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Design and Industrial Integration of Automated Coordinate Measuring Machines for Automotive Production

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Abstract

Recent advances in machine design, automation, and industrial digitalization have transformed Coordinate Measuring Machines (CMMs) from standalone inspection devices into fully integrated elements of automated manufacturing systems. In the automotive sector, CMMs increasingly operate in workshop, near-line, and in-line environments, interacting with production equipment and contributing directly to process control and zero-defect manufacturing strategies. This paper presents a structured methodology for the industrial deployment of automated CMMs in automotive mechanical manufacturing. The proposed approach is illustrated through an industrial use case involving the dimensional inspection of mechanically machined components under real production conditions. The methodology addresses machine design selection, sensor configuration, environmental constraints, and multi-axis architectures, as well as validation and acceptance procedures based on the ISO 10360 series. Particular attention is given to the integration of CMMs within automated manufacturing systems, including robustness against thermal variations, vibrations, and contamination, and the use of metrological data for feedback to machining processes. Rather than introducing new metrological principles, the proposed approach focuses on the structured integration of established engineering practices into a coherent lifecycle-based deployment framework. Based on industrial experience, the proposed methodology is illustrated through an industrial case study to support the reliable of automated dimensional inspection, reduce measurement-related risks, and support the integration of CMMs as active components of modern automated manufacturing systems.

Keywords: Coordinate Measuring Machine (CMM); machine design; industrial automation; automotive manufacturing; dimensional inspection; metrology integration; smart manufacturing; zero defect manufacturing

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1. Introduction

Coordinate Measuring Machines (CMMs) have traditionally been used for off-line dimensional verification in metrology laboratories [1]. In recent years, their use has expanded beyond laboratory environments [2–6], allowing CMMs to be applied closer to manufacturing processes and production equipment. As a consequence, dimensional inspection is increasingly positioned closer to the production process and contributes directly to manufacturing control activities [4,5].

This evolution is particularly relevant in the automotive sector, where high production volumes coexist with increasingly demanding dimensional and geometric tolerances. In such environments, CMMs are progressively deployed in workshops, near-line, and in-line locations, interacting with production equipment and supporting activities such as process monitoring and machine tool adjustment [3,4]. For this reason, the design and integration of CMMs can affect the robustness and performance of the production process.

Despite significant technological progress, the industrial deployment of CMMs is often addressed in a fragmented manner [3]. Key aspects such as machine selection, metrological validation, adaptation to industrial environments, and operation during series production are frequently addressed as independent stages. As a result, a unified lifecycle-based approach that considers the measurement system as a whole is often lacking [2]. This separation can result in inadequate design decisions, increased metrological risks, and limited automation capability when the CMM is deployed in a real production environment [4].

Accordingly, the aim of this work is to propose a structured methodology for the industrial deployment of automated CMMs in automotive manufacturing. The proposed approach integrates machine design decisions, validation procedures, and production operation requirements within a coherent lifecycle-based framework. The objective is to ensure reliable and robust dimensional inspection under real industrial operating conditions. This lifecycle-based approach has been represented in Figure 1.

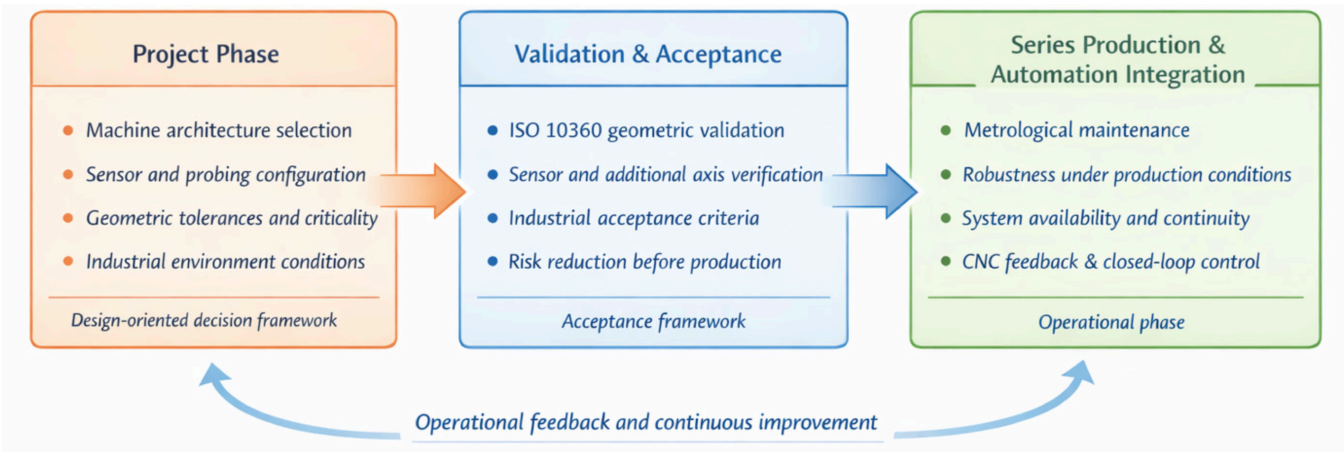

Figure 1. Lifecycle-based methodology for the industrial deployment of automated Coordinate Measuring Machines (CMMs), integrating machine design decisions, metrological validation and acceptance, and series production operation within automated manufacturing systems.

This approach is based on international standards and industrial experience in the manufacturing of mechanical components for the automotive sector and is illustrated through a representative industrial case study. The objective is to enhance the robustness and consistency of dimensional metrology in alignment with the principles of industrial automation and smart manufacturing. Within this framework, CMMs are considered automated machines integrated into the production process rather than standalone inspection devices.

In line with this approach, it is necessary to analyze CMM from the perspective of their design as automated industrial systems. Aspects such as machine mechanical architecture, sensor configuration, the incorporation of additional axes, and adaptation to the working environment directly affect both metrological performance and the capability for integration into automated manufacturing systems. For this reason, the following section reviews the main CMM configurations and their evolution toward workshop and production-line environments, focusing on the design implications that enable reliable operation as active components of modern automated manufacturing systems.

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Rather than addressing CMM selection solely as a specification-matching exercise, this work proposes a lifecycle-based engineering perspective that integrates dimensional requirements, environmental conditions, validation standards, and automation constraints into a unified decision framework [1,4]. By structuring the deployment of CMM as part of an industrial risk-management and automation strategy [3,5], the proposed approach bridges the gap between metrological validation and real production environments, ensuring that accuracy, robustness, and system availability are considered from the earliest project stages through series production [2].

It should be noted that the contribution of this work does not lie in the introduction of new metrological principles or fundamentally new selection criteria. Instead, the novelty resides in the structured integration of established engineering practices—such as tolerance-based selection, environmental assessment, and standardized validation—into a coherent lifecycle-based framework specifically adapted to the deployment of automated CMM systems in manufacturing environments.

Based on the identified gap, this work aims to structure the industrial deployment of automated CMM within a lifecycle-based engineering framework. The main contributions of this work can be summarized as follows:

- Integration of lifecycle phases into a unified framework for CMM deployment in automated manufacturing environments.
- Explicit linkage between tolerance– Maximum Permissible Error (MPE) criteria, environmental conditions, and automation requirements within the decision-making process.
- Application-oriented validation strategy that connects standardized metrological verification with industrial acceptance and production performance.

The remainder of this paper is organized as follows. Section 2 reviews the main CMM architectures and design considerations relevant for automated manufacturing environments. Section 3 presents the proposed lifecycle-based methodology for industrial deployment and validation of automated CMMs. Section 4 illustrates the methodology through an industrial case study and discusses the main results. Finally, Section 5 summarizes the conclusions and outlines future research directions.

2. Coordinate Measuring Machines as Industrial Automated Systems

In automated manufacturing environments, CMMs are not only used for metrological purposes. Their evolution has been driven not only by advances in measurement technology, but also by developments in machine design, control systems, and industrial production requirements [2,3,5]. Mechanical architecture, sensor configuration, and adaptation to the operating environment therefore influence metrological performance and the use of CMMs in production lines [1,4,6].

2.1. Machine Architectures

One of the primary design factors in assessing the suitability of a Coordinate Measuring Machine for integration into automated environments is its mechanical architecture [1]. Figure 2 illustrates the most common CMM architectures used in industrial contexts, highlighting their accessibility, metrological performance, and suitability for automated inspection [1,6].

