



Baština Akademije nauka i umjetnosti Bosne i Hercegovine

SMART MANUFACTURING ON THE HORIZON: A Conceptual Shift from Industry 4.0 to Industry 5.0: Industrija

Karabegović, Isak

2026

Academy of Sciences and Arts of Bosnia and Herzegovina

<https://bastina.anubih.ba/handle/123456789/875>

Preuzeto s Baštine Akademije nauka i umjetnosti Bosne i Hercegovine

<https://bastina.anubih.ba/>

An Integrated Model of Industry 4.0 and Industry 5.0 for Quality Management During the Entire Life Cycle of Plastic Injection Molds

Dušan Janković^{*1}, Goran Janković¹, Zora Joković¹, Aleksandar Supurović¹,
Vidosav Majstorović²

Abstract: Plastic injection molding tools are a key component that directly affects product quality, production efficiency, production costs, and sustainability throughout the product's life cycle. Recent advances in Industry 4.0 technologies, including Industrial Internet of Things (IIoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI), Big Data Analytics (BDA), cloud/edge computing, digital twins (DT) and advanced automation (cobots), have enabled significant improvements in tool performance (quality) monitoring and control. However, most existing approaches primarily focus on technological optimization and operational efficiency, while insufficiently addressing people-centeredness, sustainability and resilience, which are the core principles of Industry 5.0. Consequently, a comprehensive quality management framework that integrates Industry 4.0 and Industry 5.0 paradigms throughout the life cycle of plastic injection molding tools remains largely unexplored. This study proposes an Integrated Industry 4.0 - Industry 5.0 model for quality management throughout the life cycle of plastic injection molding tools, which includes the stages of design, production, inspection, operation, maintenance, renewal (overhaul) and end of life. The research methodology combines an extensive literature review, analysis of current industry practices, conceptual modeling and the development of a multi-layered architecture, which integrates digital technologies with human-centered and sustainable quality management principles. The proposed model consists of interconnected physical, data layer, intelligent, DT, human-centric, sustainability and resilience layers, in an overall multi-layered structure. Industry 4.0 technologies provide real-time monitoring, predictive analytics (quality, maintenance, as well as other KPI parameters), virtual quality assessment and automated decision support, while Industry 5.0 principles enable collaborative human-AI interaction, knowledge-driven quality improvement, resource efficiency, circular economy practices and resilient manufacturing operations. The main contribution of this research is the development of a holistic, lifecycle-oriented quality management framework with a developed set of KPI parameters, which bridges the gap between the technology-driven Quality 4.0 approach and the human-centered Quality 5.0 approach. Expected benefits include improved tool quality, reduced downtime and maintenance costs, improved decision-making capabilities, increased sustainment performance, extended tool life, greater process resilience and improved competitiveness of the injection molding company.

^{*1}Company Inmold Group, Požega, Serbia

²University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

E-mail: dušan.jankovic@inmold-ltd.com

Keywords: *Industry 4.0, Industry 5.0, Quality Management, Plastic Injection Molding Tools, Smart Manufacturing, Digital Twin, Artificial Intelligence, Machine Learning, Sustainability, Human-Centered Manufacturing.*

1. Introduction

Plastic injection molding is one of the most commonly used manufacturing processes for producing large plastic components with complex geometry, tight dimensional tolerances and high repeatability. Industries such as automotive, aerospace, electronics, medical devices, packaging and consumer goods rely heavily on injection molding technology for its productivity, flexibility and cost-effectiveness. At the core of this process are plastic injection molds, which determine the shape, dimensional accuracy, surface quality and overall functionality of the finished products. Injection molds represent significant capital investments and often make up a significant portion of the total cost of manufacturing plastic products. Their design complexity, production accuracy and operational reliability directly affect production efficiency and business competitiveness. Since molds are exposed to repeated thermal, mechanical and chemical stresses during operation, maintaining their quality throughout the entire life cycle is crucial to ensure stable production and minimize operational risks. That is why effective quality management of injection molding tools, in their lifetime, has become a strategic requirement for modern manufacturing organizations, which are looking for higher productivity, reduced costs and sustainable business, Figure 1.

Industry 4.0 represents the fourth industrial revolution, characterized by the integration of digital technologies, intelligent systems and interconnected production resources. In the production of plastic injection molding tools, Industry 4.0 enables the transformation of conventional production systems into smart, data-driven and highly automated environments [1]. The adoption of digital technologies supports improved quality, productivity, flexibility and lifecycle management of injection molding tools.

Digitization is a fundamental pillar of Industry 4.0 and involves converting physical processes, assets and information into digital formats that can be collected, analyzed and used for decision making. In mold manufacturing, digitization begins during the design phase through the use of computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) systems.

Digital technologies enable the creation of comprehensive digital records throughout the tool life cycle, including design specifications, machining parameters, dimensional inspection data, maintenance records and operational performance information.

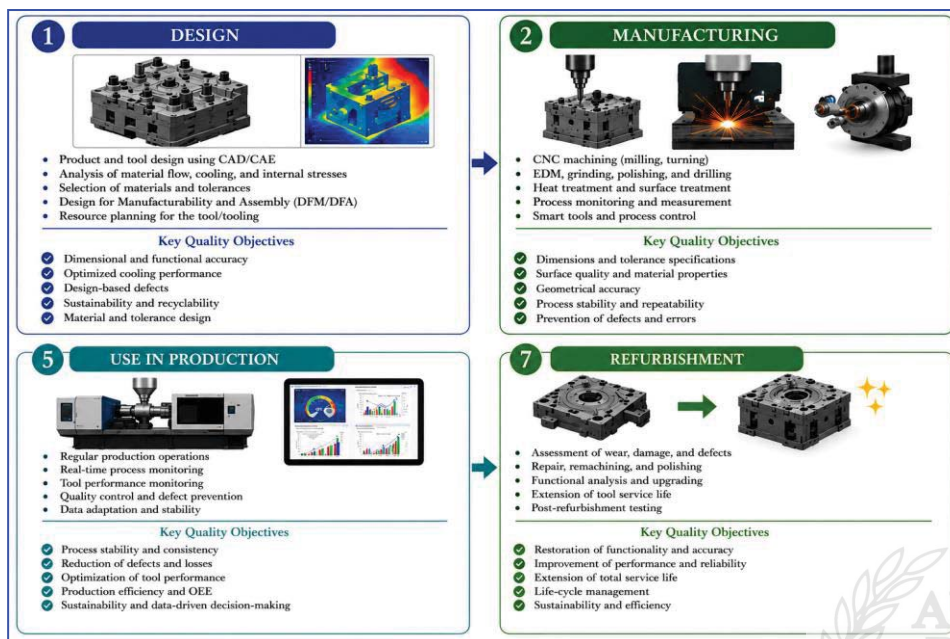


Figure 1. The life cycle of plastic injection molding tools from the perspective of quality management for the two most important phases

Advanced systems for product life cycle management (PLM) enable seamless data exchange between organizational units for design, production, quality and maintenance. The application of Industrial Internet of Things (IIoT) technologies further advances digitization, enabling real-time data collection from machine tools, sensors, coordinate measuring machines (CMM) and production equipment. These digital data streams provide valuable insights into tool condition, machining performance and quality characteristics, supporting data-driven quality management and continuous improvement initiatives.

While Industry 4.0 primarily focuses on digitization, automation and operational efficiency, Industry 5.0 expands this vision by emphasizing collaboration between people and intelligent technologies, while promoting sustainability and resilience. The concept recognizes that technological progress should not only improve productivity, but also create value for people, society and the environment [15]. In the context of plastic injection tooling manufacturing, Industry 5.0 introduces a more holistic approach to quality management, integrating human expertise, environmental responsibility and adaptive manufacturing capabilities throughout the tool life cycle, to increase the resilience of the plastic injection molding system.

1.1 Research Shortcomings

The application of Industry 4.0 technologies in manufacturing has attracted considerable attention from both researchers and practitioners over the past decade. Numerous studies have explored the application of Industrial Internet of Things (IIoT), Artificial Intelligence (AI), Machine Learning (ML), Cyber-Physical Systems (CPS), DT, Cloud Computing, and Big Data Analytics (BDA) to improve manufacturing efficiency, predictive maintenance, process optimization, and product quality. In the field of plastic injection molding, these technologies have been successfully applied to process monitoring, defect prediction, tool condition assessment, and production optimization. However, despite significant progress in the development of manufacturing systems based on Industry 4.0, there are still several important research gaps, especially in the area of quality management throughout the life cycle of plastic injection molding tools [1-28].

Predominant focus on Industry 4.0 technologies. Most existing studies primarily concentrate on the technological aspects of digital transformation, with an emphasis on automation, connectivity, data collection and intelligent analytics. Although these approaches have shown significant improvements in operational performance, they are largely technology driven and focus mainly on productivity, efficiency and cost reduction. Current research often evaluates individual technologies in isolation, such as AI-based quality prediction, IoT-enabled monitoring systems, DT, or predictive maintenance platforms. As a result, there is limited research into how these technologies can be integrated into a comprehensive quality management framework that covers all phases of the life cycle of plastic injection molding tools. Furthermore, the broader goals introduced by Industry 5.0, including human-centeredness, sustainability and resilience, are rarely incorporated into existing quality management models.

