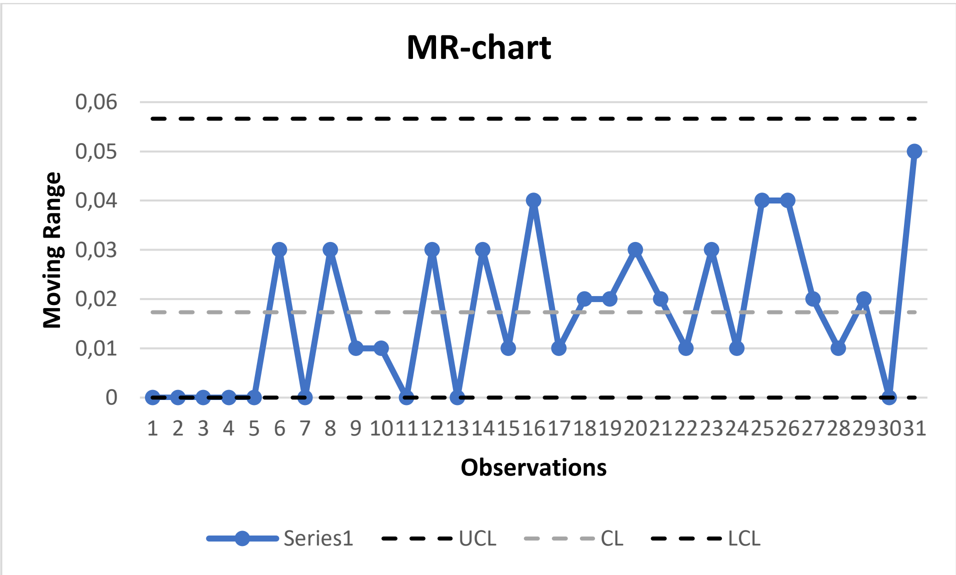

Figure 4.32 – Sample 2, measurement 4 MR-chart excluding outlier (obs.24)

The x-chart goes on indicating the presence of a downward trend, indicated by the red line. Since there are no more outliers, Kendall's test can be performed to verify the feasibility of the t-test.

A number of 11 turning points are counted. By using formulas *(4.11)* and *(4.12)*, the values $\mu_{tp} = 19{,}33$ and $\sigma_{tp} = 2{,}28$ have been obtained and put into the formula *(4.13)* obtaining:

$$\begin{cases} \text{UCIL} = 23{,}80 \\ \text{LCIL} = 14{,}87 \end{cases}$$

Being t_p not included into the interval, the sequence does not follow a normal distribution, i.e., it is not random. The performance of the t-test is not allowed.

4.4. *Results obtained*

Digitization gives several advantages regarding both measurement and analysis operations: they can be schematized as follows.

1. Automation of analysis process.
2. Reduction of time for analysis, e.g., there is no need for any transcription from paper to excel.
3. The software will provide all the analysis and conclusions without the presence of a qualified operator that interprets data and makes analysis on it.
4. Future implementations: thanks to machine learning and other technologies, it is possible to find more and more accurate solutions to complex problems taking into consideration a high number of variables coming from both machines and people.

In addition, control charts and statistical tests have given particular results: in most of the cases the measurements did not follow a normal distribution, i.e. they were not following a random pattern. In others, this feature was satisfied, but the t-tests always gave the result of statistically significant difference between the theoretical and the actual values. It means that obviously theory and real cases are not the same, considering all the potential events that may happen.

It is important to analyze the data in a chronological order, as it is the only way to study real performance of the process, and consequently understand whether the variability of the measurements is due to *casual factor*s, i.e., the process is under statistical control, or to *specific factors*, i.e., the process is out of statistical control. The x-charts are useful since the trend of the linear regression line can tell something.

Three situations can be faced during the analysis:

1. There is a process drift towards a control limit (upper or lower). It may be due to rapid tool wear, inaccuracy of the axis, motion components wear, etc.
2. The process is quite stable around the mean value (central limit), but the latter is upper or lower than the nominal value. Some possible causes may be imperfect resetting of the machine, tool wear, motion components wear, etc.
3. A combination of both. It is possible that, at the beginning of the process, a drift is verified and after a certain time the process and measurements are stabilized; this usually occurs when, at the beginning of the process, the spindle is not warm enough. In this case, the spindle warms up during the machining causing its extension, that leads to inaccuracies during the first working phase. When the right temperature is achieved, measures stabilize.

A more detailed analysis can be done with a cause-effect logic:

- Effect: *error due to materials*
  Causes: defective from supplier, primer type and viscosity, damage in handling, eventual paint viscosity, etc.
- Effect: *error due to machine*
  Causes: worn tool, wrong tool, too much play, too high temperature or humidity, presence of dust, surface finish, lack of electricity etc.
- Effect: *error due to methods*
  Causes: wrong work sequence, wrong planning, errors in materials handling, etc.
- Effect: *error due to measurements*
  Causes: incorrect specifications, faulty gauge (caliber, micrometer, etc.), unclear specifications, etc.
- Effect: *error due to personnel*
  Causes: poor attitude, insufficient training, inadequate supervision, pressure to reduce processing time, etc. [63]

Some of the features described above may be the root causes of the fluctuations observed in the previous paragraph. For example, the x-charts of measurements 1 and 4 of the first sample seem to have a quite flat trend *(Figs. 4.6 and 4.18)*. In fact, the number of turning points shows that they follow a normal distribution.

It is also evident in measurements 2 and 3 of the same sample where, in addition to outliers' presence, the trend is more pronounced. In the second one *(Fig 4.8)*, it is clear that most of the last points are below the central limit, and the trend does not change even removing the outlier *(Fig. 4.10)*. In the third one *(Fig. 4.12)*, there is a symmetric situation, since most of the last points are above the central limit and, as before, the trend remains unaffected also with the removal of the outliers. As expected, both of them do not follow a normal distribution since their x-charts do not present a sufficient number of turning points.

Regarding sample 2, measurements 2 and 3 follow a normal distribution. In particular, the second one *(Fig. 4.25)* presents a quite flat trend following the central line in the x-chart; the third measurement has instead a significant decreasing trend *(Fig. 4.27)*; however, the number of turning points is enough to consider its points distribution as normal. Moving to measurements 1 and 4, it is possible to say that their x-charts before *(Figs. 4.21 and 4.29)* and after *(Figs. 4.23 and 4.31)* the removal of outliers present a downward trend and a number of turning points quite high but not enough to be considered as normal distributions.

