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TOWARDS SMART MANUFACTURING METROLOGY IN INDUSTRY

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Abstract: *Smart manufacturing metrology (SMM) integrates advanced measurement techniques with digital technologies such as CPS, IoT, BDA, AI and cloud/edge computing to improve manufacturing. This approach improves accuracy, reduces errors (zero manufacturing) and optimizes quality control through real-time data analysis and automation (BDA, DML). Key aspects of this model include digital twin (DT) technology, in-line and non-contact measurements and AI-driven quality management. These innovations support the Industry 4.0 model, enabling flexible manufacturing processes, minimizing scrap and increasing manufacturing efficiency. The transition to smart metrology is essential for modern industry, ensuring its greater productivity and competitiveness in a data-driven manufacturing environment. This paper presents a case study for SMEs in manufacturing from the smart manufacturing metrology issue.*
Key words: *Industry 4.0, Smart manufacturing metrology, CMM, Digital twin, AI.*

1. INTRODUCTORY REMARKS

Smart Manufacturing Metrology (SMM) is a model that integrates advanced metrology systems with digital tools, big data analytics (BDA) and intelligent systems to support real-time decision-making, quality assurance and optimization of metrology processes in manufacturing environments [1-4]. This model uses enabling technologies such as: IoT (IIoT) - industrial internet of things, artificial intelligence (AI), machine learning (ML) and deep machine learning (DML), cloud / edge computing, digital twins (DT), and cyber-physical metrology systems (CPMS) [5-7]. This model implements automated, adaptable and connected measurement processes, which are closely aligned with the elements of Industry 4.0. This paper aims to provide a comprehensive concept of SMM, highlighting its potential to drive the industrial transformation of this important field. By presenting and analyzing the enabling technologies, application examples, challenges and future development directions, the paper seeks to offer useful insights for researchers, engineers and industry leaders in adopting smart engineering solutions for SMM. This paper also has partial objectives related to different aspects of SMM, and they are given in Table 1.

Table 1. Overview of different aspects of SMM

Aspects of SMM	Focus areas of research and analysis
Real-time measurement & monitoring	Continuous quality control, through the integration of sensors, IoT, AI and automation in manufacturing processes
Automation & robotics in metrology	Robotic systems for measurements and inspection
Data-driven quality control	Use AI, IoT, BDA and sensor networks online
Digital Twin and Virtual Metrology	Model-based, data-driven measurement systems
Interoperability and standardization	Exchange of metrological data between CPS, software and enterprise system
Enhanced traceability and compliance	Maintenance standards quality , fulfillment regulatory request and security responsibilities in throughout chain procurement
Adaptive and self-correcting systems	The CPS (machine tool) is self-adjusting in real time

The analyzes and syntheses shown in this paper should contribute to new academic knowledge, industrial innovations and practices, as well as the creation of industrial policy, which should

ensure that SMM develops as a safe, efficient and sustainable solution for the contemporary challenges of the digital revolution in smart manufacturing.

2. SMART METROLOGY MODEL - LITERATURE REVIEW

This model is based on the concept of Industry 4.0 and includes elements, the detailed analysis of which is given as follows. The references analysis was performed according to the PRISMA methodology. The sample included 312 papers, and 31 papers satisfy the set criteria. **Real-time measurement and monitoring** is the cornerstone of SMM, which enables continuous quality control, through the integration of sensors, IoT, AI and automation of manufacturing processes. This approach provides immediate is fed back data, thus reducing scrap and thus losses and downtime. The components that enable measurement and monitoring in real time are [8-10]: (i) *sensor technologies* (optical, tactile and contact, non-contact and environmental sensors), (ii) *data collection and processing* (5G, industrial ethernet and edge computing), and (iii) *integration with SM*: CPS (CMM), DT, virtual metrology (VM), AI and ML for anomaly detection. By analyzing the literature, benefits can be identified, as well as potential challenges and solutions in the application of this model, table 2.

Table 2. Advantages and challenges for real-time SMM (adopted according to [10])

Benefit in application	Description	Challenge - possible situations	Potential solution
Reduced defects and rework	Detection of deviations and prevents faulty manufacturing	Data overload	Edge AI filters noise and extracts key features
Higher productivity	Eliminates post-process inspection bottlenecks	Sensor calibration drift	Self-calibrating sensors
Adaptive manufacturing	Machines auto-adjust	High-speed measurement accuracy	Advanced laser doppler
Cost savings	Less scrap, optimized tool life	Interoperability issues	Standardized protocols (OPC UA, MTConnect)
Improved traceability	History is logged for compliance	Cybersecurity risks	Blockchain of data integrity

Automation and robotics in metrology they transform metrology in SMM, enabling fast, precise and adaptable processes measurements and inspections. Automatic robotic systems replace traditional offline measurement methods, using automatic robotic systems for inspection, reducing human errors, increasing accuracy and precision and enabling control quality of online. This approach support several technologies, table 3.