Limited integration of human-centered quality management. Human expertise plays a key role in mold design, manufacturing, inspection, maintenance, troubleshooting and quality improvement. However, many Industry 4.0 studies predominantly focus on automation and autonomous decision-making, often neglecting the contribution of engineers, operators, quality experts and maintenance personnel. The new paradigm of Industry 5.0 emphasizes the collaborative interaction between people and intelligent technologies. However, research investigating human-centered quality management within the mold manufacturing environment is still limited. Existing studies rarely address topics such as AI-assisted decision support, operator knowledge integration,

collaborative quality management, human-machine collaboration, workforce empowerment, and organizational learning during the tool life cycle. Consequently, there is a need for quality management frameworks that combine digital intelligence with human expertise to improve decision quality, adaptability, innovation and continuous improvement.

Lack of life-cycle-oriented quality management models. Another significant research gap is related to the lack of comprehensive life cycle oriented quality management models for plastic injection molding tools. Most available studies focus on specific phases of the life cycle, such as tool design, manufacturing, process optimization or maintenance, without considering the entire life cycle as an integrated system. The life cycle of plastic injection molding tools includes design, manufacture, assembly, inspection, commissioning, operation, maintenance, refurbishment and end-of-life management. Quality-related information generated during one phase is often not effectively transferred to subsequent phases, resulting in fragmented decision-making and reduced opportunities for continuous improvement. Although product life cycle management (PLM) and DT systems offer mechanisms for life cycle integration, their application in mold quality management remains relatively limited. Existing research lacks a single framework capable of linking life cycle data, quality indicators, maintenance information, sustainability metrics and human knowledge into a single integrated environment.

The need for an integrated quality management model of Industry 4.0 and Industry 5.0. Based on the identified shortcomings, there is currently no widely accepted model that integrates Industry 4.0 technologies with Industry 5.0 principles for quality management throughout the life cycle of plastic injection molding tools. Existing approaches usually deal separately with either technological innovation or organizational and sustainability aspects. Therefore, there is a clear need for a holistic quality management model, combining digital technologies, cyber-physical systems, DT, AI-driven analytics, human-centered decision-making, sustainability goals and resilience capabilities within a single lifecycle framework. Such a model would enable manufacturers to achieve not only higher quality and operational efficiency, but also greater adaptability, sustainability and long-term competitiveness. This study addresses this research gap by proposing an integrated Industry 4.0-Industry 5.0 model for quality management throughout the life cycle of plastic injection molding tools, providing a comprehensive framework that aligns technological innovation with human, environmental and resilience goals.

1.2 Research Objectives

The growing complexity of the production of plastic injection molding tools, combined with the increasing adoption of Industry 4.0 technologies and the emergence of Industry 5.0 principles, creates the need for a comprehensive approach to quality management that encompasses the entire life cycle of the tool. Although existing studies have shown the advantages of digital technologies for process optimization and quality control, integrated frameworks that simultaneously address technological, human-oriented, sustainable and resilience dimensions are still lacking. Therefore, the primary goal of this research is the development of an Integrated Quality Management Model of Industry 4.0 - Industry 5.0, which supports continuous quality improvement throughout the life cycle of plastic injection tools. To achieve this goal, the study pursues the following research objectives:

O1: Development of a life cycle-based quality management framework.

Development of a comprehensive quality management framework, covering all phases of the life cycle of plastic injection molding tools, including design, manufacture, inspection, commissioning, operation, maintenance, refurbishment and end-of-life management. The aim of the framework is to establish a continuous flow of information, traceability and quality feedback mechanisms in all phases of the life cycle, enabling proactive data-based quality management, with defined KPI parameters.

O2: Integration of Industry 4.0 and Industry 5.0 principles. Design an integrated model that combines the technological capabilities of Industry 4.0, including Industrial Internet of Things (IIoT), Cyber-Physical Systems (CPS), Artificial Intelligence (AI), Machine Learning (ML), Big Data Analytics (BDA), Cloud Computing and Digital Twins (DT), with Industry 5.0 principles of human-centeredness, sustainability and resilience. The goal is to create a balanced approach to quality management that uses advanced digital technologies while preserving the key role of human expertise and organizational adaptability.

O3: Improving tool quality, sustainability and resilience. Improving the overall performance of plastic injection molding tools by improving quality consistency, extending tool life, reducing maintenance costs, minimizing environmental impact and increasing operational resilience. The proposed model seeks to support predictive quality management, resource efficient operations, circular life cycle practices and adaptive responses to production disruptions and emerging risks. Together, these objectives provide the basis for the development of a holistic quality management framework, which aligns technological innovation with

human and organizational priorities, as well as with the environment, thus supporting the transition from traditional quality management approaches to the integrated paradigms of Quality 4.0 and Quality 5.0 in the production of plastic injection tools.

1.3 Organization of Paper

This paper has the following units: Introductory analysis of the basic concept and ideas for quality management of plastic injection tools, in their lifetime. The second part refers to the most important references from this field and their deep analysis, which confirms the need for research, which is the main part of this work. In module three, I present the concept of the Integrated Model with a detailed description of its most important elements. The most important part of this paper is the application of the Integrated Model in the practice of the INMOLD Company, which is shown in detail in point 4. In point 5 of this paper, there was a discussion of the application of the elements of the Integrated Model in the practice of this company, with special reference to the KPI parameters of this model, so that at the end of this paper, point 6, conclusions would be given with directions for future research in the development and application of this model.

2. Literature Review

The life cycle of a plastic injection molding tool includes all activities, from the initial development of the tool concept, to its final disposal or recycling. Effective quality management requires continuous monitoring and control during each phase of the life cycle, because decisions made during one phase directly affect tool performance, product quality, production costs, sustainability and operational reliability in subsequent phases [27,28]. A lifecycle-oriented approach enables manufacturers to improve traceability, optimize resource utilization, extend tool life and support continuous tool quality improvement.

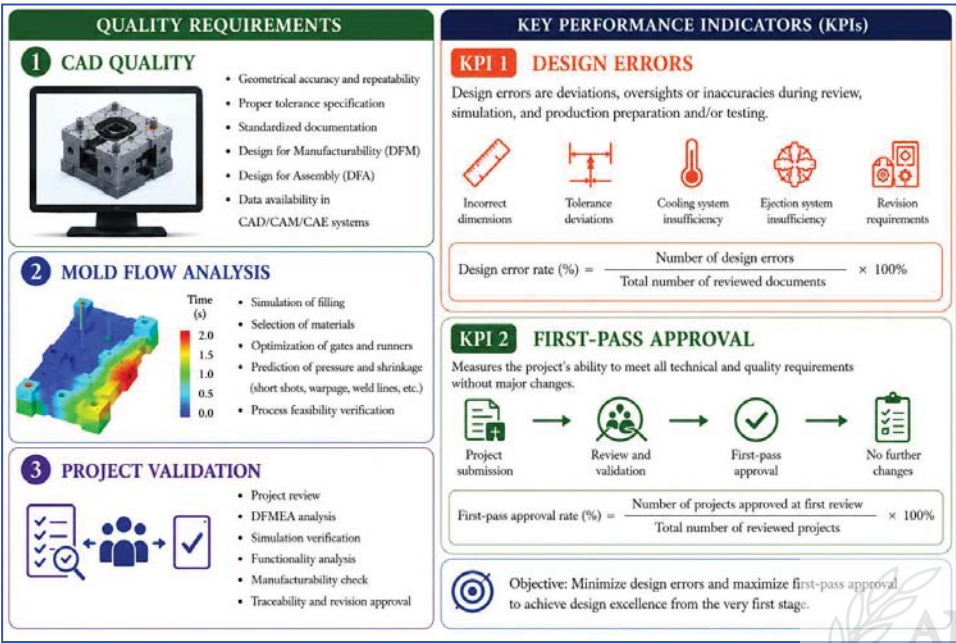


Figure 2. Quality requirements in the design phase of plastic injection molding tools

The design phase is the foundation of the tool life cycle and has a significant impact on future tool performance, Figure 2. During this phase, product requirements are translated into mold design using CAD, CAE and simulation tools. Key activities include cavity design, channel system design, cooling channel optimization, material selection, tolerance specification, and manufacturability analysis, i.e. processing capabilities. Quality objectives in this phase include: ensuring dimensional accuracy and functionality, optimizing cooling performance, reducing potential manufacturing defects, improving maintainability and usability, supporting sustainability through materials-efficient design. Design errors made at this stage can propagate throughout the entire life cycle and significantly increase production and maintenance costs.

A literature review was also performed for the tool life cycle, Table 1 [1-28].