Analyzing the data of measurements, it has been possible to notice that distributions do not often follow the normal distribution. Moreover, of all the measurements verified to be normally distributed, none of them has satisfied the null hypothesis of the one sample t-test, i.e., the difference between the theoretical and the actual observations is statistically significant. This means that finding the possible causes of the drifts to avoid errors during the production process is necessary.

First of all, it must be considered that every measurement has been performed in summer season[14]; the first sample in a range of time of a week (23rd – 29th of August 2023), the second one in about two months (27th of June – 21st of August 2023). The high temperatures, but also sudden temperature changes and the hour of the day, may have affected the materials and the tools. *Table 4.14* reports the temperatures transcribed by the operators for each observation of every measurement of the samples 1 and 2 respectively:

Table 4.14 – Temperature recorded during each observation

Sample 1		**Sample 2**	
Observation	*Temperature (°C)*	*Observation*	*Temperature (°C)*
1	32	*1*	35
2	35	*2*	35
3	36	*3*	35
4	36	*4*	35
5	33	*5*	35
6	34	*6*	35
7	36	*7*	35
8	36	*8*	35
9	33	*9*	35
10	34	*10*	33
11	36	*11*	36
12	36	*12*	33
13	30	*13*	33
14	31	*14*	34
15	30	*15*	35
16	30	*16*	37
17	27	*17*	38
18	27	*18*	38
19	27	*19*	38
20	28	*20*	38
21	28	*21*	38
		22	38
		23	38
		24	38
		25	38

[14] This information is written by the operators that took the measures of each sample on the control boards.

26	38
27	38
28	38
29	38
30	38
31	38

The very high temperature recorded during the last observations for each measurement of sample 2 can explain the decrease of the trend.

Regarding the state of wear of the tools and machineries, it should be remained unchanged during the single week of measurements for the sample 1; sample 2, instead, may have been affected by tools and machines wear since in two months several process may have been worked.

In addition, other environmental factors may have affected the processes, like pressure, humidity, vibrations due to other machineries, electromagnetic fields, etc.

Last, human errors and change of the operator cannot be excluded, followed by the imprecision of the measurement tools, caliber in this case.

4.5. OCAP generation

Since the presence of process drifts has been verified, the next step consists into giving suggestions that improve the production process choosing the best corrective actions to bring the process in control and at the same time enhance production, marginality and assets of the company. An example of an Out-of-Control Action Plan is presented in the subsequent flowchart *(Figure 4.33)*. Obviously, each situation and production type will have its customized OCAP, e.g., in case of a spray-printed unit, there will be decisions (questions, the ones in the rhombus) about paint and surface. The subsequent is about a generic situation where for each decision contained in the red rhombus, there are two possible ways: if the problem is not the one indicated, the operator must move to the next one until he finds it; when it happens, the operator must execute the operation written in the process indicated (orange rectangle). This goes on until all the requirements have been verified and the problem comes out; then the suggestion is to reset and re-enter the data.

The next chapter will present how the study aims to automate all the steps faced above and what are the innovations proposed.