Table 3. Robotic measurement and its key technologies (adopted according to [11,12])

Type of technology	Technology description	Application
Robotic coordinate measuring machines (CMMs)	Automated CMM arms with touch probes or laser scanners	Automotive, aerospace, precision engineering
Vision-guided robots (VGR)	Robots with 2D/3D cameras for optical inspection	Electronics, food packaging, pharmaceutical QC
Autonomous mobile robots (AMRs) with metrology sensors	Mobile robots carrying portable CMMs or scanners	Large-scale manufacturing, shipbuilding
Collaborative robots (cobots) for metrology	Human-robot shared workspace for flexible inspection	Small-batch manufacturing, medical devices

The following AI and ML approaches are applied to robotic metrology [13]: *automatic defect recognition* (ADR) – AI classifies defects from scan data, *adaptive path planning* – robots adjust the path of the measuring sensor based on real-time data, and predictive metrology, AI predicts the path of the measuring sensor and performs automatic recalibration. This means that integration with SM is carried out, through DT, where the measurement results are simulated using virtual models before physical delivers. In this way, a closed is fed back loop data is results, which is used for online management of processing accuracy (corrections due to tool wear). This is provides through IIoT, using edge computing for real-time analysis, using OPC UA or ISO 10303 (STEP-NC) protocols to standardize interoperability in SMM. **Data-driven quality control (DDQC)** is an SMM approach that uses AI, IoT, BDA, and real-time sensor networks to improve measurement accuracy, predict defects, and optimize manufacturing quality. Unlike traditional statistical process control (SPC), it enables predictable and prescribed quality assurance, eliminating scrap and improving efficiency [14]. An overview of this concept from different aspects is shown in Table 4.

Table 4. Overview of analyzes of some aspects of DDQC (adopted according to [15,16])

Technology	Role in DDQC	QC Method	Application
In-Line metrology sensors (laser scanners, vision systems, CMMs)	Capture real-time dimensional and surface data	ML for defect recognition	Classifies anomalies in real-time
IoT-enabled smart probes	Embedded in CNC machines for live feedback	Predictive analytics	Forecasts tool wear, drift, and failure
Vibration/temperature sensors	Monitor environmental factors affecting measurements	Statistical process control (SPC) 4.0	AI-enhanced SPC with dynamic control limits
RFID/QR code tacking	Links measurement data	Digital twin simulations	Predicts measurement outcomes

The presented features of the model in Table 3 allow us to create a closed is fed back data loop in the DDQC model, by automatically adjusting tool wear during processing on CNC machines, based on metrological data on the quality of manufacturing conformity, or for example adaptive sampling, where AI determines the optimal inspection frequency based on risk [17]. Bearing in mind the situation where quality parameters during processing are monitored here, special care should be taken of data overload and noise, when edge AI filters irrelevant data before cloud processing should be used, then integration with legacy systems, especially in cases with middleware (OPC UA) bridges old and new equipment, then care should be taken of AI model bias and over fitting, which means that federated learning improves generalizability across factories should be used. **Digital Twin and Virtual Metrology,** represent a paradigm shift in manufacturing quality control, moving from physical inspection to data-driven model-based measurement systems. This technology creates a real-time, digital replica of physical manufacturing processes, enabling quality assurance predictions without interrupting manufacturing. Thus, metrological DT represents a dynamic virtual model of a metrological system that simulates, predicts and optimizes the performance of measurements and inspections using real-time data. Virtual metrology is a subset of DT that assesses product quality, using process data (sensor readings) instead of direct physical measurement. One analysis of this model is shown in Table 5.