Table 1. Analysis of key references for the development of an Integrated Industry 4.0 and Industry 5.0 model for quality management during the life cycle of plastic injection molding tools

Ref.	Main focus of the work	Industry 4.0 technologies	Industry 5.0 concepts	Tool life cycle	Focus on quality	Research gap
Kagermann et al. (2013) [1]	Industry 4.0 concept	CPS, IoT, Smart Factory	Not processed	No	Digital integration of production	A human-centric approach is lacking
Lasi et al. (2019) [2]	Definition of Industry 4.0	CPS, IoT			Operational efficiency	No quality 5.0
Xu et al. (2018) [3]	Industry 4.0 Overview	CPS, Cloud, IoT		Partially	Smart manufacturing	No sustainability
Frank et al. (2019) [4]	I4.0 implementation	IoT, Cloud, Big Data		No	Operational excellence	The human factor is missing.
Culot et al. (2020) [5]	Analysis of I4.0 technologies	IoT, AI, Cloud			Process efficiency	No lifecycle approach
Tao et al. (2019) [6]	Digital twin	DT, IoT, Big Data		Partially	Product optimization	Sustainability is lacking.
Jones et al. (2020) [7]	DT Architecture	DT			Performance monitoring	Quality 5.0 is missing.
Lang et al. (2021) [8]	DT for smart manufacturing	DT, IoT, AI	Limited	Yes	Quality monitoring	There is no humanocentrism
Fuller et al. (2020) [9]	DT technologies	DT, AI	Not processed	Partially	Predictive analysis	Sustainability is lacking.
Rosen et al. (2019) [10]	CPS and DT	CPS, DT			Process optimization	No quality
Sony et al. (2020) [11]	Quality 4.0	AI, Big Data, IoT	Limited	No	Quality 4.0	No Quality 5.0
Sony et al. (2021) [12]	Implementation of Quality 4.0	AI, Analytics			Digital quality	No sustainability
Jacob (2020) [13]	Quality 4.0 assessment	Big Data, AI			Quality measurement	No resistance
Antony et al. (2022) [14]	Development of Quality 4.0	AI, ML, Analytics			Quality management	Industry 5.0 is missing
Breque et al. (2021) [15]	Industry 5.0	I4.0 technologies	Human-centeredness, Sustainability Resilience		Indirectly	No quality model
Xu et al. (2021) [16]	Industry 4.0–5.0	AI, DT, CPS	Humanocentricity	Partially	Smart manufacturing	No quality tools
Lu et al. (2022) [17]	Human-centric manufacturing	AI, CPS			Decision support	No tool life cycle
Maddikunta et al. (2022) [18]	Industry 5.0 Overview	AI, IoT, Cloud	Human-centeredness, Sustainability	No	Indirectly	No quality
Lee et al. (2018)	Industrial AI	AI, Big Data	Not processed	No	Intelligent quality	No life cycle
Javaid et al. (2021) [19]	AI in manufacturing	AI, ML, IoT	Limited		Production quality	No sustainability
Wuest et al. (2016) [20]	Machine learning	ML	Not processed		Quality prediction	There is no humanocentrism

Kusiak (2018) [21]	Smart manufacturing	AI, Big Data		Partially	Quality optimization	No Industry 5.0
Carvalho et al. (2019) [22]	Predictive maintenance	AI, IoT	Limited	Maintenance	System reliability	No quality 5.0
Zonta et al. (2020) [23]	PdM in I4.0	AI, IoT, Analytics		Maintenance	Equipment reliability	Sustainability is lacking.
Ghobakhloo (2020) [24]	Sustainability and I4.0	IoT, AI, Cloud	Sustainability	Partially	Resource efficiency	No quality
Ghobakhloo et al. (2024) [25]	Sustainable production 5.0	AI, IoT	Sustainability Circular Economy		ESG performance	No quality tools
Rajput & Singh (2020) [26]	Circular economy	IoT, Analytics	Sustainability		Resource efficiency	No QM
Amanov et al. (2019) [27]	Mold life span	Wear monitoring	Not processed	Yes	Mold reliability	No digitization
Mourtzis et al. (2023) [28]	The digital life cycle of tools	DT, AI, IoT	Limited		Digital quality	No Industry 5.0 integration

Based on the analysis of the presented references, the following scientifically relevant conclusions can be drawn: *(a) dominance of Industry 4.0 technologies in the existing literature*. The analyzed literature shows that research in the field of quality management during the last decade has been dominantly focused on Industry 4.0 technologies, such as IoT, DT, AI/ML, cloud environments and CPS. Most authors investigate the possibilities of digitalization, automation and optimization of production processes, while human, social and sustainable aspects are mostly in the background, *(b) Quality 4.0 is well developed, while Quality 5.0 is still in the early stages of development*. Papers [11-13] show that the concept of Quality 4.0 has advanced significantly through the application of AI, Big Data and IoT technologies for quality prediction, process analysis and decision support. However, the concept of Quality 5.0 is still not sufficiently defined, especially regarding the integration of human-centricity, sustainability and resilience in quality management systems, *(c) digital twins represent a key technology for life cycle management*. Works [6-8,28] confirm that DT is one of the most promising technologies for connecting design, production, exploitation and maintenance of products and tools. However, most of the existing solutions are focused on the technical optimization of the process, while the aspects of sustainability, human knowledge and Quality 5.0 are insufficiently researched, *(d) human-centricity represents the biggest drawback of the existing models*. Although Industry 5.0 emphasizes the importance of humans as the central element of the production system, the literature analysis shows that most works do not integrate the expert knowledge of operators, quality engineers and managers into digital decision-making systems. Human-AI collaboration, knowledge management and human decision support remain significantly under-researched areas, *(e) sustainability is largely viewed separately from quality*. Papers [15,24,26] emphasize the importance of sustainability and circular economy in Industry 5.0. However, most research treats sustainability as a separate topic, without directly linking it to

quality management during the life cycle of a product or tool. The integration of quality KPIs and ESG indicators is still an open research question, *(f) the resilience of quality systems is insufficiently researched*. Although predictive maintenance and risk management are active research areas, the literature shows that there are very few works that relate resilience to quality systems. Adaptive quality systems capable of responding to disruptions, failures and changes in market demands represent a significant research opportunity, and *(g) a complete life cycle approach to plastic injection molding tools is lacking*. Most of the analyzed papers focus only on certain phases of the life cycle, most often design, production or maintenance. Very little research covers the complete life cycle of plastic injection molding tools, so this represents one of the biggest gaps in the existing literature.

An Integrated Industry 4.0 and Industry 5.0 model for tool quality management is missing. The most important conclusion of the analysis is that there is currently no single model that simultaneously integrates: Industry 4.0 technologies (IoT, AI, ML, DT, Cloud, Edge), Industry 5.0 principles (human-centricity, sustainability and resilience), Quality 4.0 and Quality 5.0 approaches, and quality management during the entire life cycle of plastic injection tools.

A major research gap. Based on the analyzed literature, it can be concluded that there is a significant lack of an integrated framework that connects Industry 4.0 technologies with Industry 5.0 principles for quality management during the complete life cycle of plastic injection tools. Existing research is mainly focused on the digitalization and optimization of individual processes, while human-centricity, sustainability, resilience and the life cycle of tools are insufficiently integrated into a unique quality model.

3. Integrated Model of Industry 4.0 and Industry 5.0 for Quality Management During the Life Cycle of Plastic Injection Tools

The production of plastic injection molding tools has gone through a significant digital transformation with the adoption of Industry 4.0 technologies. Modern facilities of the INMOLD company for the production of molds use integrated digital production systems (CPS), which connect the functions of design, analysis, production, inspection and business management in a unique information environment, according to the Industry 4.0 model. This integration enables real-time information sharing, improved traceability, improved quality control and data-driven decision making throughout the mold lifecycle.

The existing digital manufacturing system for plastic injection molding tools consists of seven main components: CAD/CAM, CAE, CNC, EDM, CMM, MES and ERP [29-32]. Together, these systems support the planning, execution,

monitoring and optimization of the mold manufacturing process, according to the model in Figure 3.