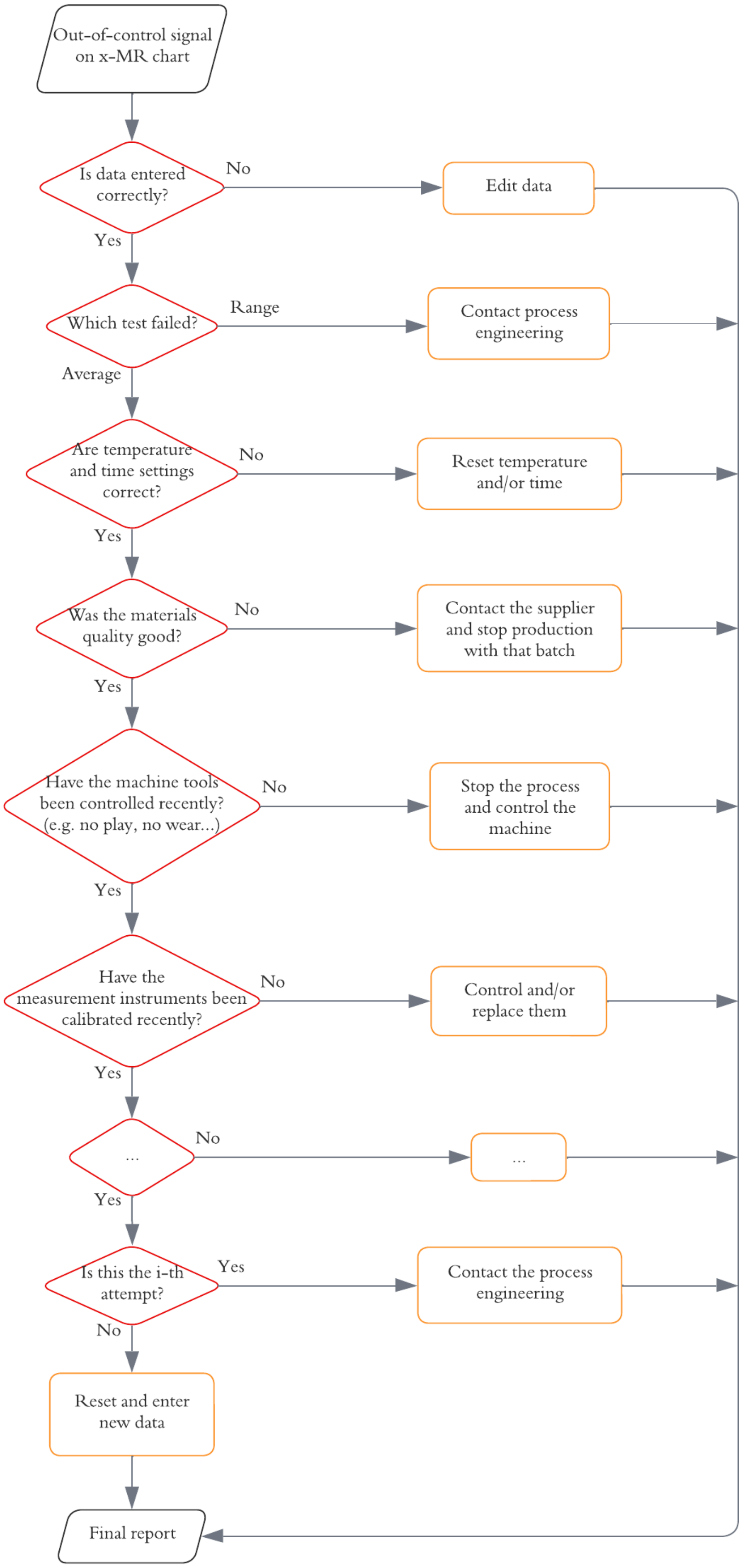

Figure 4.33 – Example of flow chart as an OCAP

5. *Discussion*

Planoplast production seemed to be compliant with the requirements, but the study and the calculations performed showed that some trends came out. This means that the process drifts would have brought the production out of control, and highlights that preventive controls are necessary to avoid waste and errors.

Up to now, theoretical rules have been used to make statistical calculations to find out-of-control processes. It is important to analyze the step between the theoretical part and the implementation, i.e., the switch from the known rule to the development of an algorithm that automates the mechanism. In particular, the study aims to find algorithms to automate and implement collection of measurements, calculations, control charts, OCAP, making them "smart" in the 4.0 paradigm. Anyway, before talking about algorithms, the digitization of quality control methods must be analyzed; it consists in the utilization of machines or in the support of manual inspections with digital devices.

5.1. Measuring Machines

Coordinate Measuring Machines, also called CMM and represented as example in *Figure 5.1*, have an important role in the quality control field: they represent a fully 4.0 integrated system, since they have a high measurement accuracy thanks to mechanical or optical equipment. They provide benefits like speed increase and reduction of human errors. Their role is reproducing the real 3D model on the computer, so that its dimensions can be compared with the designed one. There are different types of CMM: in the case of 3-axis scan by contact inspection, 3D controls are executed with a measuring probe (a sensor) that reports the coordinates' position (x, y, z) of the object's surface once they are in contact. Despite this, since they move on 3 axes, they are quite rigid systems.

Figure 5.1 – CMM (source: https://shop.mitutoyo.it/ [65])

Other tools using 3-axis scan mechanisms are scanning probes. Scan is a fast way to acquire data about measurements and shape of the product. Unlike contact inspection, which acquire single points, scan inspection collects several points on the surface generating a more complete and accurate image of the object's shape. Even if the scanning probe is in contact with the surface, the technology to measure the probe's deflection is completely different respect to the previous case; now, in fact, it must be correlated to the machine position to obtain the surface position, i.e., an accurate and fast scan.

In addition, 5-axis measurement systems also exist. They are more flexible, with a wider range of movements, and move continuously without the necessity to detach from the surface. The accuracy of these CMM is due to an articulated probe that during the measurement moves to two rotary axes; meanwhile, the machine shifts to one direction with constant speed. As the probe is lightweight and dynamic, it traces rapidly the geometry changes of the object, without the introduction of dynamic errors. This significantly decreases the measurement time. [66 - 68]

Another very accurate technology is offered by laser scan. Unlike the previous solutions, it is not based on contact with the surface, and it is specialized in complex products inspection. This type of machine consists of a laser source, an optic module, and a control device. The first sends a focused beam of energy on the surface, the second converts the latter into an electrical impulse, and this is processed by the control device. The laser takes measurements of the dimensions and geometry of the object and verifies the eventual presence of structural properties like irregular geometries or dimensional variations respect to the theoretical ones. They assure a high level of accuracy and accelerate the process. [69]

Then, Machine Vision Systems, MVS (*Figure 5.2*), are used to perform visual inspections with the support of one or more cameras, PC and usually a controlled lighting and closed environment. 1D and 2D MVS are able to take measurements, to inspect surface and depth, perform thermal inspection, etc. Instead, 3D MVS are specialized in the extraction of geometrical information by the measurements of the object's image; the features are then compared to the 3D model to find eventual non-conformities or mismatches. This type of control guarantees a constant and very fast performance, more than an operator could do. [71 - 72]

Figure 5.2 – MVS detail (source: https://www.sick.com/ [70])

More generally, Geometrical Measuring Systems (GMS), which include manual and automatic gauging systems for dimensional tasks, and coordinate, form and surface texture measuring systems, provide information for data transfer via a uniform interface that can be used by digital data processing systems such as MES systems. This technology is considered as the "information supplier" on the quality of production, since it interacts with production systems through digitization via OPC UA Companion Specification for GMS, that aims to provide a unique interface for communication partners from different manufacturers to allow for interoperability. [73 – 74]

The topic of quality control in phase or during the phase, explained in the previous chapters, can be applied also to machines. In fact, depending on several variables like work phases, rigidity of the process, stations, functionalities, etc., it is possible to apply both cases. Quality control during the phase may be a solution allowing to understand if there is any problem before the process ends, while quality control phase is a dedicated phase, with an assigned workstation, performed once the previous process has finished.

Anyway, it must be said that controls executed by machines are related to larger firms, namely to a limited number of companies. In fact, most of the firms use manual inspections done by operators on board machines. Sometimes, it is possible to find hybrid systems with machines taking some measurements and operators taking others.

5.2. Manual measurements

Manual measurements, which represent most of the Italian enterprises' way of quality control performance and are suitable for great variability of products, and low-medium volumes, are more complex to manage, since the main objective of the digitization is simplifying the process to make it available to everyone, even to operators unskilled in quality control. The latter will be guided by clear and intuitive instructions, in order to reduce response time and human errors. Obviously, the calibration of measuring instruments and their conditions must be verified.

The following flow chart *(Figure 5.3)* represents the development of the quality control algorithm, where the red rhombus are the decisions, the orange rectangles represent the processes, and the grey lines regard the internal flows, stating inputs and outputs. It highlights the next step to take for each possible situation, in particular it can be translated as: once the raw material has arrived, it is used as an input to perform the process; it gives products (units) as output, which are the input to make quality checks. From this, data is obtained, and control charts are released. It is important to pay attention to the difference between tolerance and control limits: the first strictly regards the physical tolerance limits of the process, while the other is about the limits over which the distribution of points should not go.

If the tolerance is respected, the product is compliant and the algorithm can stop; otherwise, the process is out-of-control and suggestions to solve the problem are given with an OCAP.