Table 5. Overview of the basic characteristics of DT and VM in the SMM model (adopted according to [18,19])

Layer	Function	Technology	Method	How it works	Use case
Physical layer	Real-world sensors	CMMs, laser scanners, IoT sensors	Physics-based VM	Uses first-principles models	Semiconductor wafer warpage prediction
Model layer	Physics-based and ML models	FEA, CFD, neural networks	Data-driven VM	ML algorithms for quality	CNC machining surface roughness estimation
Application layer	Predictive analytics	AI-driven SPC, AR/VR interfaces	Hybrid VM	Physics models with AI for accuracy	AM porosity detection

The model shown in table 5 enables excellent results in real-time quality forecasting, cost reduction and risk reduction for product quality. For example, using this approach, risk is reduced by simulating "what-if" scenarios for testing new products, as well as predicting the impact of tool wear on dimensional accuracy, when machining on a machine tool. **Interoperability and standardization**, means that in SMM, interoperability is ensured by seamless exchange of metrological data between CPS, software and enterprise systems, while standardization ensures consistent data formats, protocols and interfaces [20]. Together they form the backbone of the SMM model, aligned with the elements of Industry 4.0. Until now, we had different databases between metrology equipment and manufacturing systems, then inconsistent measurement protocols in supply chains, vendor lock-in due to proprietary systems, and compliance with international quality standards. A detailed analysis of this concept is presented in Table 6.

Table 6. Overview of communication protocols and semantic models for SMM (adopted according to [21,22])

Standard	Application in metrology	Key features	Model	Purpose
OPC UA	Universal data exchange for metrology devices	Platform-independent, secure, supports semantic modeling	QIF (Quality information framework)	End-to-end digital metrology data flow
MTConnect	Manufacturing equipment monitor	HTTP-based, XML schema for measurement data	STEP (ISO 10303)	3D model data exchange including GD&T
ISO 23247	Digital twin framework for	Includes metrology data interoperability	SEMI E125	Equipment data acquisition for semicondu

	manufacturing			ctor metrology
DMC (Dimensional Measuring Interface Standard	CMM programming standardization	Neutral format for measurement plans	Automation ML	XML-based for manufacturing system integration

The advantages of standardized interoperability from an operational point of view enable us to plug-and-play integration of new metrology devices, then provide automated data flows from CMMs to MES/ERP systems, and finally reduced validation effort when changing equipment. As far as business is concerned [23,24] this model ensures supply chain integration by suppliers sharing/using measurement data in standardized formats, compliance with regulations and standards, such as ISO/IATF/FDA, and finally, product life cycle management, generating historical measurement data, which remains usable despite system upgrades. Technical advantages are also realized, such as: lossless data conversion between CAD → (CAI) CMM → QA (QM) databases, the ability to perform analytics on multiple platforms, using unified data models, and future-proof systems that are adaptable to new technologies. **Enhanced traceability and compliance**, in SM measurement has evolved from traditional manual inspections to automated, data-driven measurement systems that provide real-time feedback. Improved traceability and compliance are critical in this ecosystem to maintain quality standards, meet regulatory requirements and ensure accountability throughout the supply chain [25]. Traceability refers to the ability to trace measurement data to recognized standards (SI units, NIST, ISO) with an unbroken chain of calibrations. In SM, traceability is ensured by digital calibration certificates (DCC), replacing paper certificates with digitally signed tamper-proof records, and enabling automatic validation according to international standards (ISO/IEC 17025) [26]. All of the above, supported by blockchain technology, ensures data integrity and prevents unauthorized use, as well as compliance checks. Metrology traceability is defined as a requirement in the following standards: ISO 9001 (Quality Management), ASME B89 (Dimensional Metrology Standards), FDA 21 CFR Part 11 (Compliance with Electronic Records in Metrology), and EU MDR (Medical Device Metrology Regulation). An overview of the benefits of improved traceability and compliance is shown in Table 7.

Table 9. Traceability and compliance for SMM - an overview (adopted according to [27])

Aspect	Traditional Metrology	SMM
Data Integrity	Manual logs, prone to errors	Block-chain-secured, tamper-proof
Regulatory Audits	Time-consuming paperwork	Automated, real-time reporting
Measurement Speed	Slow, offline analysis	Real-time AI-driven corrections
Cost of Non-Compliance	High (recalls, fines)	Reduced via predictive analytics

Adaptive and self-correcting systems, as a part SM, which also contains SMM, where measurement - based process control, which ensures that the CPS (machine tool), self-regulates in real time, to ensure conformance quality management. Adaptive process control (APC) and closed-loop control (CLC) are key elements of adaptive manufacturing, where measurement data directly affect processing parameters without human intervention [28]. Adaptive control dynamically adjusts process parameters (the position of the tool blade relative to the workpiece) based on real-time sensor is fed data on tool wear. Closed-loop control is a self-correcting system where metrology data is fed back to actuators for immediate compensation. These systems are fundamental in achieving zero-defect manufacturing (ZDM) and Industry 4.0 objectives. Today, three models are applied in practice for adaptive quality control of manufacturing conformity [29]: (i) *geometric adaptive control* (GAC), where it adjusts tool paths based on in-process dimensional measurements (laser scanning data is fed), (ii) *force/torque adaptive control*, where it modifies cutting parameters to avoid tool wear or breakage (common in CNC machining), and (iii) *thermal adaptive control*, where it compensates for thermal drift in high-precision machining (semiconductor wafer manufacturing). Closed-Loop Process Control (CLC), is an approach to SMM where a is fed back system is used where metrology data (from in-line sensors) directly controls actuators to correct deviations. Main components for those approaches are (i) *in-process metrology sensors*