In automotive manufacturing, bridge-type CMM configurations are the predominant solution, as they provide a well-balanced compromise between measurement volume, accessibility, and metrological performance [1]. Their structural rigidity and well-defined kinematic behavior enable the inspection of a wide range of machined components and support reliable automation under industrial operating conditions [1,6].

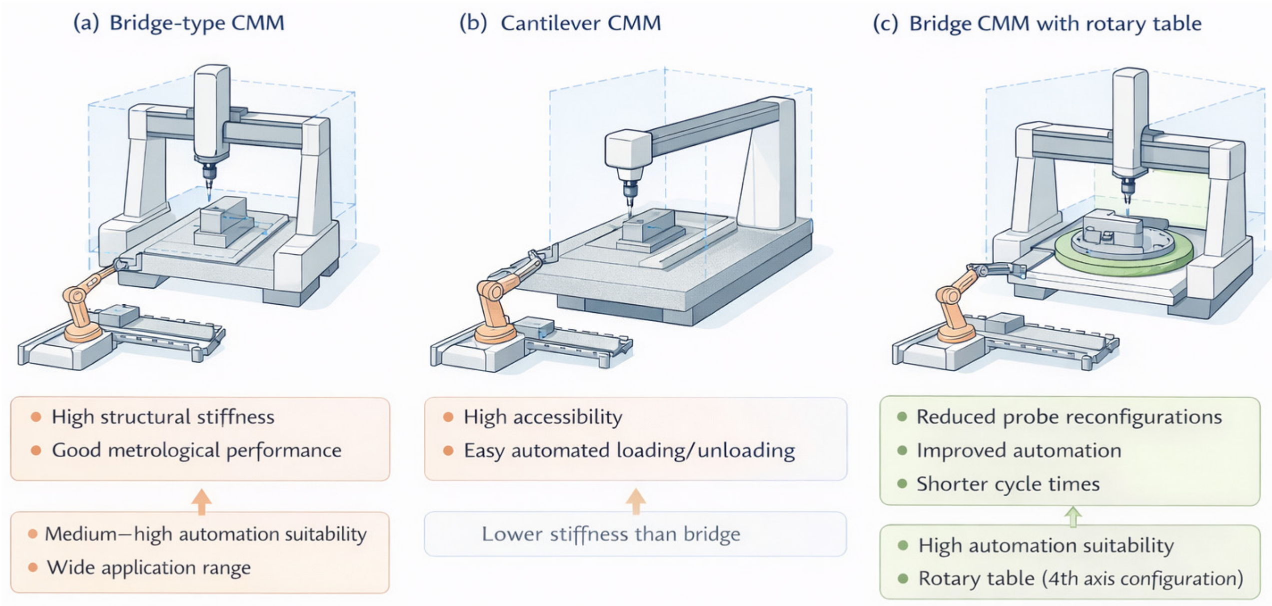

Figure 2. Typical Coordinate Measuring Machine (CMM) architectures used in industrial environments: (**a**) bridge-type CMM, (**b**) cantilever CMM, and (**c**) bridge CMM equipped with a rotary table, highlighting their implications for accessibility, metrological performance, and suitability for automated inspection.

Cantilever CMM configurations are increasingly used in workshop and near-line applications, especially for small- to medium-sized components [1]. While offering lower structural rigidity than bridge-type machines, they provide enhanced accessibility and support automated loading and unloading, making them suitable for applications where flexibility and production-line integration are key requirements [1,6].

The integration of additional axes, such as rotary tables, is a key design feature of CMMs intended for automated applications [1,4]. These axes enhance access to geometric features, limit the need for multiple probing configurations, and streamline measurement programs [4]. In automated inspection systems, the reduction in reconfigurations improves repeatability, shortens cycle times, and increases the overall robustness of the measurement process [4,6,7].

From a lifecycle perspective, CMM architecture selection directly influences accessibility, structural stability, and integration constraints, which are critical factors in defining selection criteria and validation requirements in automated production environments.

Table 1 summarizes the main characteristics of typical CMM architectures with respect to their suitability for automated industrial deployment [1].

Table 1. Comparison of typical Coordinate Measuring Machines (CMMs) architectures with respect to automation-oriented design criteria.

CMM Architecture	Metrological Accuracy	Structural Robustness	Accessibility to Measurement Volume	Suitability for Automation	Typical Industrial Application
Bridge-type CMM	High	High	Medium	High	Wide range of machined automotive components requiring tight tolerances
Cantilever CMM	Medium to High	Medium	High	Very High	Near-line and workshop inspection of small- to medium-sized parts

Table 1. *Cont.*

CMM Architecture	Metrological Accuracy	Structural Robustness	Accessibility to Measurement Volume	Suitability for Automation	Typical Industrial Application
Bridge CMM with Rotary Table	High	High	Very High	Very High	Automated inspection of complex geometries and multi-sided components
Gantry-type CMM	Very High	Very High	Medium	Medium	Large automotive components and structures

Note: The qualitative assessment presented in this table is based on industrial experience and literature review, and is intended as an indicative comparison rather than a standardized classification.

2.2. Sensors and Multisensor Configurations

The selection of sensors and their configuration play a decisive role in both the metrological performance and the automation capability of a Coordinate Measuring Machine [1,4]. In automotive mechanical manufacturing, contact-based probing systems remain the predominant solution due to their high repeatability and suitability for tight dimensional and geometric tolerances, as well as for features with limited accessibility, such as holes and internal surfaces [1,4,8].

Within contact probing systems, the choice between touch-trigger probes and continuous scanning probes involves a trade-off between robustness, flexibility, and measurement capability [4,6]. Touch-trigger probes are widely used in manufacturing environments because of their simplicity, reliability, and ease of implementation, whereas scanning probes enable a more comprehensive evaluation of form and profile characteristics [4]. However, scanning systems typically require more careful configuration and are more sensitive to environmental conditions and system dynamics [6].

The adoption of rotary probe heads and multisensor configurations has become a key enabler for automated dimensional inspection [1,4]. These systems reduce the need for manual probe changes and allow access to multiple measurement orientations without operator intervention [6]. In addition, the combination of contact probes with non-contact sensing technologies, such as optical or laser sensors, extends the measurement capabilities of CMMs and enables inspection strategies adapted to different stages of the manufacturing process [4,8].

From the perspective of automation, multisensor configurations contribute to reduced non-productive times, increased system flexibility, and improved integration within production lines characterized by high product variability [3,8]. As a result, sensor configuration must be considered a fundamental design decision when deploying CMMs as automated inspection systems in production environments [3,5].

From a lifecycle perspective, the selection of sensing and probing technologies affects measurement strategy definition, achievable accuracy, and inspection cycle time, thus playing a key role in both validation procedures and production integration.

2.3. Design Implications for Accuracy and Robustness

Design decisions in a Coordinate Measuring Machine (CMM) affect not only metrological accuracy but also the robustness of the system under real industrial operating conditions. Factors such as structural stiffness, material selection, axis kinematics, and compensation systems directly influence the ability of the machine to maintain stable performance in the presence of external disturbances [1,9].

In industrial production environments, thermal variations, vibrations, and contamination are major sources of measurement error. Modern CMMs address these effects through integrated temperature sensing, advanced compensation algorithms, and passive and active vibration isolation, enabling reliable measurement performance under variable operating conditions [1,6].

From an automation perspective, robustness to environmental variations is a fundamental requirement. When a CMM is integrated into a production line, it must ensure reliable and predictable operation, as even minor deviations in measurement performance can directly affect manufacturing process stability [3,8].

From a lifecycle perspective, environmental conditions such as temperature variations, vibrations, and contamination directly impact measurement reliability and must be considered as key constraints in machine selection, validation, and long-term operational performance.

2.4. Evolution Toward Workshops and In-Line Environments

Dimensional metrology is no longer confined to laboratory environments, but is increasingly applied in workshops, near-line and in-line contexts [1,8]. This transition is driven by the need to shorten process feedback loops and to use metrological data as an active element of manufacturing control rather than solely for post-process verification [3].

CMMs designed for workshop, near-line, and in-line environments incorporate enhanced protection against contamination, advanced environmental compensation systems, and mechanical architectures that facilitate automated part loading and unloading [1]. In in-line measurement applications, CMMs can be integrated with robots, material handling systems, and machine tools, enabling them to operate as active components of automated manufacturing systems rather than as passive inspection devices [3,8]. This shift supports proactive process control strategies and contributes to the implementation of smart manufacturing and zero-defect production approaches [2,5].