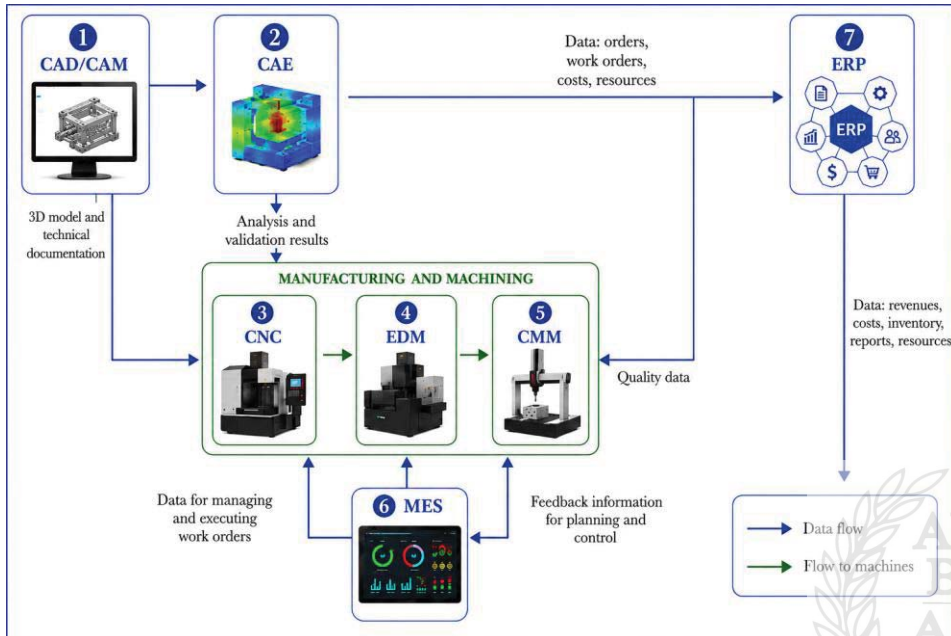


Figure 3. Industry 4.0 model for quality management of plastic injection molding tools at the INMOLD Company

CAD/CAM (1) systems form the basis of digital mold manufacturing. They enable the creation of three-dimensional digital models and the automatic generation of machining programs for production equipment. CAD/CAM improves quality through: accurate geometric modeling, reduced design errors, improved manufacturability, standardized design procedures, and reduced programming errors. The quality data generated are: CAD models, tolerance information, production drawings, CNC programs and process documentation. Coordinate Measuring Machines (CMMs) (5) are the primary metrology equipment used for dimensional verification of mold components. They provide very precise measurements: dimensions, geometric tolerances, surface profiles and shapes and prominent locations. In this Company, the CMM system supports: automated measurement programs, digital reporting, cloud connectivity, DT integration and AI-assisted inspection planning. CMM's contribution to quality management is: production quality verification, process capacity analysis, defect detection and traceability. The quality data generated are: inspection reports, SPC data, process capability indices and certified metrology protocols. A manufacturing

management system (MES) (6), acts as an operational management layer between plant equipment and enterprise-level systems, providing real-time insight into manufacturing operations. Contribution to quality management of MES are: quality monitoring in real time, non-conformity management, traceability and process control. The quality data generated are: production records, quality records, process histories, and performance indicators.

The proposed Integrated Quality Management Model of Industry 4.0 - Industry 5.0 represents the main contribution of this research, Figure 4. The model combines the technological capabilities of Industry 4.0 with the human-oriented, sustainable and resilient principles of Industry 5.0, in order to establish a comprehensive quality management framework oriented towards the life cycle of plastic injection tools.

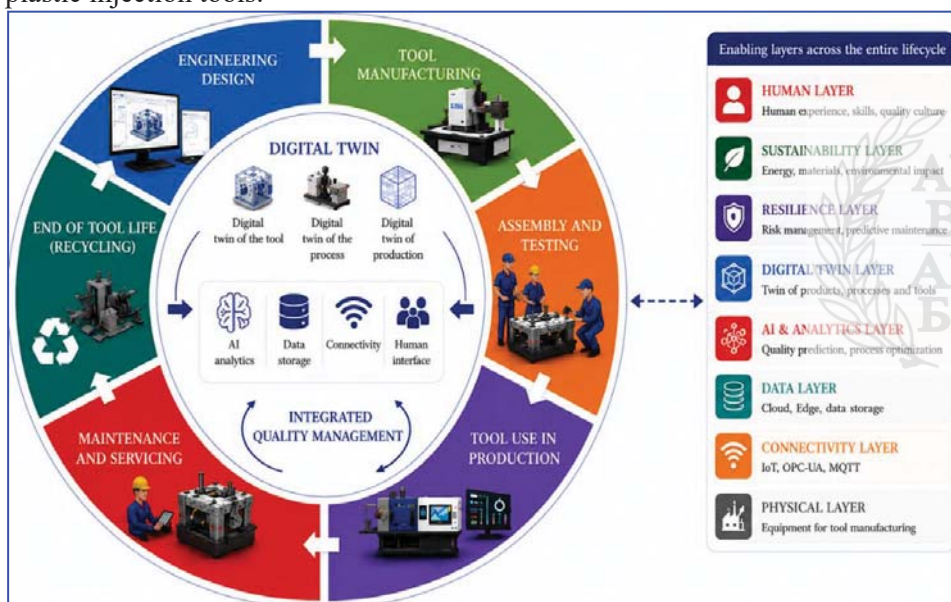


Figure 4. Proposed integrated model of Industry 4.0 and Industry 5.0 for quality management - general model

Existing approaches to quality management primarily focus on isolated phases of the life cycle, specific digital technologies or traditional quality methodologies. In contrast, the proposed framework provides a holistic architecture that integrates physical manufacturing systems, digital technologies, human expertise, sustainability goals, and resilience capabilities throughout the life cycle of a plastic injection tool. The model is defined in seven interconnected layers that

together support data collection, intelligent analytics, virtual representation, decision making, continuous improvement, sustainability improvement and resilience development.

Architecture of the proposed model follows a bottom-up structure, where information originates from physical production assets and moves progressively through connectivity, data management, analytics, DT, resilience mechanisms, sustainability evaluation and people-centered decision-making, Figure 5.

 HUMAN LAYER	Integrate design with quality	Qualified operators and technicians	Integrated quality validation and approval	Operational performance and measurement	Structure for decision-making and actions	Developing employees and knowledge transfer	Market awareness and customer satisfaction	Cross-functional teamwork	Human-centered leadership
 SUSTAINABILITY LAYER	Include human input and experience	Energy efficiency awareness	Optimize resources through integration	Efficient use of energy and materials	Continuous learning and improving skills	Share knowledge and best practices	Understand customer needs and create value	Improve internal communication and information flow	Create a healthy working environment
 RESILIENCE LAYER	Eco-friendly design and material selection	Reduce energy consumption	Optimize resources through integration	Efficient use of energy and materials	Reduce waste and emissions	Recycle, reduce waste and water usage	Reduce emissions and carbon footprint	Promote circular economy	Create long-term sustainable value
 DIGITAL TWIN LAYER	Risk assessment during design	Manage risks in processes and quality	Quick detection of defects and risk mitigation	Reaction to changes and uncertainties	Predictive maintenance and prevention	Improve the organization's resilience	End-to-end risk management and control	Ensure continuity and stability of processes	Adaptability and rapid recovery
 AI & ANALYTICS LAYER	Digital twin of the product	Digital twin of the process	Digital twin of the data	Digital twin linked to the real-time system	Digital twin for monitoring status and performance	Digital twin for simulation and prediction	Real-time digital twin updates and feedback	Data integration for better information	Transparency and traceability in real time
 DATA LAYER	AI for project and defect prediction	AI for process and tool optimization	AI for supply chain optimization	AI for process monitoring and alerting	AI for predictive maintenance and servicing	AI for quality control and improvement	AI for material selection and smart actions	AI for failure prediction	Intelligence for better decisions
 CONNECTIVITY LAYER	Data for design and simulation	Data for manufacturing and control	Data for testing and measurement	Data from IoT sensors and machines	Data for monitoring and system status	Data for analysis and reports	Data for traceability and life cycle	Data for change and initiatives	Secure and integrated data sources
 IoT Sensors  Wireless Connectivity  OPC UA  MQTT Enable seamless data acquisition and communication across all phases of the lifecycle.									
 PHYSICAL LAYER	Workstations for design and simulation	CNC, EDM, machines and other equipment	Equipment for assembly, CMM and testing	Machines for injection and testing	Machines for initial machining and texturing	Devices for sensing and measuring	Equipment for finishing and inspection	Systems for maintenance and repairs	Automation and physical safety

Figure 5. Integrated model of Industry 4.0 and Industry 5.0 for quality management of plastic injection molding tools - detailed structure

Layer 1 – Physical layer, represents the operational production environment in which quality-related information is generated. The component layers are *CPS processing systems* (Cutting, EDM, Grinding, Heat Treatment, Polishing and Plastic Injection Molding), *CMM, Mold Tools and Smart Sensors*. Primary functions include: production execution, inspection activities, process monitoring, tool condition monitoring, and product quality generation. This layer serves as the source of all quality data throughout the life cycle.

Layer 2 – Connection Layer, enables communication between physical devices, machines, sensors and higher-level digital systems. Its components are: *Internet of Things (IoT)* - enables device connectivity and real-time data collection, *OPC-UA* - supports secure and interoperable communication between industrial

systems, *MQTT* - enables easy and efficient communication between sensors, edge devices and cloud platforms. The functions of this layer are: real-time data transmission, interoperability, remote monitoring and system integration.