(laser micrometers, vision systems, CMMs), (ii) *real-time data processing* (edge computing, AI analytics), and (iii) *actuators and controllers* (servo motors, CNC adjustments, robotic manipulators). For example in manufacturing a CNC machine uses in-process laser scanning to detect dimensional errors and automatically adjusts tool offsets. Bases technologies enabling adaptive and closed-loop control are defined in table 10.

Table 10. Overview of the main components of the APC and CLC model (adopted according to [30,31])

Technology	Role in Adaptive/Closed-Loop Control	Example Applications
In-Line Metrology Sensors	Provide real-time measurement is fed back	Laser trackers, 3D scanners, vision systems
AI/ML Algorithms	Predict optimal process parameters & detect anomalies	Predictive maintenance, adaptive machining
Digital Twin	Simulates process adjustments before execution	Virtual validation of machining corrections
Edge Computing	Low-latency data processing for immediate control	Real-time toolpath adjustments
Industrial IoT (IIoT)	Connects sensors, machines, and control systems	Cloud-based adaptive process optimization

3. CYBER PHYSICAL MANUFACTURING METROLOGY MODEL (CPM^3)

Our research in this area has resulted in the development of a cyber-physical manufacturing metrology model (CPM^3) [32,33] , which represents a virtual model of manufacturing metrology for application in the Industry 4.0 model, figure. 1.

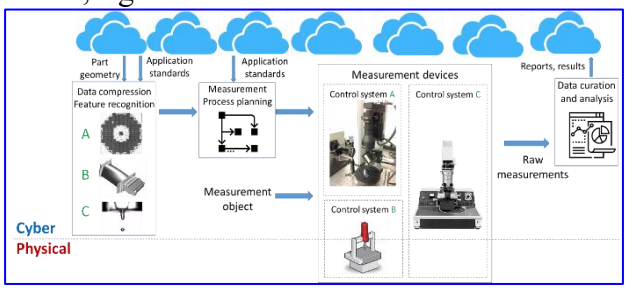


Figure 1. Basic structure of the CPM^3 model

The basic structure of the CPM^3 model shown in Figure 1 has two levels: virtual and physical. The virtual part consists of the following modules: (a) *a module for recognizing geometric features* (GF) from the CAD/GD & T model of the measuring part and metrological features (MF) defined based on them, (b) *a module for intelligent inspection planning (IIPP)*, where GF and metrological features (MF, for example TL - length tolerances) are connected, in the knowledge base of this model, which also includes: inspection sequences (IS), measuring sensor configuration (MS) and inspection plan (IIP), (c) *coordinate measuring machine (CMM)* - generating a list of control data for the UJ CMM that are transferred to it using cloud technology, and (d) *a module for analyzing results and generating inspection reports*. Therefore, this model performs: (a) *integration of the entity's* geometric-metrological knowledge base, using the ontology, (b) *modeling and simulation* of the path of the measuring sensor, with collision checking, using the ACO optimization model, (c) *defining the inspection plan* as an interface for a specific CMM, (d) *inspection on the CMM* and obtaining results. All this is done on the SaaS cloud computing platform, as support for the functioning of this model in practice. Also, this model was tested and applied for: (i) *tolerances of length, shape and orientation*, for prismatic parts, and (ii) *tolerances of curved lines and surfaces* in space (turbine blades). The model of Figure 1 is extended with a digital twin (DT) for virtual manufacturing metrology, which is a digital replica of a real-world coordinate measuring machine (CMM)-based measurement system, Figure 2.