Moving to control limits, it is necessary to understand whether the points are included in the limits; if yes, Kendall's normality test can be performed, otherwise the process is again out-of-control and, as before, an OCAP is provided. In the case of normal distribution, the one sample t-test is performed; if not, a possible systematic factor related to the process may be present, e.g., it may be due to repeated actions that always generate the same result, and again suggestions are given. Last, performing the t-test, if it is successful, the product is compliant and the algorithm stops; otherwise, the process is out-of-control and the OCAP is generated.

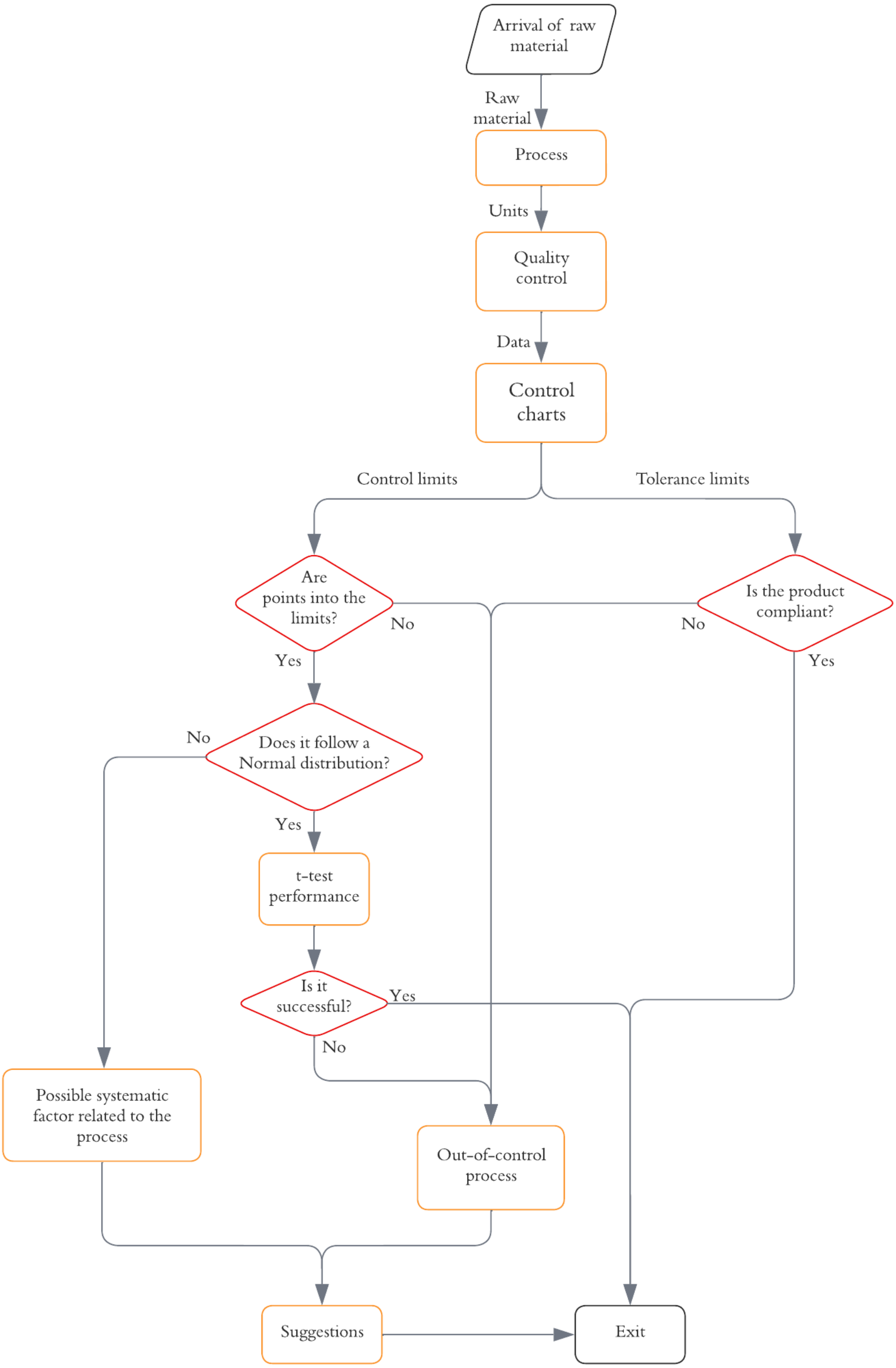

Figure 5.3 – Quality control algorithm flow chart

5.2.1. Development of the user interface

All of this information is displayed on the user interface, which has been developed following the CRUD (create, read, update and delete) principles. The implementation of the quality management involves three different sections of the software:

Production order tab is the first window that the display presents in the MiniMES' Quality Control section is the Production Order page (*Figure 5.4*): here, the office staff inputs or imports from external systems (ERP, MRP, etc.) all the information about a certain product ordered by customers, starting from its name (Part of the carriage)[15] and code (AC10132), the quantity ordered by the customer (1000 units), selecting the unit of measurement (pieces, kilograms, square meters, etc.), and the date and time of picking/delivery (09/04/2023 at 10:00 am). Then, the dimensions of the product and the different work phases, identified by the sequence (indicated as 1, 2, 3 in the screenshot), can be inserted.

For each sequence, it is possible to define the processing type (milling, cutting, turning, etc.), the pieces multiplier, which is used by machines that can produce more than one unit in a single process, and the number of cycles, that is the actual number of repetitions of a single step in the process; both are single in this case. After, the part program button is the place where the receipt, i.e., the information about the sequence of instructions to perform the process, is selected. Then, raw materials (such as PPE, PET, PA6, PEEK, etc.) and he must insert the cycle time of the phase on that machine (in the following example, 38 minutes for the milling phase) can be chosen too.

In the end the determination of the necessary Quality Checks has been added, containing relevant information for the operators that take measurements on board the machine. The office staff selects the file containing the drawing of the product (in this case "Sample1_Drawing.pdf") and all the data obtained from it. In particular, the type of physical dimension measurements (diameter, length, thickness, width, etc.), the code of the object's part measured, its nominal value and tolerance range. Once the data is inserted, it can be modified, approved or deleted.

The subsequent image represents how the interface appears on a tablet or PC.