This evolution highlights the need for structured engineering approaches that address the design, validation, and integration of CMMs as automated industrial systems throughout their entire lifecycle. In this context, the following section introduces a methodology for the industrial deployment of automated CMMs, with particular emphasis on design-oriented decision-making, metrological validation, and integration within automated manufacturing environments [3,5].

From a lifecycle perspective, automation requirements and production integration constraints influence system configuration, cycle time compatibility, and operational robustness, linking design decisions with validation and series production performance.

3. Methodology for Industrial Deployment of Automated CMMs

In this work, terms such as availability, robustness, and predictability are used from an industrial perspective to refer to the capability of the measurement system to maintain stable performance, consistent results, and operational continuity under real production conditions.

The deployment of an automated CMM should be addressed as a structured engineering process rather than as a simple equipment installation. In automated manufacturing environments, decisions taken during the early project stages have a significant impact on measurement reliability, system availability, and effective integration within the production process [3,6,8].

For this reason, machine design, metrological capability, environmental conditions, and automation requirements must be considered jointly from the initial project phase [6,8].

The methodology proposed in this work follows a lifecycle-based approach to the measurement system and is organized into three main phases [3,10]:

- the project phase, focused on the selection of the machine and the measurement system;

- the validation and acceptance phase, aimed at reducing industrial and metrological risk prior to production start-up; and
- the series production phase, focused on long-term robustness, maintenance, and integration with automated production systems.

3.1. Project Phase: Machine and Measurement System Selection

The project phase plays a key role in ensuring the reliable operation of the CMM as an automated industrial system. Design decisions are therefore guided by product requirements and process constraints, with particular emphasis placed on the criticality of the characteristics to be inspected [1,6]. To address this need, a structured decision framework is defined to ensure that the selected configuration supports automated dimensional inspection under real production conditions.

Based on these principles, the proposed framework supports machine and measurement system selection during the project phase by integrating tolerance requirements, MPE-based criteria, and industrial environment conditions, as illustrated in Figure 3 [6,7].

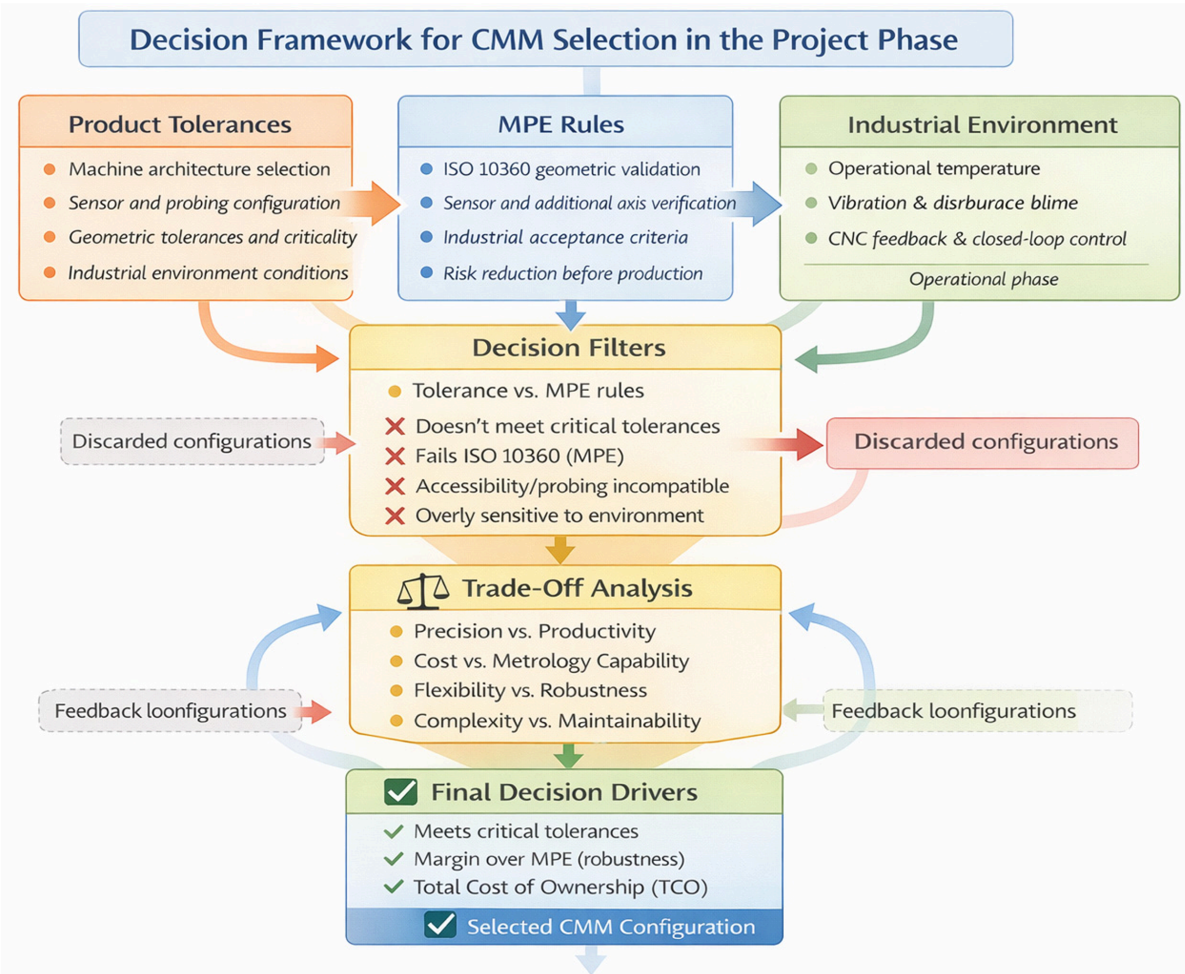

Figure 3. Decision framework for Coordinate Measuring Machines (CMMs) selection in the project phase, illustrating the progressive elimination of non-compliant configurations, the evaluation of trade-offs between competing criteria, and the identification of the final solution based on industrial decision drivers. The framework integrates product requirements, metrological validation constraints, and environmental conditions within a lifecycle-based decision process.

Figure 3 illustrates the proposed decision framework as a structured and iterative selection process. It incorporates successive filtering steps to eliminate non-compliant configurations, followed by a trade-off analysis to balance conflicting criteria such as accuracy, productivity, and robustness. The final selection is driven by key industrial decision factors, ensuring compliance with tolerance requirements, MPE constraints, and environmental conditions.

3.1.1. Geometric and Metrological Criteria

The first step of the decision-making process consists of identifying the set of geometric characteristics that must be verified using the CMM. These include both final product characteristics and intermediate process characteristics that influence subsequent manufacturing operations. Each characteristic is associated with a specific geometric tolerance and a defined level of criticality, determined by its impact on product functionality and process stability [7]. For each characteristic to be measured, the Coordinate Measuring Machine (CMM) must provide sufficient resolution and discrimination capability to reliably detect critical features. This requirement extends beyond nominal accuracy and includes aspects such as repeatability, long-term stability, and sensitivity to environmental variations [1,4]. Consequently, geometric accessibility, probing strategies, and sensor configuration must be evaluated in conjunction with the mechanical architecture of the machine [1,4,6].

During the project phase, these product and process requirements are translated into quantifiable metrological constraints that support objective CMM selection. This approach ensures consistency between quality planning, measurement system capability, and the objectives of production automation [1,6].

3.1.2. Tolerance- and MPE-Based Selection

In industrial practice, when the maximum permissible error (MPE) of a Coordinate Measuring Machine is known, an additional capability criterion is frequently considered in which the task-specific measurement uncertainty (U's) should remain below approximately 10% of the declared MPE. This condition is commonly used as a practical indicator of the adequacy of the measurement system for a given application [1,6]. However, for critical characteristics, a final verification of task-specific measurement uncertainty (e.g., according to ISO 15530-3 or simulation-based approaches such as ISO 15530-4) is recommended as part of the acceptance phase to ensure the adequacy of the measurement system for the intended application.

A practical and widely used approach for the preselection of CMM configurations consists of comparing the tolerance intervals (TI) of the characteristics to be inspected with the maximum permissible errors (MPE) declared in accordance with the ISO 10360 series [10–13]. This comparison allows an initial filtering of candidate machines during the project phase [1,6].