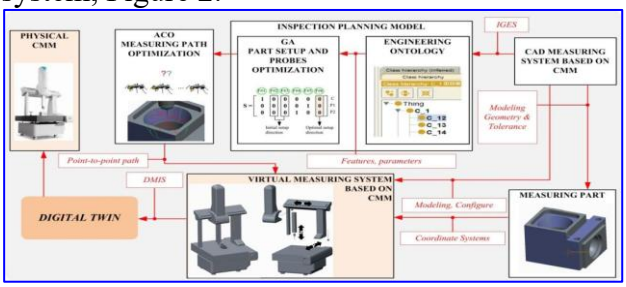


Figure 2. DT model for CPM^3

The developed DT included modeling, simulation, optimization and verification of the measurement path of the virtual CMM. Modeling includes the creation of elements of the measuring system such as the CMM, the measuring part, the measuring sensor and the accessories for clamping the measuring object. The path optimization of the measurement sensor was performed using the ACO model (colony of 5000 ants and 1000 visit iterations). The inspection planning model includes the

application of engineering ontology and genetic algorithms for defining the position of the measuring object on the measuring table, through the connection of four coordinate systems (CMM, measuring sensor, adjusting the measuring object, and the measuring object), optimizing the path of the measuring sensor and checking the collision between the measuring object and the measuring sensor. In this experiment, the real CMM was DEA global S. The virtual CMM was created in PTC Creo software according to the measurements of the real CMM. Also, the kinematic modeling of this CMM was performed with the same software. The results of savings in the length of the measuring path compared to the PTC Creo path show at least 12.81% for the metrological primitive - cylinder, of small dimensions. However, our research for prismatic measuring objects of larger dimensions, on which there are all kinds of tolerances in length, shape and position, showed us savings in the path length of the measuring sensor of about 40% per measuring part. On the other hand, DT allows monitoring the measurement process online.

4. CASE STUDY - APPLICATION OF ELEMENTS OF CPM^3 IN MANUFACTURING

In Serbia, the national Industry 4.0 Project has been organized since 2015. One of the results was the adoption of the Digital Platform Industry 4.0 of Serbia in 2019. This document represents a unique vision of all interested parties (decision-makers, academia and the economy), for the sake of digital transformation, primarily of the economy, with the aim of increasing the competitiveness of Serbian industry on the global market. Most of the work was done on the digitization of manufacturing, in order to build a digital business model for the industry. The focus was on SMEs in the metalworking industry, so this example relates to one such company - SPP, Konjevići, Čačak, whose digital business model is presented in this paper, with a special focus on manufacturing metrology. This company has more than eight thousand parts, sub-assemblies and assemblies in its portfolio, and Figure 3 shows some of the characteristic ones.

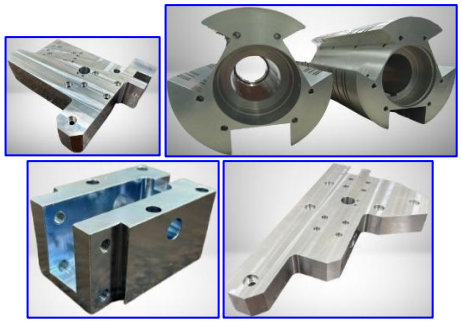


Figure 3. Appearance of some parts from the SPP manufacturing program

SPP is a company that uses the most modern manufacturing and metrological equipment in its manufacturing, striving for zero-defect manufacturing, although as a rule it is small- and medium-series manufacturing parts, Figure 4.

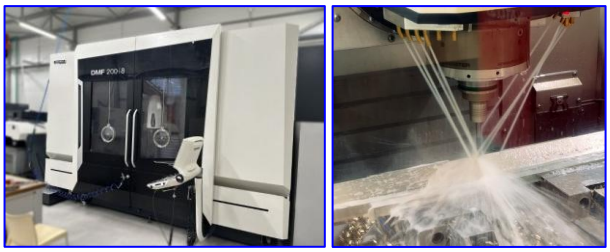


Figure 4. One view of the workshop for machining in SPP Company

All manufacturing technology cutting including laser cutting, welding and plastic deformation processing technologies (sheet metal processing and bending) are represented in this factory. This company has modern CAD/CAM/CAI software and the SAP system, which included the ERP and MES model. It also has the appropriate hardware and software infrastructure that supports its digital business model on the SaaS platform. **Sales Management (CRM) and Procurement (SCM).** The request from the customer arrives in the form of a 3D model of the product, with the required quantity. Thus begins the construction of a digital manufacturing chain, with the receipt, review, reconciliation and acceptance of customer orders (CRM). After that, the accepted order is assigned the necessary and available resources, after which the process of procurement of materials and raw materials (SCM) is accessed. Figure 5 shows an example of the Material Procurement Report for an accepted order, which contains: all data on the ordered material, the work order for the product, the quantity of the ordered material, the date of the order and the

date of availability of the material in the warehouse.