Layer 3 - The data layer stores, organizes and manages the production and quality information generated during the life cycle. The components are: *databases* - data on design, production, inspection, maintenance history and quality reports, *edge computing* provides local processing, low-latency analytics, and provides immediate decision-making support, *cloud computing*, provides central database generation, provides enterprise-wide accessibility, and scalable computing resources. The functions are: data management, traceability, historical analysis and preservation of knowledge about the life cycle of the tool.

Layer 4 – AI Analytics Layer, transforms raw data into actionable knowledge and predictive insights. Its components are: quality prediction using AI, related to - *dimensional deviations*, surface defects, process instability, and product inconsistencies, *process optimization, with the support of AI - processing parameters and modes, injection molding conditions, maintenance plans and energy* consumption monitoring. The technologies that support this concept are: AI, ML, BDA, DML, predictive analytics. This layer supports defect prevention, intelligent decision support, continuous process improvement, and predictive quality management.

Layer 5 – Digital Twin Layer (DT), creates virtual representations of physical entities and production processes, and its components are: *product digital twin* - represents the shaped product and its quality characteristics, which is applied for product validation, quality prediction, and life cycle analysis, *process digital twin* - represents production operations, and it is applied for process simulation and optimization and virtual commissioning, *digital twin tool* - represents the mold during its entire life cycle, and it is applied for: monitoring of wear, assessment of remaining useful life, predictive maintenance and overhaul planning. Features include virtual quality management, life cycle simulation, predictive maintenance, and continuous optimization.

Layer 6 – Resilience layer, introduces Industry 5.0 capabilities that improve system robustness, adaptability and business continuity. Its components are: *risk management* - risk identification, risk assessment, failure mode analysis, and quality risk prediction, *predictive maintenance* - preventing breakdowns, improving tool availability, reducing downtime, and optimizing maintenance. The functions of this layer are: enabling operational continuity, adaptive

manufacturing, cyber resilience, and supply chain resilience. The benefits are reduced downtime, improved reliability, and faster recovery from disruptions.

Layer 7 - Layer of sustainability, integrates aspects of environmental protection and resource efficiency in quality management. Its components are: *energy consumption monitoring* - machine energy consumption, process energy efficiency, and life cycle energy performance, *materials* - utilization and recycling of materials and waste generation, *carbon footprint - production-related CO₂ emissions*, life-cycle environmental impacts, and performance sustainability. The functions of this layer are: optimization of resources, reduction of environmental impact, application of circular economy, and sustainable quality management. The advantages are: reduced waste, lower energy consumption, and improved environmental performance.

Layer 8 – Human layer, represents the highest level of architecture and embodies the human-centric philosophy of Industry 5.0. People remain the final decision makers within the system. Its components are: *engineers* - responsible for design decisions, process optimization, and solving technical problems, *operators* - responsible for process monitoring, operational feedback, and participation in continuous improvement, *quality managers* - responsible for quality strategy, quality assurance and performance evaluation. The functions are: decision-making with the help of AI, integration of expert knowledge, human-robot collaboration and continuous learning. The benefits are better decision quality, increased innovation, improved organizational learning, and improved workforce engagement.

4. Application of the Integrated Model in the INMOLD Company

Here are three examples from the digital manufacturing model of the company Inmold, which illustrate the practical application of the elements of the Integrated Model. They relate to digital quality management (CAI/QMS), work order (ERP/MES) and new tool commissioning (MES).

The first example is related to the CMM, and the shown Figure 6 is the CMM measurement report for the control of the machined part M-975 NF #1 from the rear after the milling operation.

The report was created by integrating the 3D CAD model and CAI (PC DMIS model), and the control includes a total of **42 measurement locations (LOC1–LOC42)**. Most of the 42 controlled locations show very small deviations, usually in the range of a few micrometers to approximately 0.010 mm. Special attention is required for LOC5 and LOC6 with a deviation of **0.495 mm**, LOC34 with a diameter deviation of **+0.200 mm**, as well as three depth features LOC40–LOC42 with uniform deviations of approximately **-0.055 mm**.

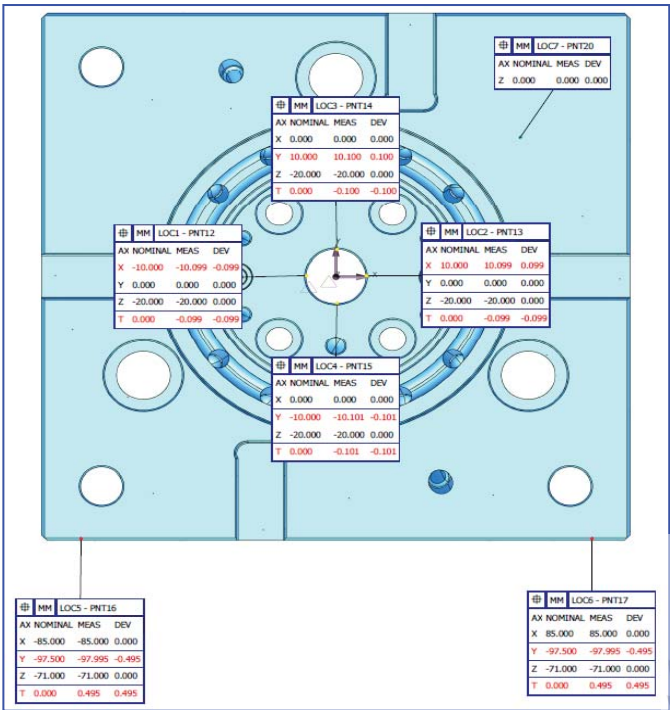


Figure 6. CMM report for part M- M-975 NF #1

Without the displayed tolerance limits, the conformity status cannot be definitively determined, but the image clearly enables the identification of critical features and is the basis for milling process correction, additional CMM checking and making a decision on part acceptance.

Another example refers to Work Order management, as part of the ERP/MES model, whose project is now being implemented, Figure 7.

In this company, the work order is given as a production work card, which contains a detailed work plan for the production of the part of the plastic injection **tool**, made within the project **M-990**, and it includes the complete technological flow of the production of the part (CAPP), from the initial preparation of the raw material, to the final CMM control. In the header of the first page, the basic information about the project is listed: project type is *M Packaging Mold M-XXX*, drawing number **prd-27373255-01857268**, article number **M-990-F-1.1-01-01**, and the name of part **33 – Cavity (NF)**. It is a part of a quadruple tool for the production of a bucket, where the planned quantity is four pieces. The project

implementation period is defined as of **March 25, 2026. until 14.08.2026.** The central part shows a 3D CAD model of the controlled part of the tool.

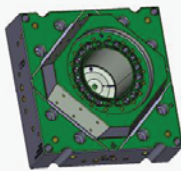
		Radna karta & Plan rada		Br. Projekta: M-990	
Vrsta projekta: M_Packaging_Mold M-XXX			Jedinična cena: NG/03		
Br. Crteža: prd-27373255-01857268		Datum dodavanja: 25.03.2026		Datum završetka: 14.08.2026	
Količina: 4 Piece		Opis: Four cavity bucket JST13-9 mold (I02773)			
Br. artikla: M-990-F-1.1-01-01			Naziv: 33 - Cavity (NF)		
					
10	Aktivnost: M_Rough milling preparation Komethnar: Obrada spoljašnjih gabarita Po visini ostaviti 1mm dodatka. Raspodela dodatka je pola/pola.			Datum: 06.05.2026 Datum / ime: 30.04.2026 ✓ DDomanović	
P846354					

Figure 7. Front page of the Work Order (Work Card) for part M-990

The work card includes **25 numbered activities**, from 10 to 250, and shows a complete digitally traceable flow: **preparation → CAPP/CAM programming → CNC milling → drilling cooling channels → five-axis drilling → control → finishing → heat treatment → grinding → finishing → EDM → CMM control → polishing → final CMM control (CAI inspection).** The document shows a high level of organization and traceability of production in the ERP/MES model. Each activity is associated with a corresponding code and barcode, which enables the connection of the Work Order with production data, operators, execution dates (scheduling) and process status.

The picture represents a practical example of **digitally supported quality management in the life cycle - the manufacturing phase of a complex part of a plastic injection molding tool.** The most important feature of the document is the integration of design (CAD/CAE), CAM programming, CNC and five-axis processing, EDM processes, thermal processing, grinding, polishing and CMM control into a single technological sequence. The existence of control and corrective loops is particularly important: the part is controlled before heat treatment, refined and re-controlled if necessary, while intermediate and final CMM measurements (CAI inspection) are carried out in the final phase. This structure of the Work Order is the basis for connection with **ERP, MES,**

CAPP/CAM/CNC/CAI and QMS systems. as well as for the application of the concept of digital traceability in the model of digital production of tools, and as a basis for blockchain.

Finally, the third example refers to the trial operation of a new tool, before its release into regular production, Figure 8.