A commonly adopted guideline is the so-called "10% rule," according to which the measurement uncertainty should not exceed 10% of the tolerance interval. More restrictive ratios, such as one-tenth of the tolerance interval, are typically applied to highly critical characteristics, whereas fractions such as one-eighth or one-quarter may be adopted when balancing metrological risk and industrial feasibility. These stricter margins aim to reduce the risk of incorrect conformity decisions [14].

In cases involving extremely tight tolerances, the strict application of a one-tenth ratio may require disproportionately expensive high-accuracy equipment. Therefore, industrial practice may intentionally adopt a one-eighth fraction as a risk-balanced compromise between measurement reliability and economic viability. In such situations, the associated risk must be explicitly assessed in accordance with the relevant decision rules defined for coordinate metrology [15].

Table 2 presents example tolerance-to-MPE decision criteria typically applied under controlled industrial risk assumptions. These criteria should be understood as structured decision guidelines rather than as absolute acceptance limits. The final selection must also consider characteristic criticality, production environment stability, and automation requirements.

Table 2. Example of tolerance- and MPE-based decision criteria derived from industrial practice and supported by standards (e.g., ISO 10360 series for Coordinate Measuring Machines (CMMs) performance verification, ISO 14253-1 for conformity decision rules, and ISO 15530-3/4 for task-specific uncertainty evaluation) and literature [1,6,15].

Geometric Tolerance Interval	Characteristic Criticality	Applied Rule *	Required MPE Range	Decision Implication
≥0.20 mm	Low	1/4 tolerance	MPE ≤ 25% of tolerance	Broad range of CMM configurations acceptable
0.10–0.20 mm	Medium	1/8 tolerance	MPE ≤ 12.5% of tolerance	Standard industrial CMMs suitable
0.05–0.10 mm	High	1/10 tolerance	MPE ≤ 10% of tolerance	High-accuracy CMMs required
<0.05 mm	Very High/Critical	1/10 (recommended) or risk-assessed alternative	MPE ≤ 5–10% of tolerance	Only robust, high-performance configurations acceptable

* Note: The selection of the tolerance fraction is not determined solely by the width of the tolerance interval, but also by the criticality of the characteristic, the industrial environment, and the conformity decision rules adopted. In certain industrial contexts, less restrictive fractions may be applied provided that the associated measurement risk is formally assessed according to ISO 14253-1 [15].

It should be noted that this tolerance-based preselection does not replace a complete measurement uncertainty evaluation when extremely narrow tolerances or safety-critical features are involved. In such situations, experimental or model-based approaches for the identification of measurement uncertainty and error sources may be required [13,15].

This distinction highlights that the proposed approach is suitable for standard industrial applications, while critical or safety-related features may require additional uncertainty-based analysis.

The tolerance-to-MPE criteria presented in Table 2 are derived from established industrial practice, supported by relevant standards (e.g., ISO 10360, ISO 14253) and literature references. These values should be understood as practical engineering guidelines rather than strict normative limits.

3.1.3. Influence of the Industrial Environment

Working environmental conditions represent a determining factor in the deployment of automated CMMs. Temperature variations, vibrations, and contamination typical of manufacturing environments can significantly affect metrological performance and system availability if they are not adequately considered during the project phase [1,6].

In workshop and near-line installations, floor-transmitted vibrations from machining centers, material handling systems, or forklifts may significantly affect measurement repeatability [1]. In typical near-line automotive machining environments, vibration levels transmitted through the floor may range approximately from 0.5 to 2 m/s^2, depending on the proximity to machining processes and the dynamic behavior of the production system. Similarly, temperature variations in such environments are commonly within ±2 °C to ±5 °C over a production shift, depending on climate control conditions. These environmental variations can influence measurement repeatability and introduce systematic deviations if not properly compensated.

Passive isolation systems (e.g., pneumatic anti-vibration supports) or active damping solutions are frequently required to maintain performance within the MPE limits declared according to ISO 10360-2 [11]. The vibration spectrum and amplitude should therefore be evaluated during the project phase, particularly when the CMM is integrated close to high-dynamic machining processes [1,6].

The proposed methodology explicitly integrates the industrial environment as a decision criterion in machine selection. Regardless of the selected installation context, whether a metrology laboratory, a controlled room adjacent to the workshop, a near-line location, or an in-line production environment, each scenario imposes specific requirements. These requirements include the level of thermal compensation, vibration isolation, and protection against contamination that must be provided by the system [1,6].

Proper management of environmental conditions is essential for the design of machines with advanced compensation systems and robust structural configurations [1]. Although this may involve a higher initial investment, it typically results in improved system reliability over the long term. From an automation perspective, environmental robustness is directly related to system availability and operational continuity. A CMM integrated into an automated production system must exhibit stable and predictable behavior over time, minimizing unplanned downtime and corrective actions [3,8].

In this context, environmental characterization is not treated as a secondary constraint but as an integral element of the decision-making framework, directly influencing machine selection, validation strategy, and long-term production performance. Early consideration of these factors therefore constitutes a key element of the overall methodology.

3.2. Validation and Acceptance Framework

Once the machine and measurement system configuration has been defined, a structured validation and acceptance framework is required to verify that the CMM performs as expected under representative industrial conditions [1,6,8]. In automated environments, acceptance is therefore treated not merely as a formal compliance requirement, but as a critical step for reducing industrial and metrological risk prior to production start-up [1,6].

Figure 4 summarizes the proposed validation and acceptance framework, integrating ISO 10360 series [10–13] standardized verification procedures together with application-oriented decision criteria. When task-specific measurement uncertainty (U's) is considered at the application level, approaches based on ISO 15530-3 [16] or ISO 15530-4 [17] may be applied depending on the availability of calibrated artifacts or simulation-based methods.

In addition to standardized geometric verification and uncertainty evaluation, application-level validation of measurement programs and probing strategies forms part of the industrial acceptance process [4,6,16].

3.2.1. Geometric Validation According to ISO 10360

Geometric validation of the CMM is performed in accordance with the ISO 10360 series [10–13], which defines standardized procedures for assessing the metrological performance of CMM. These procedures evaluate key parameters such as the maximum permissible error in length measurement, probing errors, and repeatability indicators [1,6].

Rather than considering these parameters in isolation, they are evaluated in relation to the specific industrial application. The validation results are analyzed to verify that the machine maintains sufficient margins with respect to the most demanding tolerances identified during the project phase, even under representative environmental operating conditions [8,18].

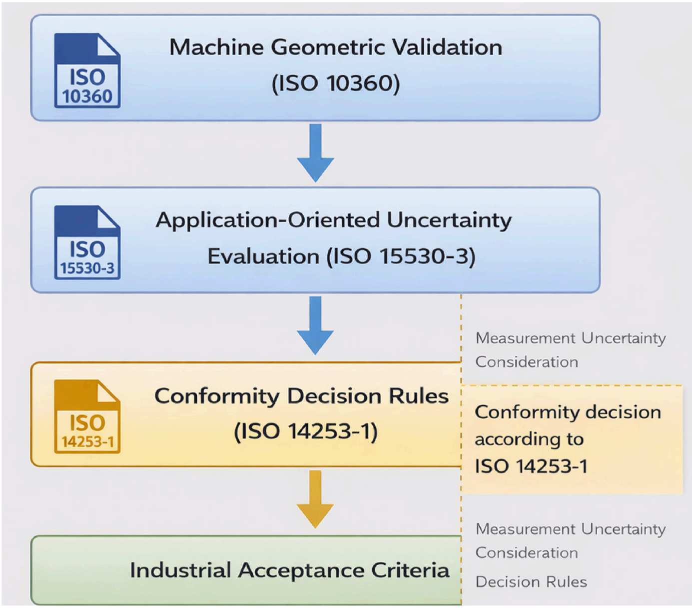

Figure 4. Validation and acceptance framework integrating ISO 10360 series [10–13] standardized tests with industrial decision rules to ensure the suitability of automated Coordinate Measuring Machines (CMMs) for operation in production environments.

3.2.2. Verification Strategies for Sensors and Additional Axes

Automated CMMs often incorporate complex sensor configurations, such as rotary probe heads, scanning systems, and additional axes, including rotary tables and other auxiliary axes [1,4]. The verification of these elements therefore constitutes an essential part of the acceptance framework [6].