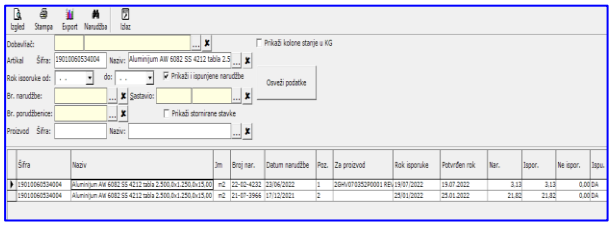


Figure 5. Examples of reports for SCM

Engineering design and planning (CAD/CAPP/CAM modules). As we have already said, SPP already has a 3D model of the product, from which all technical drawings are immediately generated. Based on the above, engineers and planners in the system generate EBOM and MBOM components (constructional and technological). Now technological planning of product manufacturing (CAPP) is carried out, taking care of: tolerance requirements, availability of machine tools and their accuracy. Once this is done, the technology planners work out the machining technology, with the cutting modes in the CAM software. Technology planning includes the sequence of operations (CAPP - Figure 6a) and the definition of processing conditions and modes (CAM - Figure 6b).



6a) CAPP report 6b) CAM report

Figure 6. Examples of Reports for CAPP/CAM (6a and 6b) for the part shown at the bottom of this figure

Figure 6 shows the 3D model of the part, for which the sequence of CAPP manufacturing operations (6a) and the detailed CAM manufacturing plan (6b) are planned. In this way, all the technological information for access to the generation of the digital work order and the schedule of the manufacturing plan (MES and ERP) are defined. **Work order management (MES module).** This module is the key to the digitalization of manufacturing, because on the one hand it integrates information entities from manufacturing planning (ERP), and on the other hand the Work Order (WO), and other activities in the plant related to manufacturing (metrology and quality management, maintenance, etc.). Digital model WO, as part of the MES module in this organization is shown in Figure 7.

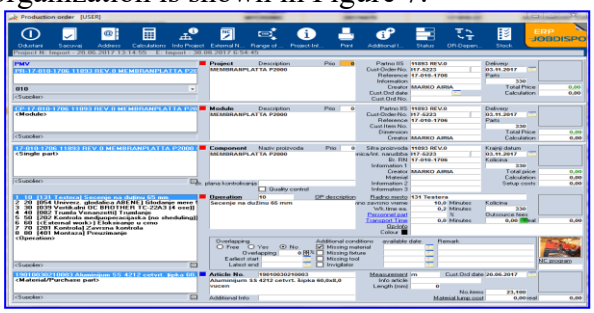


Figure 7. Work order (WO) panel in SPP company

A work order (WO) contains the following information: order number, WO number, number of pieces to be made, workpiece material, workpiece dimensions, a list of all operations per machine, and the time required to complete each operation. The set of this information provides all the key data in one place, on the basis of which the analysis is performed. So for example, Figure 8, we have a digital panel of overview of WO by machine.

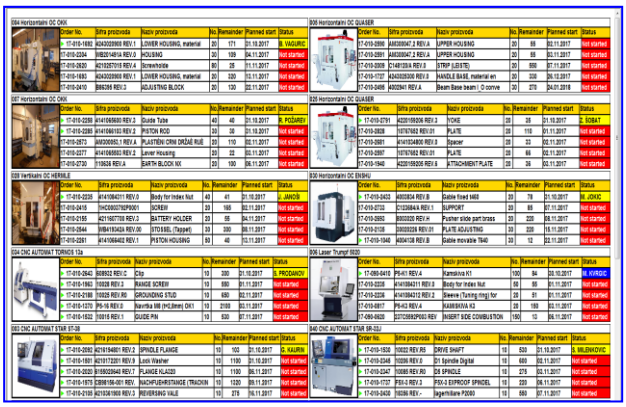


Figure 8. Overview of work orders (WO) per machine tool

On the said Panel we have the following information: a photo of a specific machine tool with its number, then the work order currently being worked on is shown in yellow, while the next work order is marked in red, according to the delivery date. A green dot, next to the work order number, indicates that all prerequisites for the start of manufacturing of that work order have been met (provided material, cutting tool, accessories). Online monitoring of the state of machines in operation is also a module in the MES system, which, using BDA analysis, provides

an overview of the state of machines in operation, Figure 9, by parameter overall equipment effectiveness (OEE), according to the time dimension (day, week, month).

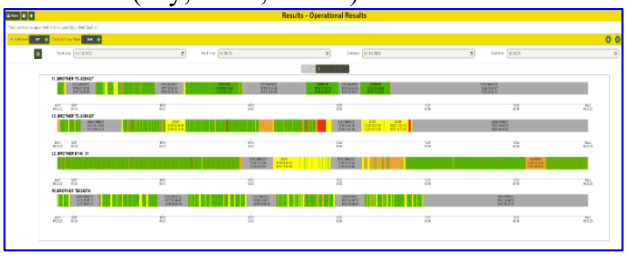


Figure 9. Overview of OEE parameters by machine tools in SPP

Resource planning (ERP module). When we generated all information for the digital WO, the fine term manufacturing plan is generated, as part of the ERP module. It contains all the relevant planning information for the manufacturing plan according to manufacturing-technological resources, Figure 10.