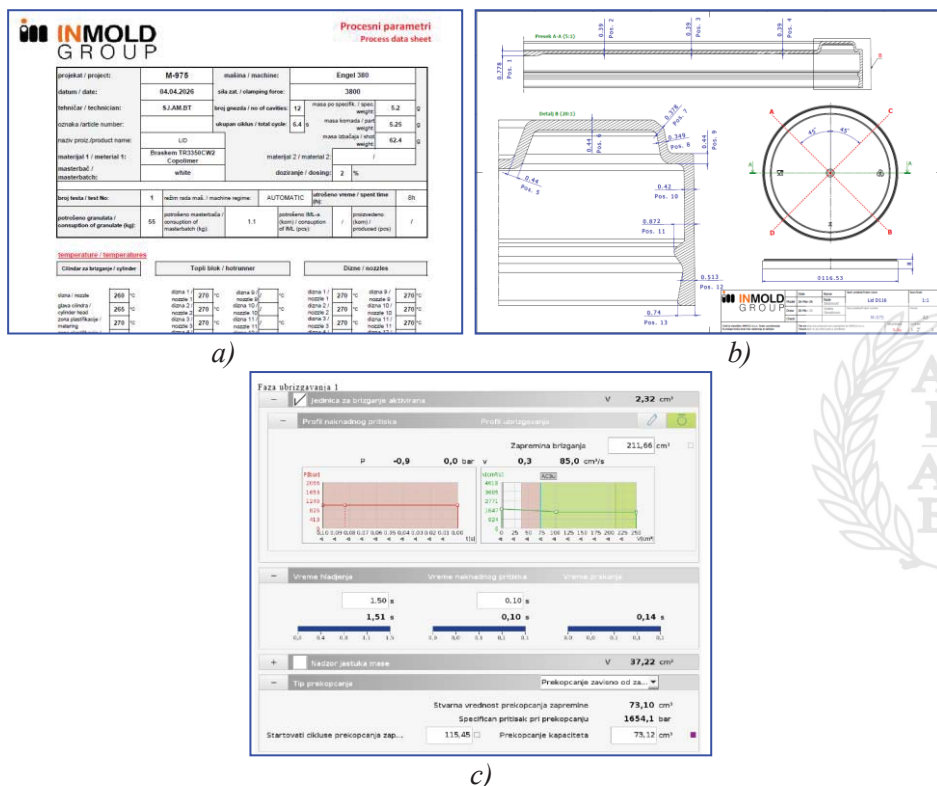


Figure 8. Tool commissioning - test injection molding for part M-975

Document 8a is a technical report on the process parameters of the test injection molding of the plastic part for the M-975 project and provides a complete overview of the process settings on the Engel 380 machine. The header contains basic data about the test: date **04/04/2026.**, technicians **S.J.A.M.B.T**, tool with **12 nests**, product **LID**, material **Braskem TR3350CW2 Copolymer** and white masterbatch with dosage of **2%**. The total cycle time is **6.4 s**, the mass of the individual part is **5.25 g**, and the mass of the ejection is **62.4 g**. The test was performed in automatic mode and lasted **8 hours**. The main part of the document shows the key groups of process parameters: injection cylinder, hot block and

nozzle temperatures; tool closing and opening parameters; parameters of injection molding and subsequent pressure; as well as the parameters of dosing and movement of the auger. Cylinder temperatures range from approx **260 to 270 °C**, while the temperatures of the hot block and active nozzles are set at around **270 °C**. A height of **878.2 mm**, an opening stroke of **500 mm**, a closing time of **1.02 s**, an opening time of **0.75 s** and a locking force of **2700 kN** were recorded for the tool. In the injection molding section, a cooling time of **1.5 s**, a switching pressure of **1654.1 bar**, and a maximum subsequent pressure of **1033.2 bar** are shown. and a clutch position of **72.13 cm³**. The document represents an important record for **tool validation, process reproducibility, cycle optimization and product quality control**. It can be used as a reference process sheet for future tests, batch production and process parameter deviation analysis.

Figure 8b shows a **technical drawing of the control points of the plastic product "Lid D116"**, made within the **M-975 project**, belonging to the Inmold Group company and serving as the basis for dimensional control of the product after the injection molding process. The mass of the product is **5.2 g**. The drawing shows the basic projections of the product, a side view, **section A-A in a scale of 5:1** and enlarged **detail B in a scale of 20:1**. The product is circular in shape, with a nominal diameter of **Ø116.53 mm** and a total height of approximately **8 mm**. **The 13 numbered control positions (pos. 1–13)** are of particular importance. Wall thicknesses and local geometric characteristics of the product are checked on them. Nominal values shown include **0.778 mm** at position 1; **0.39 mm** in positions 2, 3 and 4; **0.44 mm** in positions 5, 6 and 9; **0.378 mm** at position 7; **0.349 mm** at position 8; **0.42 mm** at position 10; **0.872 mm** at position 11; **0.513 mm** at position 12 and **0.74 mm** at position 13. Enlarged detail B clearly shows the complex geometry of the product rim: thin walls, transition radii, stepped surfaces and local thickness changes. This display enables precise control of critical zones that may be subject to deformation, shrinkage or uneven filling during injection molding.

Figure 8c shows a **screenshot of the parameters of the first injection stage** on a plastic injection molding machine, recorded **on April 4, 2026**. The document represents an operational record of actual and set process parameters during the test operation of the **M-975 tool**. The upper part shows the **injection profile**, with graphical representations of pressure and speed as a function of time and volume. The specified **injection volume is 211.66 cm³**, while the displayed injection speed is **85.0 cm³/s**. The graphics enable visual monitoring of changes in process parameters during filling of mold cavities. The central part shows the time parameters of the process. **The cooling time is 1.50 s**, the actual registered value is **1.51 s**, **the subsequent pressure time is 0.10 s**, and **the spraying or injection time is 0.14 s**. These very short time intervals indicate a highly productive process

with a short overall cycle. **The monitoring of the mass cushion**, whose value is **37.22 cm³**, is shown in particular. In the section for switching from the filling phase to the afterpressure phase, the actual switching volume of **73.10 cm³**, the set capacity value of **73.12 cm³** and the specific switching pressure of **1654.1 bar** are shown. In the section **Injection pressure**, the limit value of the specific pressure of **1859.7 bar** is specified, while the actual specific value of the injection pressure is **1654.1 bar**. It shows that the process is taking place below the defined maximum limit. The lower part of the picture shows a plasticizing unit with a screw diameter of **70.0 mm** and a screw geometry of **the Barrier type**. Overall, the figure represents an important process record for **test injection validation, parameter optimization, process stability control, and linking of injection parameters with the results of dimensional control of the Lid D116 product**. The drawing represents **the dimensional control plan of the product** and is used for CMM measurement, section control, tool validation and comparison of actual results with nominal values. It is especially important for connecting the process parameters of injection molding with product quality and proving the stability of the production process with the M-975 tool.

5. Discussion

For the Integrated Industry 4.0 - Industry 5.0 model for quality management throughout the life cycle of plastic injection molding tools, key performance indicators (KPIs) should cover not only the traditional quality, productivity and cost metrics, but also the three basic pillars of Industry 5.0: human focus, sustainability and resilience. The framework of KPIs can be structured according to the stages of the life cycle of the tool, Figure 9. In the design area, seven parameters are defined, from the design error rate (%), to the knowledge usage rate, also in %. For the area of tool production, ten KPI parameters were defined, from dimensional accuracy analysis in (μm), to equipment downtime (h/month). For assembly and test work activities, six parameters are defined, from the assembly defect rate (%), to the accuracy of digital balance validation (%). Using the tool in production is the next activity in the life of this product. A total of ten KPI parameters were defined for this phase, from the rate of defective products (ppm), to the time of starting work after repair (h). The next stage is tool maintenance. Eight KPI parameters are defined here, from the tool failure rate (%), to the failure prediction time horizon (days). Repairs and overhaul is one of the very important phases in the tool life, for which five KPI parameters are defined. The first is the overhaul success rate (%), to the accuracy of decisions with expert support (%). The last stage in the life of a tool is retirement or end of life. There are five KPI parameters defined for this activity, from the degree of

recycling (%) to the circularity index (%). Summarizing this analysis, we can say that a total of 51 KPI parameters were developed for this model.

Data sources for these parameters are the elements of Industry 4.0 in application, namely: IoT sensors, MES/ERP systems, SCADA systems, quality control, big data platform and cloud computing. The key element of this data hub is the DT tool, and the added value to this concept is given by the elements of Industry 5.0, and they generate KPI parameters related to: human-centeredness, sustainability, resilience, human-AI cooperation and knowledge and experience sharing. This concept is implemented in the KPI feedback loop of continuous quality improvement, which includes: real-time data collection, KPI monitoring at each stage, analysis and diagnosis (AI & expertise), actions and improvements (corrective / preventive), and validation of results, where KPI improvements are measured. Based on all fifty-one KPI parameters, its integral framework was defined, which has five dimensions: quality (Q), productivity (P), sustainability (S), human-centeredness (H), and resilience (R). On the axis of these elements and weight coefficients (Wi), the Total Quality Index during the life cycle of the tool is defined - OLQI. It should be emphasized here that as part of the developed Integrated Model, there is also a set of strategic KPI parameters for the management level, six basic ones (from first time correct $\geq 90\%$, to energy per tool < 1400 kWh/tool). The six additional parameters are, from the parameter related to the carbon footprint < 350 kg CO₂ / tool, to the OLQI index $\geq 85\%$.