[15] Data inserted in the screenshot of the Figure 5.2 regards the sample 1 analyzed in the Planoplast case study.

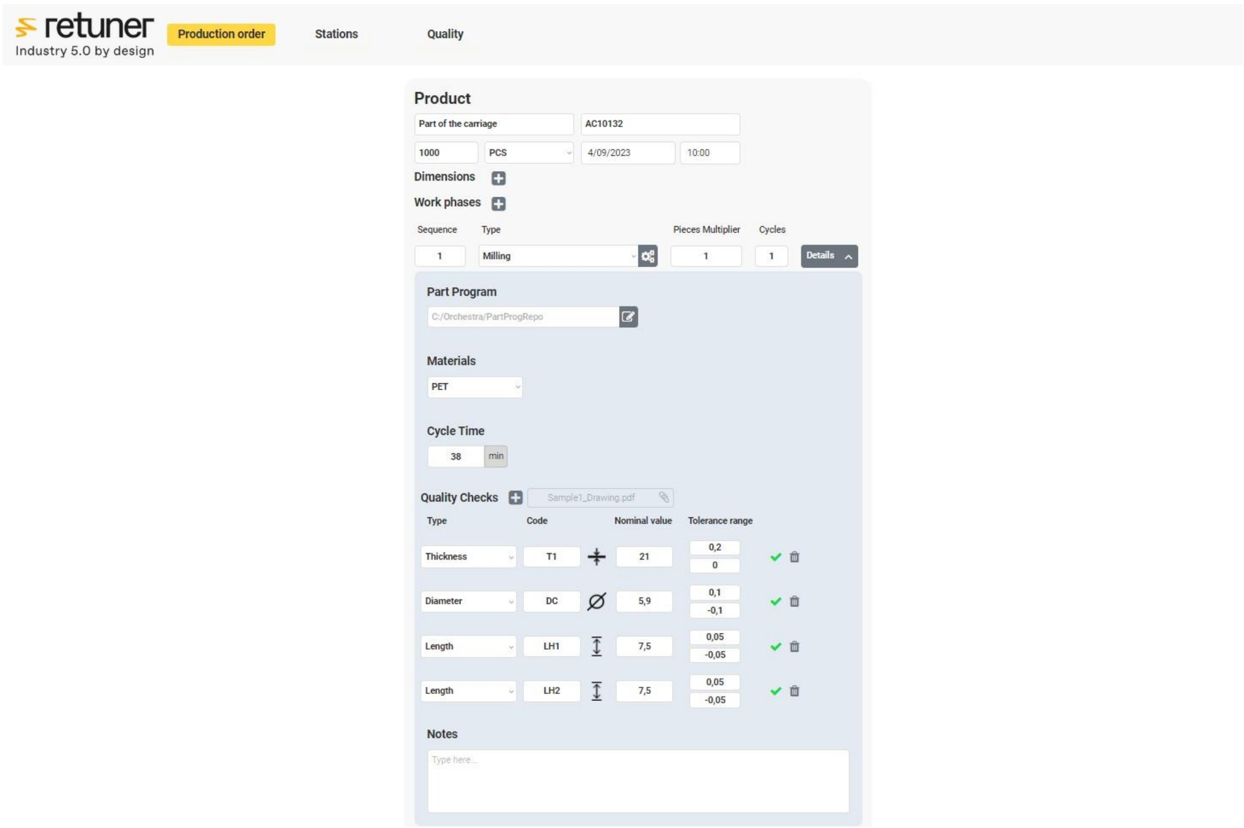

Figure 5.4 – MiniMES' Production order section

In the S*tations tab (Figure 5.5)* the highest part contains information about the machines, the processing code and the processing type; it is possible to insert process variables like the quantity produce until that moment, the number of the sample measured, the name of the operator, date, time, temperature taken during the measurements, etc.; the procedure is repeated for each observation and measurement.

The section relative to quality control measurements has been added and contains the technical drawing, uploaded in the previous section, on the left side (sample 1, reference to *Fig. 4.5*) and the information about each measurement on the right to be filled with the actual measurements taken by the operator. In particular, there are the nominal values, which has already been inserted previously, the blank spaces that must be completed with the measured value by the operator (in this example there is the first observation of each part measured), and the tool must be selected from the options listed (caliper in this case). Eventually, notes can be added, too.

Moreover, it is possible to implement the MiniMES Quality Control area with the insertion of temperature at which measurements have been taken, date, hour, etc.; the procedure is repeated for each observation and measurement.