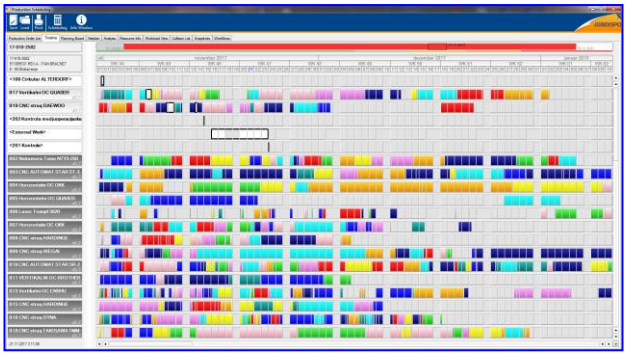


Figure 10. Fine term plan (scheduling) for plant 1 and the machine tools in it

The planning of manufacturing and technological resources is carried out by sublimation of digital information from the previous steps, which as a result gives a schedule of all operations, for a given time period, with a display of their mutual dependence. By selecting a specific Work Order (WO), we have a detailed insight into the plan for its implementation, at the planned workplaces. If there is a sudden failure of the machine tool, or some other unplanned stoppage, re-termination is performed at the drive level. **Quality management system.** SPP pays special attention to the quality of its products, which is realized in practice so that the manufacturing processes strive for manufacturing without scrap. In practice, he has been applying the Integrated Management System (IMS) for many years, which integrates three standards: QMS, EMS and OH&S, which are part of the digital business model of this organization. The entire IMS functions "without paper", and last year it was supplemented with a model related to the decarbonization of manufacturing, which is defined by special documents, which represent the fulfillment of the requirements of ISO 9001:2015, Amendment 1 - Climate action changes , as well as the CBAM document, issued by the EU. In this way, as well as with the leads to of the project of obtaining electricity from solar panels, SPP is taking great steps to start applying the concept of "green" manufacturing. **Manufacturing metrology.** This product conformity quality management segment is based on the CPM^3 model [32,33] , which is detailed in point 3. Namely, this organization was an industrial partner in the development of this model, through its Metrology Laboratory, Figure 11.

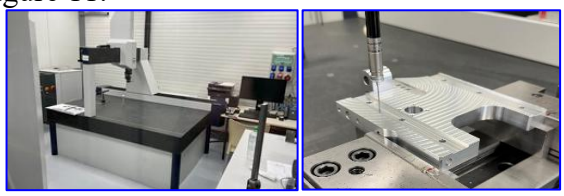


Figure 11. Metrology laboratory at the SPP company

CPM^3 model in SPP practice starts from the 3D model of the part, for which the tolerances of length, shape and position are defined, the inspection of which should be performed on the CMM. In this model, the first step is to define the geometric primitives (GF), which represent these tolerances, and then the metrological primitives (MF), whose inspection should be performed. After this, four coordinate systems are determined, and for them the sequences of inspection operations (CAIP), and the configuration of the measurement sensor (MS) for each MP are defined. The simulation of the path of the MS is then carried out to check the collision, and with the help of the DT the final inspection plan of the part is defined, Figure 12.

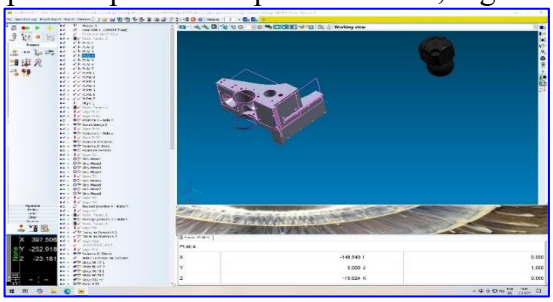


Figure 12. Inspection plan for CMM by DT

The transfer of geometric-metrological data is done with the help of the DMIS platform, and examples of reports from the inspection of parts on the CMM in the SPP are given in Figure 13.