Figure 9. Structure of KPI parameters in the lifetime of the tool

The left module contains (not shown in Figure 10) four layers of the architecture, namely: data collection, Industry 4.0 analytics, KPI calculation and decision support. This last layer is particularly interesting, because it contains the functions of online monitoring of KPI parameters, predictive warnings, determined based on the trends of KPI parameters and recommendations for action, with the aim of improving the Integrated Tool Quality Management Model according to the Industry 4.0 and Industry 5.0 models for plastic injection molding. The right module has the following overviews: (a) for management (KPI parameters for the strategic level - OLQI and so on), (b) KPI panel by stages of the tool life, seven stages in total, with an indicator - good (and this indicator can be: critical, weak, moderate, good and excellent), (c) the performance panel of Industry 5.0, for its three pillars, and (d) the OLQI panel. Particularly important is the Trend Panel, which for the six indices of the most important KPI parameters, shows their real-time In this way, the second output of this project is completed for the Integrated Management Model of Plastic Injection Molding.



Figure 10. Integrated KPI dashboard for a plastic injection molding tool

The values of the weighting coefficients of the Integrated Quality Index are specifically stated here, namely: w_1 - quality (30%), w_2 - productivity (25%), w_3 - sustainability (20%), w_4 - human moderation (15%), and w_5 - resistance (10%). From the analysis of these weight coefficients, we can conclude that tool quality and productivity (application of Industry 4.0 elements) have the greatest impact on the Integrated Index.

These KPIs provide a comprehensive measurement system, which simultaneously evaluates Quality 4.0 (digitalization, AI, DT, IoT) and Quality 5.0 (human-centeredness, sustainability and resilience), throughout the life cycle of a plastic injection tool, and they are well aligned with the model defined in this paper.

In the conclusion of this discussion, we can confirm that the basic framework of the life cycle KPI architecture is: design → production → assembly and trial operation → production → maintenance → overhaul → end of life, which provide a flow of key performance indicators (KPI) between phases, as well as feedback loops for continuous improvement. The hierarchical KPI model is defined over three levels: strategic KPIs (management level), tactical KPIs (at department level), and operational KPIs (at production plant level). The key performance indicators (KPI) layer of Industry 4.0 are: IoT connectivity index, DT accuracy, AI prediction accuracy, data availability, and cyber security index. Key Performance Indicators (KPI) for Industry 5.0: and human-centeredness index, sustainability index, and resilience index, and especially as an aggregate value - Total Life Cycle Quality Index (OLQI), Figure 11.

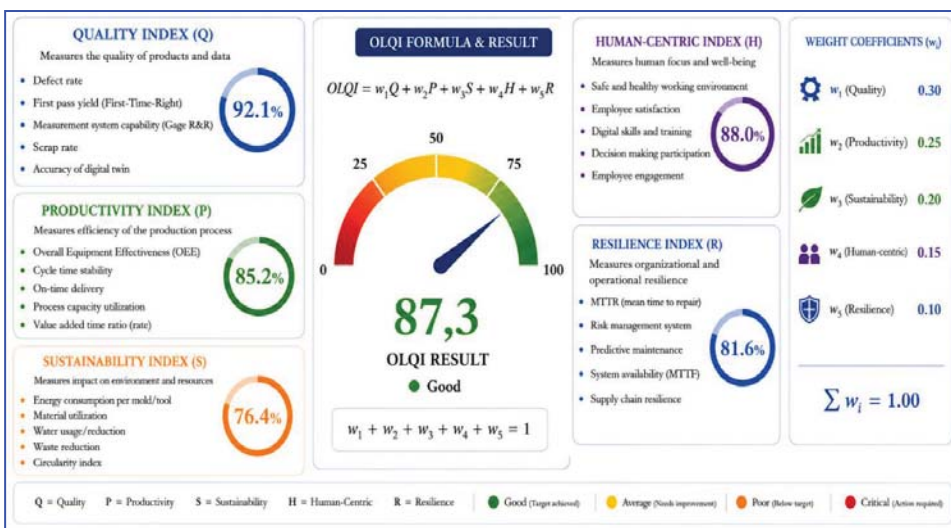


Figure 11. Table of the overall quality index of plastic injection molding tools

The proposed Integrated Key Performance Indicator (KPI) dashboard enables: quality support (reduced defects, improved dimensional accuracy, and improved process capacity), productivity support (higher OEE, reduced downtime, and faster maintenance), sustainability support (lower energy consumption, reduced waste, and increased tool life), human-centric support (better decision support, improved employee engagement, and improved knowledge sharing), and resilience support (faster recovery from disruptions, improved predictive maintenance, and better preparedness for cyber security).

The dashboard therefore acts as **the digital nervous system of the entire tool life cycle**, integrating Industry 4.0 technologies and Industry 5.0 values into a unique lifecycle-oriented quality management platform, focused on the **Integrated Life Cycle Quality Index (OLQI)** of plastic injection molding tools.

6. Conclusions and Future Research

This paper defined an Industry 4.0 - Industry 5.0 Integrated Quality Management Model for plastic injection molding tools, addressing the growing need for an intelligent, sustainable, resilient and human-centered quality management model throughout the tool life cycle. The research is motivated by the increasing complexity of the mold manufacturing process and the limitations of existing quality management approaches, which often focus either on traditional quality methods or on isolated Industry 4.0 technologies, without fully considering human-centeredness, sustainability, resilience and life cycle integration.

The research objectives were successfully achieved. First, a comprehensive life-cycle-based quality management framework was developed, covering all major phases of the life cycle, including design, manufacturing, assembly and testing, production use, maintenance and overhaul, and end-of-life management. Second, Industry 4.0 technologies such as IoT, AI, ML, BDA, cloud/edge computing, DT and cyber security are systematically integrated with the principles of Industry 5.0, which relate to human-centeredness, sustainability and resilience. Third, the proposed framework has shown potential for improving tool quality, operational performance, environmental sustainability, and organizational adaptability.

The main contribution of this research is the development of a new multi-layered architecture, which combines technological intelligence with human expertise and sustainability-oriented decision-making. The proposed framework consists of physical, connectivity, data, AI analytics, DT, resilience, sustainability and human

layers that together support predictive quality management and continuous lifecycle improvement. Unlike conventional quality management systems, the proposed model promotes proactive defect prevention, predictive maintenance, lifecycle traceability, resource efficiency, and collaborative decision-making between humans and AI.

From a quality management perspective, the framework extends the existing concepts of Quality 4.0 towards a more comprehensive approach, Quality 5.0. Integrating DT, AI-driven analytics, predictive quality management and human knowledge, enabling more efficient quality control, faster root cause identification, improved dimensional accuracy, reduced defect rates and extended tool life. Furthermore, sustainability-oriented quality management contributes to reduced energy consumption, less material waste, improved use of resources and improved application of the circular economy. The resilience layer strengthens operational continuity, through predictive maintenance, risk prediction, cyber resilience and supply chain resilience.

The practical implications of the proposed model are significant for tool manufacturers, who want to improve competitiveness in increasingly digitized and sustainably oriented industrial environments. The framework can support the implementation of smart manufacturing strategies, improve life cycle management practices, reduce operational costs, improve product quality and facilitate compliance with new sustainability and traceability requirements. In addition, the model provides a practical roadmap for organizations transitioning from traditional quality management systems to manufacturing ecosystems oriented towards Industry 5.0.

Future development, Figure 12, should focus on the integration of new technologies, such as generative artificial intelligence (GenAI) for tool design, autonomous quality systems, explainable artificial intelligence (XAI), federated learning, green digital twins and digital product passports [14,15,17,18].

These technologies have the potential to further improve lifecycle intelligence, sustainability and decision-making transparency. Furthermore, future research should explore the development of a 5.0 tool quality maturity model, quantitative validation methodology, and industrial case studies, to evaluate the practical effectiveness of the proposed framework in real manufacturing environments. In conclusion, the proposed Integrated Quality Management Model of Industry 4.0 - Industry 5.0, provides a comprehensive basis for the future of quality management of plastic injection molding tools.