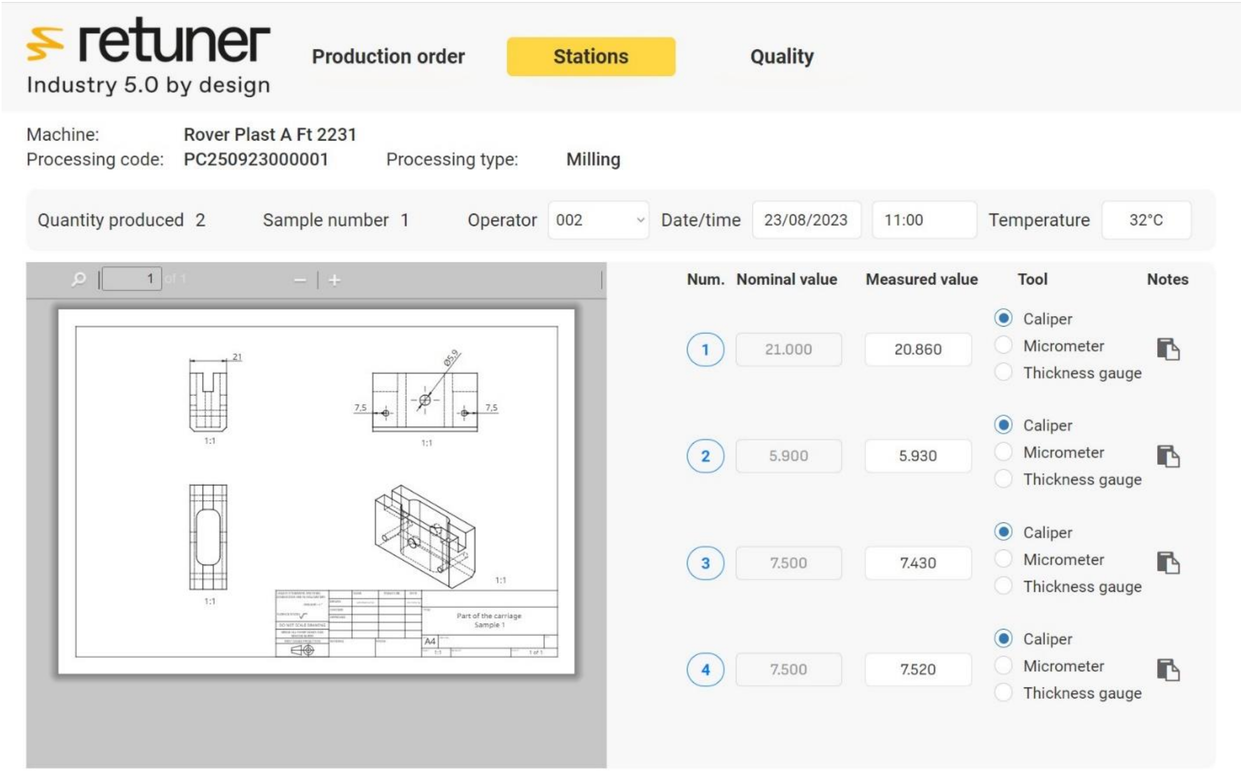

Figure 5.5 – MiniMES' Stations section

Finally, the *Quality tab* reports all the results regarding the entire production process with additional filters by time period, machine, production order, product. It is composed by three sections: in Overview tab it is possible to find a general view of the production performance, like the percentage of non-compliant units; the Process Analysis tab, shown in *Figure 5.6*, contains the details of analysis performed for each product, e.g., the screenshot shows the $\overline{x}$-chart of the thickness measurements of the product called "carriage", and it evidences that the process does not follow a normal distribution because one of the points is out of the control limits. This means that a systemic factor may have generated the presence of that outlier; it can also be stated in the case a trend is detected. Lastly, the OCAP tab contains suggestions on how to enhance the process with the support of data.

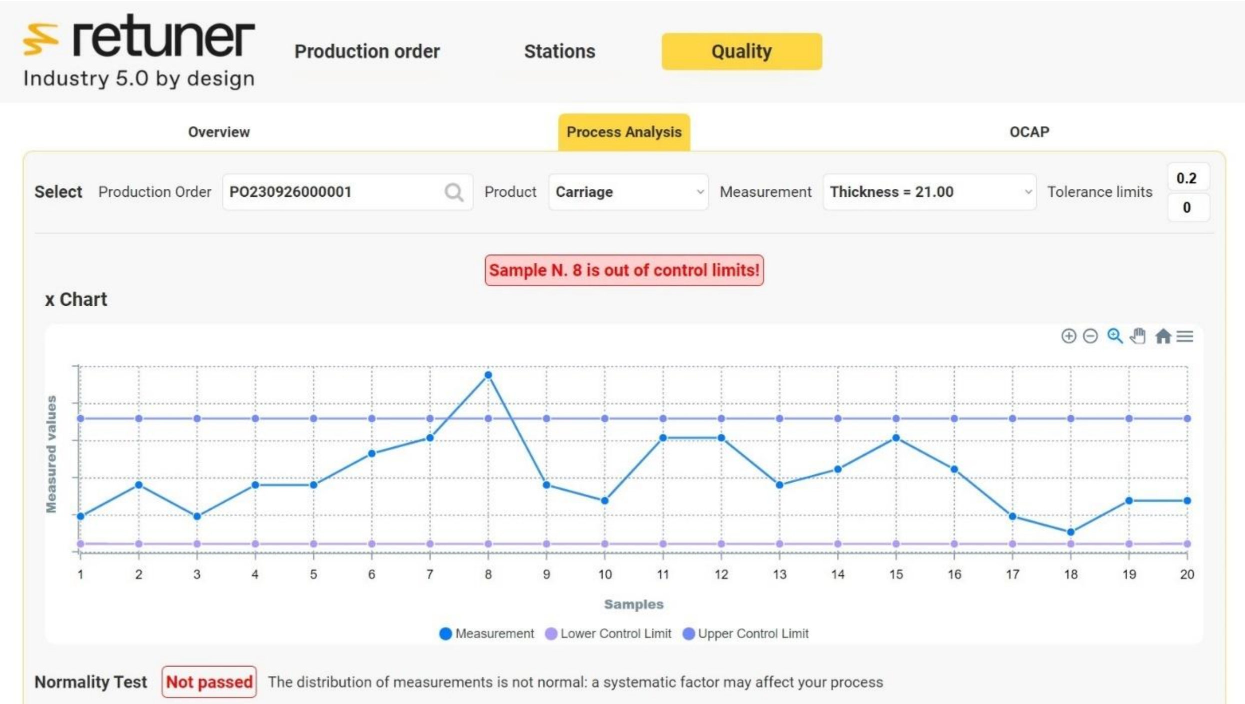

Figure 5.6 – MiniMES' Quality section

5.3. Innovations of the study

The thesis presents two important innovations that aim to improve the quality control field and simplify operators' work. The first is about the direct support to technicians, the other regards the shift from Industry 4.0 to 5.0.

5.3.1. Advantages

Innovations have a significant positive impact from both operating and management points of view.

Operators always have a constantly updated control checklist related to the process they are working on; it presents all the specifications and information about tolerance limits necessary to make the required controls.

Instead, the management counts several advantages thanks to the unification of data; they are:

1. The *complete tracking* of the production process that includes qualitative aspects of the production.
2. The *unification of the information collected and obtained*: what has been worked, how, what are the data known, what are the data collected, etc., i.e., an automated control check. When measurements are taken, the production process' state of health is generated

automatically. For example, in case of non-conformities, data collection helps the operators to detect the root causes of the error, with a complete overview of the facts.

3. The *automatic definition and generation of suggestions* with the aim of correcting the process to bring it back in control, based on the type of process drift detected.
4. MiniMES' presence that provides real-time information, so that the staff hired *does not need to be qualified or specialized* in quality control and it does not need dedicated software.

5.3.2. Shift to Industry 5.0

A detailed presentation of Industry 5.0 paradigm has been done in the previous chapters. It consists in the synergy between human and machine, and in this case quality control done by operators supported by AR devices.