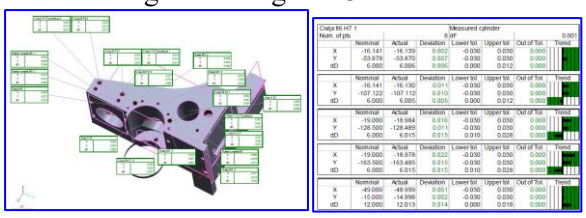


Figure 13. 3D model of the part with tolerances (left) and the results of its inspection (right)

By detailed analysis of the Inspection report (picture 13, right), we can conclude that all tolerances, after its manufacturing, were within the prescribed tolerances, which ranged from 5 to 15 micrometers. Summarizing this chapter, we can define the following conclusions: (i) *a digital model of business-engineering and manufacturing* activities was developed and applied, making this organization a digital factory, in which the elements of Industry 4.0 are applied, and (ii) *the cloud model* of Manufacturing Project is now in the process of being implemented, where all the conditions will be created for the full application of SM elements.

5. CONCLUSIONS AND FUTURE RESEARCH

SMM is evolving rapidly, driven by advances in AI, quantum computing, advanced materials, and cyber-physical systems. Future research and development will focus on autonomous, ultra-precise and sustainable measurement systems that will redefine quality control. In the coming years, in the field of SMM for SM, the key areas of research will be [34-39]: (a) *autonomous and self-learning metrology systems*, within which the following problems will be specifically investigated: AI-driven metrology robots (drones for large-scale inspection of parts in aviation), generative AI for optimization of metrology operations (topology optimization for 3D printed parts), and self-calibrating sensors, based on MEMS/NEMS technologies, where automatic adapts, using is fed back from the environment. These approaches will bring scrap-free manufacturing to the industry, with minimal involvement of metrologists, (b) *quantum metrology and nanoscale precision*, where the following problems will be investigated: quantum sensors (for measurements on the quantum scale), terahertz metrology (non-contact thickness measurement of ultra-thin coatings), and single-photon imaging (high-speed, low-light imaging for fragile materials). These approaches will advance metrology in the field of semiconductor, photonics, and biomedical manufacturing, (c) *cyber-physical metrology and DT*, with the following research directions: DT in real time (virtual replicas of physical measurement systems that predict errors before they appear), blockchain for secure metrology data (digital traceability of high-tech industries), and 5G-enabled distributed metrology (cloud-based metrology networks with sub-millisecond latency for global factories). This will bring to the industry the full application of the Industry 4.0 model, and (d) *sustainable and green metrology*, where research will be especially focused on: energy-harvesting sensors (piezoelectric/thermoelectric sensors powered by machine vibrations), biodegradable sensors (eco-friendly inspection tools for circular manufacturing) and carbon-neutral metrology (lifecycle analysis (LCA) of measurement equipment to minimize CO_2 footprint). This will bring compliance with ESG principles and lower operating costs to the industry. Summarizing these analyses, we can conclude the following: (i) *in the period 2026. - 2030*, SMM will be dominated by AI and IoT, which will enable the application of these models that will learn independently, and in the automotive and aviation industry will bring a min 50% reduction in inspection time (quality control), using edge models, (b) *in the period 2031. - 2035*, industrial quantum sensors will be developed and applied, for nanomanufacturing. Then the first quantum-calibrated medical device will be approved by the FDA, and (c) *2036.- 2040*, autonomous metrology ecosystems will come into use. These will be fully self-correcting factories with zero human QC, and ISO standards for dimensional metrology based on artificial intelligence will be developed and applied. The future of SMM in SM lies at the intersection of autonomy, precision and sustainability, where AI and quantum

technology will immeasurably overcome traditional precision barriers, green metrology will align with global net-zero goals, and regulatory frameworks must evolve to keep pace with innovation. And finally, companies that invest in these areas of research and development today, will lead the next industrial revolution - Industry 5.0.

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Către o metrologie inteligentă a producției în industrie

Rezumat: Metrologia inteligentă în fabricație integrează tehnici avansate de măsurare cu tehnologii digitale precum CPS, IoT, BDA, AI și cloud/edge computing pentru a îmbunătăți procesul de fabricație. Această abordare îmbunătățește precizia, reduce erorile (fabricație zero) și optimizează controlul calității prin analiza datelor în timp real și automatizare (BDA, DML). Aspectele cheie ale acestui model includ tehnologia geamănului digital, măsurătorile în linie și fără contact și managementul calității bazat pe inteligență artificială. Aceste inovații susțin modelul Industry 4.0, permițând procese de fabricație flexibile, reducând la minimum deșeurile și crescând eficiența fabricației. Tranziția către metrologia inteligentă este esențială pentru industria modernă, asigurându-i o productivitate și o competitivitate mai mare într-un mediu de fabricație bazat pe date. Această lucrare prezintă un studiu de caz pentru IMM-urile din industria prelucrătoare, din perspectiva metrologiei inteligente în fabricație.

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