The proposed methodology focuses on defining verification strategies that ensure consistency between the validated machine geometry and the behavior of sensors and additional axes. The influence of probe orientations, scanning modes, and auxiliary axis movements on system accuracy and repeatability is systematically evaluated to ensure that the complete configuration is compatible with the intended level of automation [6,12,14,19].

3.2.3. Industrial Acceptance Criteria and Decision Rules

Industrial acceptance criteria go beyond simple compliance with applicable standards. The proposed framework integrates validation results with decision rules derived from tolerance requirements, environmental conditions, and automation objectives [6,14]. Acceptance of the CMM is granted only when the verified performance enables reliable operation within the defined production context [3,5].

This approach ensures that the accepted CMM not only complies with relevant standards but is also demonstrably fit for purpose as an automated inspection system integrated into the production process [3,5,8].

3.3. Series Production Phase and Automation Integration

Following acceptance, the CMM enters the series production phase, in which long-term robustness and system availability become the predominant considerations [3,5].

The lifecycle perspective ensures that metrological validation is not limited to initial acceptance but is sustained through structured maintenance and performance monitoring strategies [2,6,8].

3.3.1. Metrological Maintenance

Metrological maintenance strategies are defined with the objective of preserving the validated performance of the measurement system over time [6,8]. These strategies include periodic verification, monitoring of key performance indicators (KPI), and the planning of controlled recalibration activities [6]. In automated environments, maintenance activities are closely coordinated with production planning to minimize their impact on system availability [3,5].

3.3.2. Robustness Under Production Conditions

During series production, the CMM must operate continuously under variable environmental conditions [1,8]. System robustness is achieved through a combination of appropriate mechanical design choices, compensation algorithms, and preventive maintenance measures [1,6]. Monitoring environmental parameters and machine behavior enables deviations to be detected and addressed proactively before measurement quality is affected [3,19].

3.3.3. Integration with Automated Production Lines and CNC Feedback

In advanced applications, the CMM is integrated into automated production lines and provides dimensional data for process feedback [3,5,8]. Figure 5 illustrates an example of the integration of an automated CMM within an automated production line, including the use of dimensional data for feedback to machining processes [2,18].

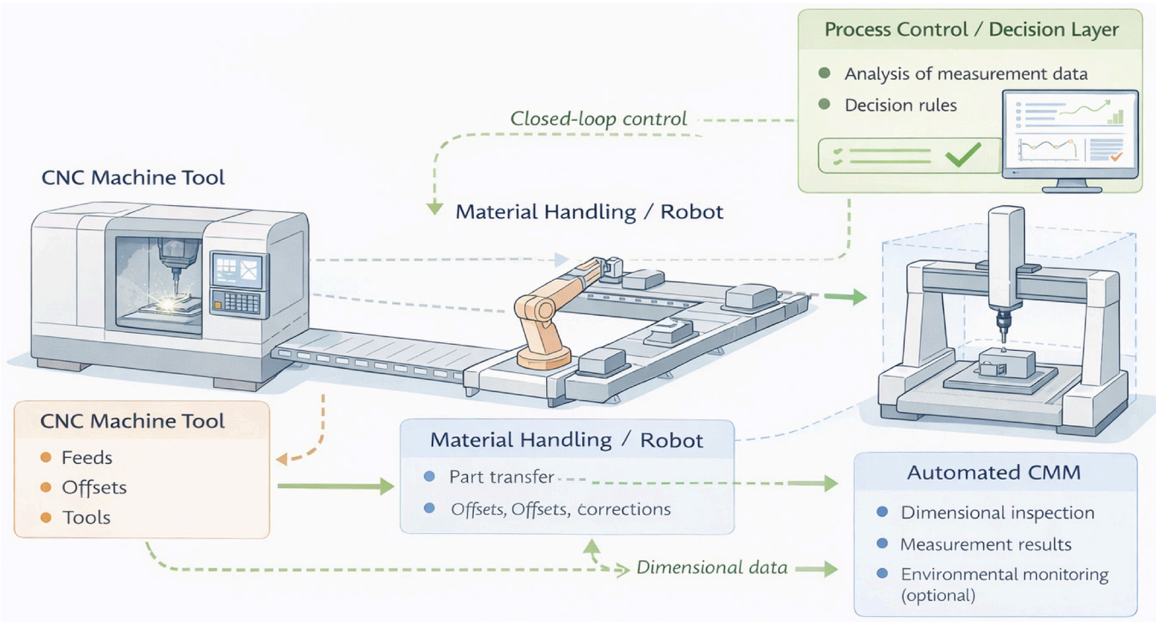

Figure 5. Integration of an automated Coordinate Measuring Machines (CMMs) within an automated production line, enabling dimensional feedback to machining processes and closed-loop control in zero-defect manufacturing strategies.

Measurement results can be used to adjust machining parameters, enabling closed-loop control strategies and supporting zero-defect manufacturing objectives [5,20].

In this context, the CMM acts as an active component of the automated manufacturing system rather than a passive inspection device, reinforcing the need for a deployment approach based on machine design criteria and structured management throughout the entire system lifecycle [2,3,8,20].

4. Industrial Case Study and Discussions

4.1. Industrial Case Study

To illustrate the practical application of the proposed methodology, a representative case study from the automotive sector is presented below. The case study is based on industrial experience in the manufacturing of machined mechanical components and has been formulated to exclude confidential information and product-specific data [3,8].

The considered component is a medium-sized machined part, manufactured through turning and milling operations and incorporating multiple functional geometric features, including holes, planar surfaces, and geometric references. From a functional perspective, the component can be classified as a typical powertrain-related mechanical part, characterized by the presence of precision bores, reference datum surfaces, and tight positional and dimensional relationships between critical features. These features are subject to tight dimensional and geometric tolerances, some of which are classified as critical due to their direct impact on assembly requirements and the functional performance of the final product [7]. Such components are representative of typical automotive machining applications where dimensional inspection is directly linked to assembly performance and process capability.

The approach adopted in this case study is based on the operational reality of a machining plant for powertrain components governed by a quality management system. The project team has the responsibility of choosing the inspection means to guarantee the product quality. The input for the selection of the CMM in a risk-based quality management logic is the Control Plan as the result of a product and process risk analysis, DFMEA and PFMEA [3,5].

As shown in Figure 6, this risk-management workflow establishes a structured linkage between Design Failure Mode and Effects Analysis (DFMEA) and Process Failure Mode and Effects Analysis (PFMEA) activities, the definition of dimensional requirements in the Control Plan, and the subsequent validation of the measuring process. This framework ensures that metrological decisions are directly aligned with product criticality and process risk considerations [3,5,6].

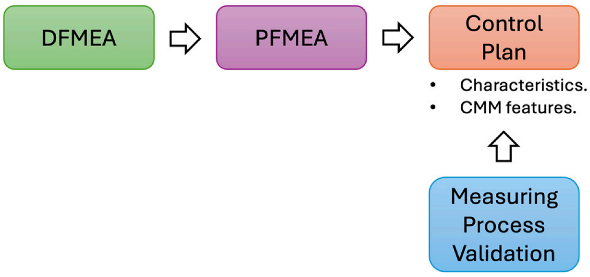

Figure 6. Example of quality management workflow linking Design Failure Mode and Effects Analysis (DFMEA), Process Failure Mode and Effects Analysis (PFMEA), and control plan definition to Coordinate Measuring Machines (CMMs) adequacy.

4.1.1. Dimensional Requirements and Industrial Context

Based on the dimensional requirements defined in the Control Plan, the first step in the CMM selection process is to ensure that the machine volume and architecture are compatible with the geometry of the component under study [1,6]. The spatial distribution, accessibility, and metrological characteristics of the critical features determine the required sensor types, probing strategies, and machine configuration [4,6].

One of the fundamental parameters of a CMM is its usable measurement volume. This must be sufficient to accommodate the part, the fixturing, the stylus configurations and the required head rotations (where applicable) [1].

Depending on the manufacturer, recommendations range from 20% to 100% additional travel beyond the maximum dimensions of the part in each axis. The most reliable approach is to use a virtual simulation (digital twin) of the machine and the part/fixture/probe system, a capability available in modern CMM software packages [21,22].

Regarding machine configuration, bridge-type CMMs are the most common in automotive mechanical environments due to their suitable size and strong metrological performance.