The inclusion of digital solutions like smart glasses allows to improve quality control phase making it less time consuming and error-proof; in this concept, the operator can take advantage of the checklist of tasks to perform – e.g., what measurements to take – projected on the product, take measurements hands-free, i.e., without the use of tools such as paper and pen, except for measuring instruments, and to use voice input or a keyboard instead of writing down the measurement.

An example of innovative and digital quality control in Industry 5.0 perspective, is Orchestra's MiniMES' Web Application QuAR, where data is collected in the database and it is exchanged with the MiniMES through API, keeping the concept of universal knowledge of the information. This is possible thanks to the MiniMES' intrinsic characteristic of web application, which allows interactivity, exchange among components, communication, etc., and the real-time monitoring of one or more stations even in case the operator has moved away from machineries. [75]

5.3.3. MiniMES 5.0 QuAR

The WebApp developed is projected into the smart glasses lens with the interface shown in *Figure 5.7*. The Quality Control tab allows the operator to insert the measurements of each type of dimension (internal or external diameter, length, width, thickness, *(Figure 5.8)*, stating if it is compliant, not compliant or to be reworked into the "Visual inspection" section *(Figure 5.9)*. Also, the settings tool allows to set the language, the name of the machine and the connections between QuAR, SMARTHinge and MiniMES.

QuAR is also automatically parametrized by MiniMES for what regards the product, and consequently the number and type of quality checks that must be done by the operator on a specific machine.

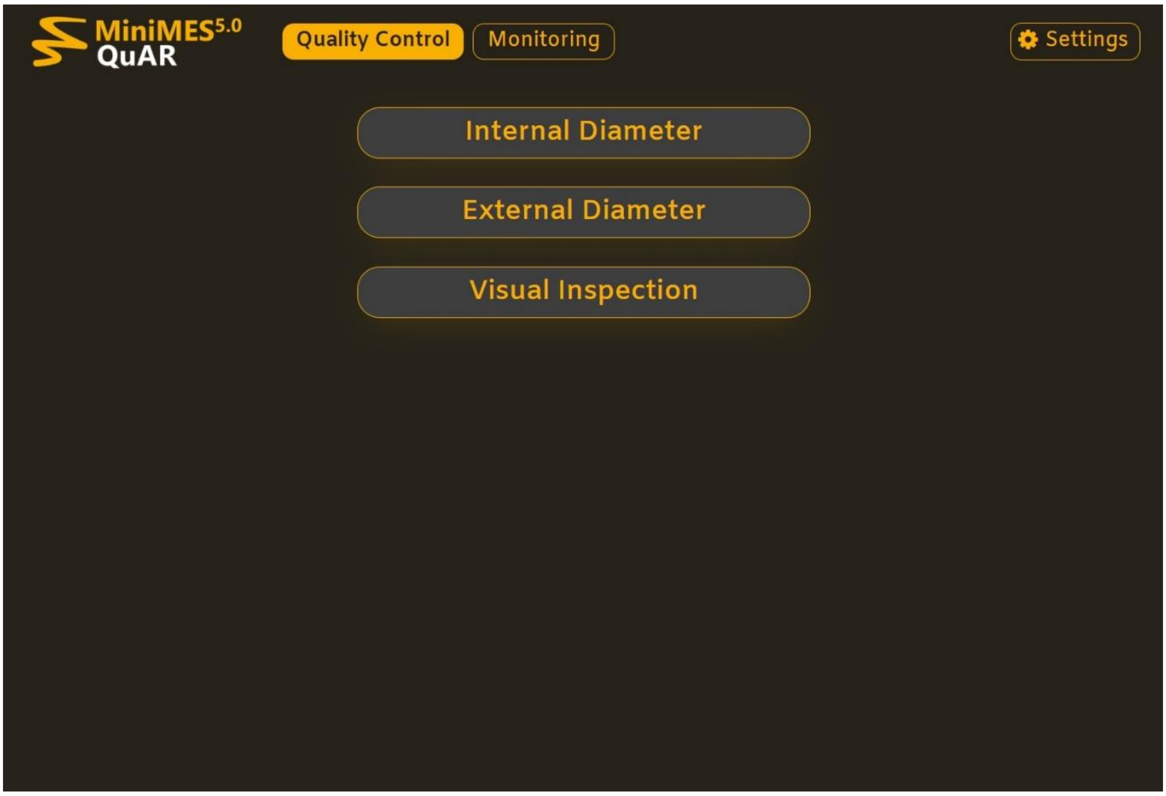

Figure 5.7 – MiniMES' QuAR Quality Control interface

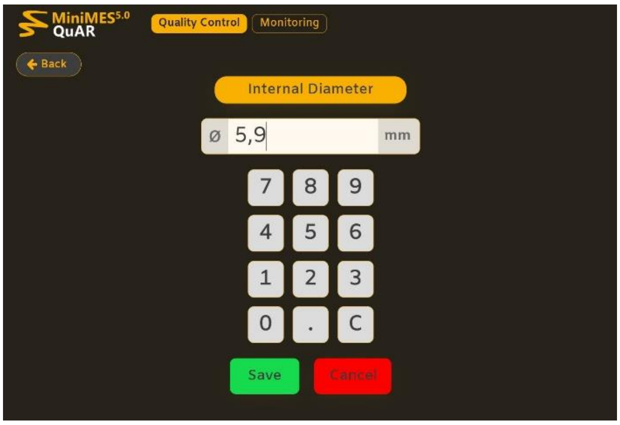

Figure 5.8 – Measurement inserting

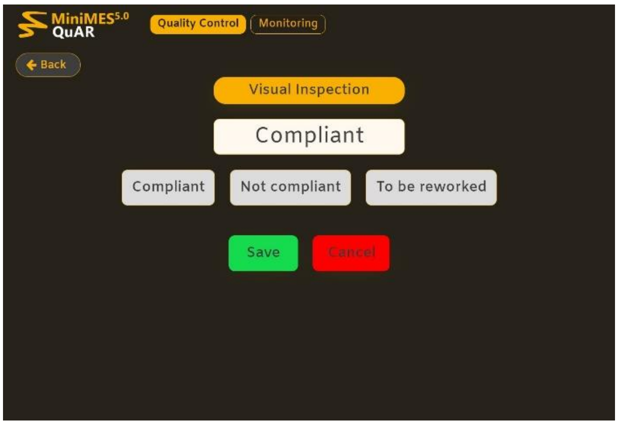

Figure 5.9 – Visual inspection

Selecting the monitoring tab, information about the name of the working machine (in this case iAXNR), the status of the machine (work, ready, hold, error, emergency, off), all the variables exchanged by the machine, in the example below the Peak Energy value of the accelerometers mounted on the axis, and the daily quantity produced are stated. *Figure 5.10* shows the interface of the page.