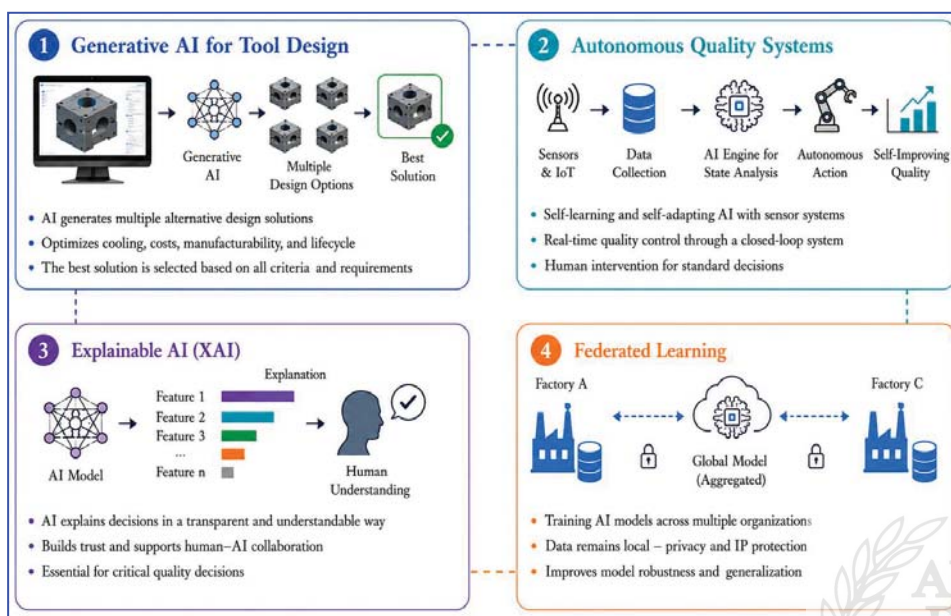


Figure 12. Future directions of research and development of the Integrated Model

Combining advanced digital technologies with human expertise, sustainability principles and resilience capabilities, the framework supports the development of intelligent, adaptive, sustainable and human-centered manufacturing systems, capable of achieving long-term excellence in quality, throughout the mold life cycle.

References

- [1] Kagermann, H., Wahlster, W., Helbig, J. (2013). Recommendations for implementing the strategic initiative Industrie 4.0. Acatech. <https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/> .
- [2] Lassi, H., et al. (2019). Industry 4.0. *Business & Information Systems Engineering*, 6 (4), 239–242. <https://doi.org/10.1007/s12599-014-0334-4> .
- [3] Xu, LD, Xu, EL, Li, L. (2018). Industry 4.0: State of the art and future trends. *International Journal of Production Research*, 56 (8), 2941–2962. <https://doi.org/10.1080/00207543.2018.1444806> .
- [4] Frank, AG, Dalenogare, LS, Ayala, NF (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. *International Journal of Production Economics*, 210, 15–26. <https://doi.org/10.1016/j.ijpe.2019.01.004> .
- [5] Culot, G., et al. (2020). Behind the definition of Industry 4.0. *Computers in Industry*, 113. <https://doi.org/10.1016/j.compind.2019.103122> .
- [6] Tao, F., et al. (2019). Digital Twin in Industry. *IEEE Transactions on Industrial Informatics*, 15 (4), 2405–2415. <https://doi.org/10.1109/TII.2018.2873186> .
- [7] Jones, D., et al. (2020). Characterizing the Digital Twin. *CIRP Journal of Manufacturing Science and Technology*, 29, 36–52. <https://doi.org/10.1016/j.cirpj.2020.02.002> .
- [8] Leng, J., et al. (2021). Digital twins-based smart manufacturing system design. *Journal of Manufacturing Systems*, 60, 119–137. <https://doi.org/10.1016/j.jmsy.2021.05.007> .
- [9] Fuller, A., et al. (2020). Digital Twin: Enabling technologies. *IEEE Access*, 8, 108952–108971. <https://doi.org/10.1109/ACCESS.2020.2998358> .
- [10] Rosen, R., et al. (2019). About the importance of autonomy and Digital Twins. *IFAC-PapersOnLine*, 48 (3), 567–572. <https://doi.org/10.1016/j.ifacol.2015.06.141> .
- [11] Sony, M., Antony, J., Douglas, JA (2020). Essential ingredients for Quality 4.0. *The TQM Journal*, 32 (4), 779–793. <https://doi.org/10.1108/TQM-12-2019-0275> .
- [12] Sony, M., et al. (2021). An empirical examination of Quality 4.0. *The TQM Journal*, 33 (6), 1241–1262. <https://doi.org/10.1108/TQM-05-2020-0118> .
- [13] Jacob, D. (2020). Quality 4.0 impact and assessment. *International Journal of Quality & Reliability Management*, 37 (9), 1165–1185. <https://doi.org/10.1108/IJQRM-07-2019-0210> .
- [14] Antony, J., et al. (2022). An exploration of Quality 4.0. *International Journal of Quality & Reliability Management*, 39 (5), 1249–1273. <https://doi.org/10.1108/IJQRM-10-2020-0362> .

- [15] Breque, M., De Nul, L., Petridis, A. (2021). Industry 5.0: Towards a sustainable, human-centric and resilient European industry. European Commission. <https://doi.org/10.2777/308407> .
- [16] Xu, X., et al. (2021). Industry 4.0 and Industry 5.0—Inception, conception and perception. *Journal of Manufacturing Systems*, 61, 530–535. <https://doi.org/10.1016/j.jmsy.2021.10.006> .
- [17] Lu, Y., et al. (2022). Outlook on human-centric manufacturing towards Industry 5.0. *Journal of Manufacturing Systems*, 62, 612–627. <https://doi.org/10.1016/j.jmsy.2022.02.001> .
- [18] Maddikunta, PKR, et al. (2022). Industry 5.0: A survey. *Information Systems Frontiers*, 24, 123–147. <https://doi.org/10.1007/s10796-021-10143-z> .
- [19] Javaid, M., et al. (2021). AI applications in manufacturing quality. *Materials Today: Proceedings*, 44, 5086–5091. <https://doi.org/10.1016/j.matpr.2021.01.585> .
- [20] Wuest, T., et al. (2019). Machine learning in manufacturing. *Engineering Applications of Artificial Intelligence*, 48, 118–133. <https://doi.org/10.1016/j.engappai.2015.10.008> .
- [21] Kusiak, A. (2018). Smart manufacturing. *International Journal of Production Research*, 56 (1–2), 508–517. <https://doi.org/10.1080/00207543.2017.1351644> .
- [22] Carvalho, TP, Soares, FAAMN, et al. (2019). Predictive maintenance review. *Computers & Industrial Engineering*, 137. <https://doi.org/10.1016/j.cie.2019.106024> .
- [23] Zonta, T., et al. (2020). Predictive maintenance in Industry 4.0. *Computers & Industrial Engineering*, 150. <https://doi.org/10.1016/j.cie.2020.106889> .
- [24] Ghobakhloo, M. (2020). Industry 4.0 and sustainability. *Journal of Cleaner Production*, 252. <https://doi.org/10.1016/j.jclepro.2019.119869> .
- [25] Ghobakhloo, M., et al. (2024). Industry 5.0 and sustainable manufacturing. *Journal of Cleaner Production*, 435. <https://doi.org/10.1016/j.jclepro.2023.140461> .
- [26] Rajput, S., Singh, SP (2020). Industry 4.0 and circular economy. *Business Strategy and the Environment*, 29 (6), 2380–2396. <https://doi.org/10.1002/bse.2517> .
- [27] Amanov, A., Pyun, YS, Sasaki, S. (2019). Lifecycle improvement of injection molds. *Wear*, 426–427, 1141–1149. <https://doi.org/10.1016/j.wear.2018.12.073> .
- [28] Mourtzis, D., Angelopoulos, J., Panopoulos, N. (2023). Digital technologies in tooling lifecycle management. *Journal of Manufacturing Systems*, 69, 639–657. <https://doi.org/10.1016/j.jmsy.2023.08.009> .
- [29] Vojin Vukadinović, Jovan Živković, Dragan Đurđanović and Vidosav Majstorović, Management of tools in digital manufacturing - A case study, *MATEC Web Conf.*, 368 (2022) 01014, <https://doi.org/10.1051/mateconf/202236801014> .

- [30] Jokovic, Z., Jankovic, G., Jankovic, S., Supurovic, A., & Majstorovic, V. (2023). Quality 4.0 in Digital Manufacturing – One Example. Preprints. <https://doi.org/10.20944/preprints202305.1156.v1> .
- [31] Karabegović, I., Majstorović, V. (Eds), 2024, *Industry 4.0: Digital Transformation Shaping the Future* (Industry 4.0: Digital Transformation Shaping the Future), *Society for Robotics in Bosnia and Herzegovina, Bihać, Academy of Sciences and Arts of Bosnia and Herzegovina, Sarajevo*. ISBN 978-9958-9262-8-0, ISBN 978-9926-410-94-0, <https://bastina.anubih.ba/handle/123456789/789> .
- [32] Majstorovic, VD, Vukadinovic, VS, & Živković, J. (2023). Towards the Digital Model of Tool Lifecycle Management in Sheet Metal Forming. *Journal of Machine Engineering*. <https://doi.org/10.36897/jme/171664>.