In near-line installations, floor-transmitted vibrations generated by machining centers, automated handling systems, or logistics equipment may significantly affect measurement repeatability and probing stability [1,8]. For this reason, vibration levels in the intended installation area were evaluated during the project phase. The selected CMM configuration incorporated passive anti-vibration supports and structural design features compatible with workshop environments, ensuring that dynamic disturbances remained within the limits compatible with the declared MPE for length measurement according to ISO 10360-2 [11].

The consideration of vibration behavior at the project stage contributed to ensuring stable measurement performance under real production conditions and avoided the need for corrective actions after installation [1,6,8].

4.1.2. Application of the Decision Framework in the Project Phase

The next step consists of selecting candidate machines from the approved supplier panel. In medium and large industrial organizations, this panel includes CMM configurations for which prior capability assessments and industrial performance data are available [3,8].

Applying the tolerance-to-MPE framework described in Section 3.1.2, the tightest tolerance identified in the control plan was 20 µm. Based on a one-eighth tolerance fraction, the target MPE for length measurement was therefore established below 2.5 µm [1,6].

The selection of a one-eighth tolerance fraction reflects a risk-balanced industrial decision. Although a one-tenth criterion would provide a larger metrological margin, the adoption of the 1/8 ratio was considered acceptable in this context due to the controlled near-line environment, the demonstrated stability of the manufacturing process, and the conformity decision rules applied in accordance with ISO 14253-1 [15]. This approach ensured adequate measurement reliability while maintaining economic and operational feasibility [1,6].

To illustrate the extraction of nominal values and tolerance intervals used for the tolerance-to-MPE comparison, Table 3 presents a simplified example of the control plan applied in the case study in Figure 7. The tightest tolerance interval identified in this document establishes the reference for defining the target metrological performance of the candidate CMM configurations [1,6].

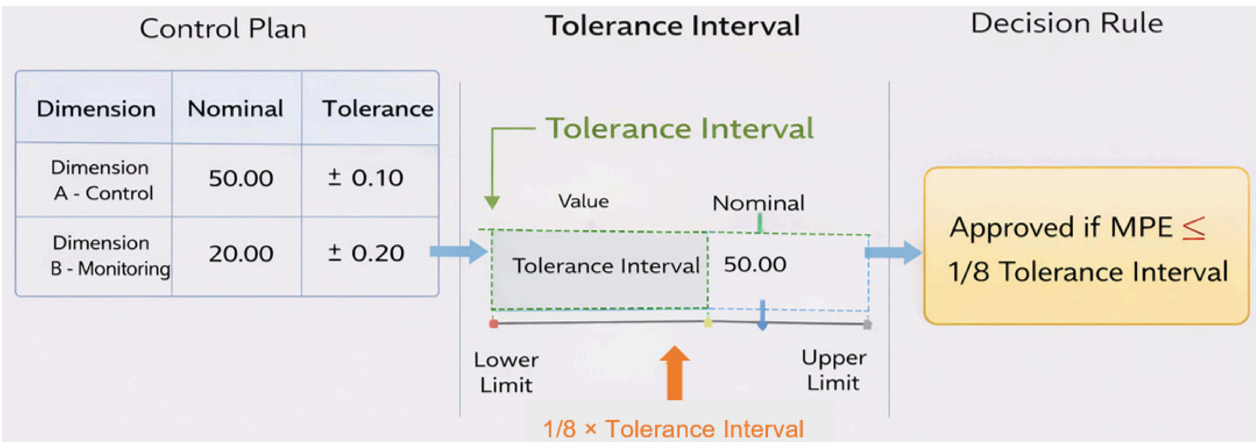

Figure 7. Extraction of nominal values and tolerance intervals from the control plan, including tolerance interval calculation and decision-making based on a one-eighth tolerance fraction.

Table 3. Basic control plan example.

SIDE	Characteristic	Nominal	LTL	UTL	TI (mm)	1/8 TI (mm)
C100	Character 001	13.000	12.970	12.997	0.027	0.0034
	Character 002	0.000	0.000	0.200	0.200	0.0250
	Character 003	9.500	9.495	9.520	0.025	0.0031
	Character 004	0.000	0.000	0.200	0.200	0.0250
	Character 005	220.458	220.408	220.508	0.100	0.0125
	Character 006	9.500	9.495	9.520	0.025	0.0031
	Character 007	0.000	0.000	0.200	0.200	0.0250
	Character 008	164.940	164.897	164.997	0.100	0.0125
	Character 009	310.030	309.970	310.090	0.120	0.0150
	Character 010	12.500	12.400	12.600	0.200	0.0250
	Character 011	138.600	138.400	138.800	0.400	0.0500
	Character 012	8.700	8.500	8.900	0.400	0.0500
	Character 013	0.000	0.000	0.200	0.200	0.0250
	Character 014	0.000	0.000	0.140	0.140	0.0175
	Character 015	224.970	224.900	225.040	0.140	0.0175
	Character 016	8.000	7.994	8.019	0.025	0.0031
	Character 017	140.830	140.750	140.910	0.160	0.0200
	Character 018	176.100	176.000	176.200	0.200	0.0250
C500	Character 019	72.200	72.200	72.220	0.020	0.0025
	Character 020	0.000	0.000	0.200	0.200	0.0250
	Character 021	72.200	72.200	72.220	0.020	0.0025
	Character 022	0.000	0.000	0.200	0.200	0.0250
	Character 023	72.200	72.200	72.220	0.020	0.0025
	Character 024	0.000	0.000	0.200	0.200	0.0250
	Character 025	72.200	72.200	72.220	0.020	0.0025
	Character 026	0.000	0.000	0.200	0.200	0.0250

The main metrological characteristics of the candidate CMM configurations are summarized in Table 4. In addition to nominal MPE values, environmental robustness, thermal stability, and compatibility with the intended automation architecture were considered during the comparative evaluation [1,6,8].

Table 4. Main metrological features for three market Coordinate Measuring Machines (CMMs).

Supplier	Model	Measuring Volume (mm)	MPE E_0/20 °C (μm)	MPE E_0/40 °C (μm)	RONt (μm)
Supplier 01	Model 01	700 × 500 × 500	1.9 + L/300	2.9 + L/200	1.6
Supplier 02	Model 02	600 × 500 × 280	2.2 + 3.5L/1000	3.6 + 6.5L/100	NA
Supplier 03	Model 03	700 × 900 × 600	1.7 + L/280	NA	1.7

Note: NA = Not Available.

This structured filtering process reduced the risk of overspecification while ensuring that the selected configuration met both metrological and industrial integration requirements [1,3,6].

Based on the comparison presented in Table 4, only Model 01 and Model 03 are initially suitable for the proposed measuring tasks under standard environmental conditions (20 °C) [1,6].

However, the CMM is intended to operate in a near-line environment, which is less strictly controlled than a metrology laboratory while remaining compatible with integration into an automated production system. For this reason, MPE values under different expected working temperatures were compared with the target tolerance limits in order to verify whether the thermal stability characteristics of the candidate machines met the project requirements [1,6,8].

In this context, measurement system accessibility, environmental robustness, and thermal compensation capabilities become critical selection criteria. Machine architectures and sensor configurations incorporating enhanced structural rigidity and temperature compensation systems were therefore prioritized [1,6].

As a result of this extended evaluation, a CMM configuration compatible with automated inspection of critical characteristics and integration into the production system was selected [3,8]. In addition, execution time of measurement programs—compatible with machining cycle times—was considered a determining factor, making CMM travel speed another decisive parameter in the final decision [23].

Following the configuration selection phase, the validation and acceptance framework was implemented to confirm compliance with the predefined metrological targets [1,6].

4.1.3. Validation, Acceptance, and Start of Production

Once the system configuration was defined, the validation and acceptance framework described in Section 3.2 was applied. The validation was performed according to ISO 10360-2 [11] and ISO 10360-5 [13], confirming compliance with the predefined MPE targets established during the project phase [1,6].

The validation results confirmed that the CMM met the defined industrial acceptance criteria, maintaining adequate margins with respect to critical tolerances under representative working environment conditions [1,6]. Following acceptance, the system was integrated into the production flow, enabling automated and repeatable dimensional inspections [3,8].