Figure 5.10 – MiniMES' QuAR Monitoring interface

This WebApp has positive consequences, like avoiding the use of paper, less waste of time and resources, lower downtime of the machine that increases the machine availability and consequently the efficiency, etc.

6. *Conclusion and future developments*

Quality control is an essential phase for manufacturing companies because it provides several benefits that enhance the firm's value. These include improvements in product quality, an increase in customers' loyalty and good reputation, resource-saving and a consequent reduction of waste. All these features contribute to the growth of the company's assets.

Recognizing the significance of quality, the project's goal was to enhance quality assurance in production processes. This was achieved by leveraging statistical methods and the paradigms of Industry 4.0 and 5.0. The primary objectives were to proactively detect process drifts to prevent the loss of statistical control within processes. In cases where this prevention wasn't feasible, the project aimed to identify process drifts promptly and initiate corrective actions as necessary.

First, calculations to perform control charts, Kendall's turning point test, one sample t-test, C_p and C_{pk} have been done; the results indicated that the production process exhibited certain trends influenced by specific factors. Therefore, it became necessary to develop an algorithm that could suggest the required actions to restore the process to statistical control.

Then, a user-friendly interface was developed to automate these tasks to accelerate the QA and to avoid human errors. Industry 4.0 paradigm has played a crucial role for what concerns digitization, allowing measuring machines to measure the products and collect and send the data quickly and efficiently. Nevertheless, Industry 5.0 is the main core of QA digitization, since SMEs organization is operator-centric; according to Industry 5.0 principles, operators can receive digital support from innovative technologies and devices that nowadays are spreading more and more, obtaining benefits such as time savings and mitigating the risks associated with transcription errors, paper document loss, and damage. To facilitate this transition, the entire workforce needs to be guided through a user-friendly and intuitive interface, eliminating the need to hire QA experts and providing step-by-step instructions for tasks execution.

The study underscored the importance of quality control as a forward-looking necessity. Even when the process appears to be under statistical control, it does not necessarily mean it is. The world is increasingly shifting towards eco-friendly production, and customers are becoming more and more conscious about environmental issues. Improving quality assurance is not only a means to conserve resources, but also a crucial aspect from a profit-oriented perspective. Companies, in fact, aim to increase their revenues, and the reduction of waste and all the other benefits already faced cannot be other than a positive asset.

Since the project has had a positive result, future implementations need to be developed.

6.1. Future developments

The first step as a future development will be, on the lower level, the improvement of the MiniMES Quality Control and MiniMES QuAR interfaces and functionalities.

On a higher level, the research shown up until now is just a part of the study; it will continue with improvements correlated with machine learning, deep learning and AI.

Machine learning is a branch of Artificial Intelligence. The latter is a framework that studies whether and how intelligent computer systems can emulate the skills and behavior of human thinking. ML focuses on collecting scientific and technical knowledge like ICT, statistics, *pattern recognition*, image processing, and many more, and generates algorithms to improve the performance facing complex tasks in an efficient and rapid way. DL, instead, is a subset of machine learning that uses artificial neural networks to simulate the learning process of human intelligence.

The introduction of ML in the project would consist in an increase in the number of variables to be handled and in the precision improvement of suggestions to enhance the process. This is made possible thanks to analysis of data coming from both machines and operators.

This type of techniques has already started to take hold in several sectors for quality control sphere: e.g., in consumer electronics it is used to identify defects in the glass like scratches, cracks, holes and bubbles causing problems of different entities; the identification process requires advanced imaging techniques to acquire, elaborate and segment the displays' images, and algorithms to extract relevant information and classify the problems. Also, the automotive sector is going to improve quality control with ML and DL: Audi will use it for metal parts inspections, where the smallest imperfections will also be detected with software based on a complex artificial neural network. In particular, the network will be trained with the analysis of millions of images that generate a huge reference database, which allows to recognize defects with the highest possible precision. [76 – 77]

Hence, the use of AI and all its subcategories can be applied to Machine Vision Systems introduced in Chapter 5. Machine learning and Deep learning transform raw data into essential information for decision making. Machine learning can be applied to features' extraction and classification where each step is constructed *separately*. At the same time, deep learning is applied in both feature extraction and classification steps as a *unified neural network solution*. [72]

Manufacturing quality improvement is obtained by detecting defects in products and identifying their sources in the production process. As said, the first task is addressed to AI; also the second one, known as root cause analysis, can benefit from its use. In fact, the manual procedure requires knowledge and experience in the field, and the introduction of AI seems to be the best alternative to simplify its development.

Another way to improve quality control with AI is the insurance of high products quality in the entire supply chain. This is possible thanks to the introduction of data from MES and ERP. Putting together all the information about product demand, availability of raw material, and supplier performance data like delivery times and pricing, manufacturers can use artificial intelligence to guarantee the best quality possible (preventive quality management). [78]

Last, the development of AI textual interfaces can be a substantial support as digital assistant to the board machine operators in the manual quality control performance. If they have any doubt about a procedure, they can ask text-based questions to the AI support that will answer with real-time solutions inherent to the problem.

AI-based inspection systems perform detailed and accurate inspection in real-time, reducing manual labor and human errors, lowering costs, and increasing efficiency. The use of deep learning algorithms and machine learning techniques allows AI to identify defects, offering a great competitive advantage since it generates positive assets, automizes and makes the decisional process faster, accelerates the time to value, and improves company reputation and customers satisfaction. Thanks to this, the great quantity of data is transformed into value for the company.

AI is undoubtedly improving quality control tasks, but human experience and opinion continue to be essential; following Industry 5.0 paradigm, artificial intelligence provides valuable insights to human analysis and decisions, making their collaboration important to enhance the accuracy and efficiency of quality inspection, and consequently the overall quality of products. It is not excluded that in the future humans and AI will work together to solve more complex QA challenges as AI is becoming more and more advanced. [79-80]

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