During the initial production phase, additional operational indicators were monitored to support the assessment of system performance under real industrial conditions. Measurement repeatability was observed to remain within the variation range identified during the validation phase, ensuring consistency of results across repeated inspection cycles. Inspection cycle time was verified to be compatible with the machining cycle, avoiding bottlenecks in the production flow. In addition, no unplanned downtime related to metrological performance or environmental disturbances was reported during the initial implementation period, supporting the assessment of stable operation and high system availability [1,6].

A summary of the industrial case study and the main decisions and outcomes is provided in Table 5.

Table 5. Summary of the industrial case study illustrating the application of the proposed lifecycle-based methodology.

Aspect	Description
Industrial sector	Automotive manufacturing
Component type	Medium-sized machined mechanical component
Manufacturing processes	Turning and milling
Key geometric characteristics	Holes, planar surfaces, and functional geometric references
Tolerance level	Tight dimensional and geometric tolerances, including critical characteristics
Installation environment	Near-line industrial environment
Selected CMM configuration	Automation-oriented CMM with suitable architecture and sensor configuration
Validation approach	ISO 10360 series geometric validation and application-oriented acceptance criteria
Automation level	Automated loading/unloading and integration into production flow
Main outcomes	Robust operation supported by stable measurement results and high system availability

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The validation process for the case study consists of several steps:

Geometry and Metrological Characteristics validation. The previous sections described how standardized criteria are applied to determine the maximum permissible errors (MPE) of a CMM and assess their adequacy with respect to the required geometric specifications and tolerance intervals [1,6]. For consistency, the same standards and criteria must be used during the acceptance phase to confirm that the selected equipment meets the project requirements [1]. Geometric verification was performed in accordance with the ISO 10360 series [10–13], including ISO 10360-2 [11] for length measurement performance, ISO 10360-3 [12] for CMMs with rotary tables, and ISO 10360-5 [13] for CMMs using probing systems, including scanning probes and multiple probe configurations. The geometric verification test was performed under controlled environmental and operational conditions in accordance with the ISO 10360 series [10–13]. The relevant test parameters, including material temperature, artifact positioning, and the applicable MPE model, are summarized in Table 6.

Table 6. Test conditions.

	Axis X	Axis Y	Axis Z	Test Artifact
Material temperature (°C)	20.00	20.00	20.00	24.07
Test artifact position (mm)	48	−1029	−155	

Note: Monitoring factor = 0.30; MPE model for length measurement defined as $E_0 = 1.7 + L/300$, according to ISO 10360-2 [11].

The measured nominal lengths, actual values, and resulting deviations are presented in Table 7. The mean deviation corresponds to the indication error E_0, while the minimum and maximum values reflect the observed measurement dispersion at each test length.

Table 7. Measurement results.

Nominal Value (mm)	Actual Value (mm)	Mean Deviation (mm)	Minimum (mm)	Maximum (mm)
19.9583	19.9578	−0.0005	−0.0005	−0.0004
179.8421	179.8416	−0.0005	−0.0006	−0.0004
359.8433	359.8434	0.0001	−0.0001	0.0001
539.8572	539.8568	−0.0004	−0.0004	−0.0003
639.8172	639.8184	−0.0004	−0.0005	−0.0003

The graphical representation of the indication error as a function of the measured length, together with the corresponding MPE limits, is shown in Figure 8.

Measuring programs validation. Regardless of whether measurement routines are developed externally or in-house, they must undergo a structured validation [1,6]. The reliability of CMM results depends not only on the intrinsic metrological characteristics of the machine, but also on the robustness of the measurement strategy and program design [1,4,6]. Best-practice guidelines—both industrial and normative—emphasize: correct definition of datums and coordinate systems, appropriate part orientation and fixturing, probes qualification, adequate probing patterns and point distribution, and the correct selection of filtering, fitting algorithms, and evaluation methods (e.g., least squares, minimum circumscribed) [6,7,13].

Program validation was complemented by repeatability testing covering 100% of the controlled characteristics and by intercomparison of relevant characteristics of selected critical features with a reference measurement process, preferably an accredited laboratory or central metrology facility with significantly lower measurement uncertainty [14,16]. Particular attention was given to characteristics with tight tolerances, complex datum systems, safety-critical or regulatory relevance, low-capability processes, or features sensitive to tool wear or special manufacturing processes [7,14].

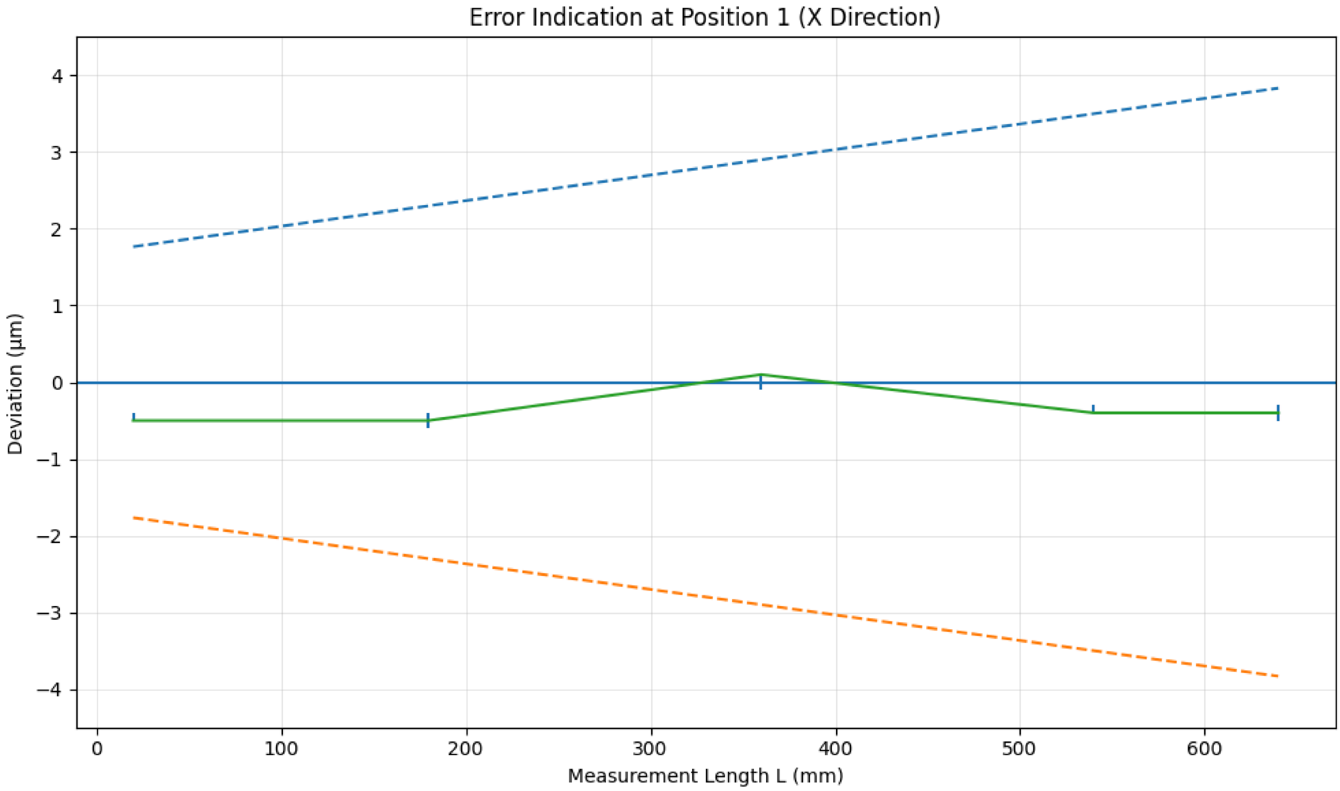

Figure 8. Graphical representation of the indication error as a function of the measured length. The solid line (green) represents the measured indication error (E_0), while the dashed lines indicate the upper (blue) and lower (orange) limits of the maximum permissible error (MPE) according to ISO 10360-2 [11]. The results confirm that the measured errors remain within the specified MPE limits.

Additional Validation Aspects. Additional validation aspects, such as safety systems, handling conditions, accessibility, and environmental requirements, were considered as part of the overall system assessment. The evaluation of these aspects was performed based on predefined industrial acceptance criteria, ensuring compliance with operational, safety, and integration requirements.

As an industrial asset, the CMM must also comply with regulations applicable to machinery, workplaces, and automated production systems. Additional verification included assessment of automation systems when integrated into production, acoustic and ergonomic considerations, safety systems (emergency stops and protective devices), environmental and utility requirements, compliance with specified cycle time, mechanical conformity of fixtures and handling systems [3,8,18,23]. These checks ensured full integration of the CMM into the industrial environment while maintaining operational safety and reliability [3,8].

The selection and validation of a CMM in industrial environments cannot be reduced to a purely metrological assessment. Instead, it requires the structured integration of product risk analysis, dimensional requirements, environmental constraints, and digital automation considerations [3,5,8,21,22]. Figure 9 summarizes this integrated decision framework, illustrating how technical specifications derived from DFMEA and PFMEA analyses are progressively translated into CMM requirements and industrial deployment criteria [3,5].

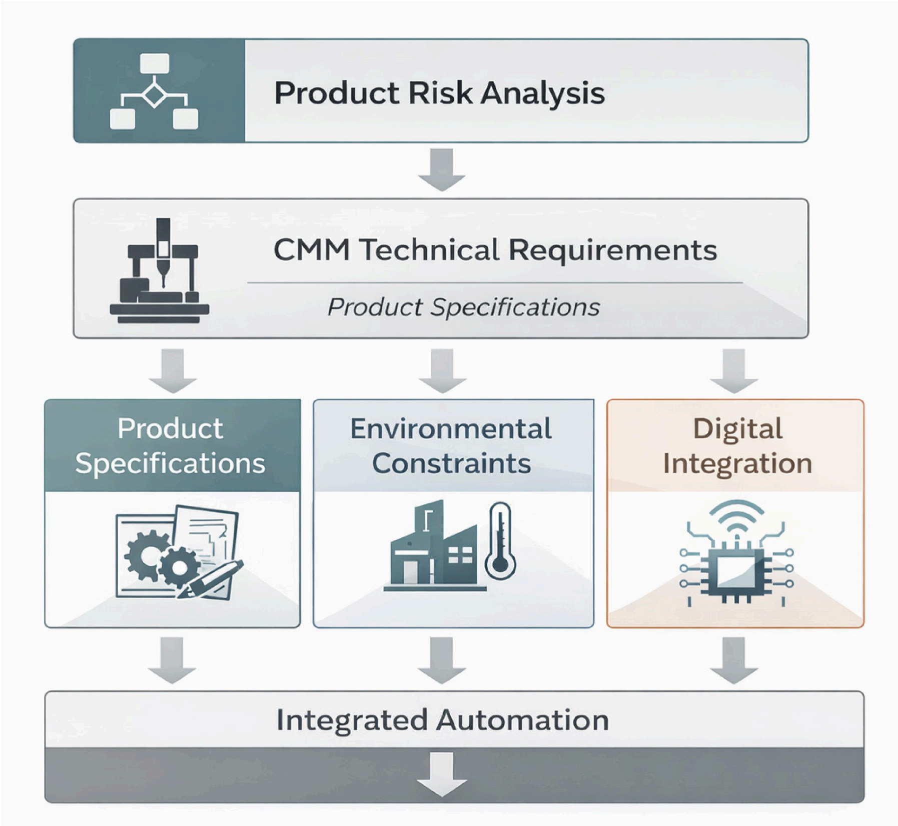

Figure 9. Integrated decision framework for Coordinate Measuring Machines (CMMs) deployment, connecting product risk analysis, technical requirements, environmental constraints, and digital integration in automated manufacturing environments.

To improve traceability between the decision framework and the industrial outcomes, Table 8 summarizes the key criteria, target values, validation results, and final acceptance decisions.

Table 8. Summary of decision criteria, validation results, and industrial acceptance.

Aspect	Criterion	Target Value/Requirement	Obtained Result	Decision/Outcome
Critical tolerance	Tightest tolerance (Control Plan)	20 µm	Identified in Table 3	Used as reference for CMM selection
Tolerance–MPE criterion	1/8 rule (industrial decision)	MPE $\leq$ 2.5 µm	Model 01: 1.9 + L/300; Model 03: 1.7 + L/280	Both candidates initially acceptable
Environmental conditions	Near-line environment	Moderate thermal variation and vibration	Passive anti-vibration supports implemented	Suitable for industrial deployment
Thermal performance	MPE under non-ideal temperature	Maintain compliance with tolerance limits	Model 01 includes 40 °C MPE data; Model 03 limited	Model 01 preferred for robustness
Machine selection	Combined criteria (MPE + environment + accessibility)	Compatibility with automation and tolerances	Configuration selected based on robustness and integration capability	Final CMM configuration selected

Table 8. *Cont.*

Aspect	Criterion	Target Value/Requirement	Obtained Result	Decision/Outcome
Geometric validation	ISO 10360-2	Compliance with declared MPE	Max deviation within ±0.0006 mm	Requirement fulfilled
Repeatability/dispersion	Measurement variation	Stable and low dispersion	Range approx. ±0.0005 mm	Acceptable repeatability
Measurement program validation	Industrial best practices	Correct datum definition and probing strategy	Verified and validated	Approved for production
Cycle time	Compatibility with production cycle	Within machining cycle time	Confirmed during implementation	Accepted
Industrial integration	Automation, safety, and environment compliance	Full integration in production system	Achieved (loading, operation, safety checks)	System accepted
Production performance	Stability and availability	Stable operation under real conditions	No significant deviations observed	High system availability

4.2. Discussion

The industrial case study highlights the strong influence of early project decisions on both the feasibility of automation and the robustness of the measurement system. In particular, the results indicate that focusing exclusively on nominal metrological performance does not provide sufficient guarantees when CMMs are intended to operate under real production conditions [1,6,8]. From an industrial perspective, the joint consideration of machine design aspects and automation requirements supports stable dimensional inspection in production environments [3,5,8].

Compared to conventional approaches where selection, validation, and operation are treated independently, the proposed methodology introduces a structured integration of these phases within a unified lifecycle-based framework. In traditional industrial practice, CMM selection is often driven primarily by nominal metrological specifications, while validation and production performance are addressed in later stages. This fragmented approach may lead to inconsistencies between machine capability, environmental conditions, and automation requirements. In contrast, the proposed framework explicitly links tolerance-based selection criteria, environmental constraints, and validation procedures from the early project phase through to series production. This integrated perspective supports more robust decision-making and reduces the risk of performance deviations when the system is deployed under real industrial conditions.

The use of structured criteria based on tolerances and MPE values significantly reduces the risk associated with machine selection [1,6]. The comparison of different CMM configurations shows that machines with higher nominal performance are not necessarily the most suitable option for real production environments [1,6,8].

The case study illustrates that configurations offering slightly lower nominal accuracy but improved environmental robustness and automation compatibility may provide superior industrial performance when long-term system availability and operational continuity are considered [3,8]. In industrial production contexts, availability, predictability, and resistance to environmental disturbances become as critical as nominal accuracy values declared under laboratory conditions [1,6].

Furthermore, the validation phase proved to be more than a formal compliance exercise. The interpretation of results obtained according to ISO 10360 series [10–13] in relation to the specific tolerance structure and environmental conditions was essential to ensure fitness for purpose. This confirms that standardized tests must be contextualized within the intended industrial application [1,8].

From a lifecycle perspective, the integration of environmental assessment, tolerance-based decision criteria, and structured validation procedures contributes to reducing industrial risk not only at start-up but throughout series production [3,5,8]. The methodology therefore supports the transformation of CMMs from standalone inspection devices into active and reliable components of automated manufacturing systems [3,8].

Nevertheless, certain limitations should be acknowledged. The rule-based linkage between tolerance intervals and MPE values provides a robust preliminary filtering tool but does not replace a full uncertainty analysis when extremely critical characteristics are involved [14,16]. Additionally, the methodology assumes a relatively stable industrial environment; highly dynamic or poorly controlled workshop conditions may require additional mitigation strategies [1,6].

Overall, the results indicate that a design-oriented and risk-informed deployment strategy enhances the reliability of dimensional inspection systems and supports the integration of metrology into automated production environments [3,8].

This lifecycle-based perspective aligns with current trends in digitalized manufacturing systems and digital twin-driven production strategies [21,22].

5. Conclusions and Future Developments

5.1. Main Contributions

The results obtained in this work underline the importance of addressing system robustness and availability from the early stages of the project. In this context, automated Coordinate Measuring Machines (CMMs) must be considered as integrated industrial systems rather than as standalone inspection devices.

In addition, the proposed approach reinforces the role of metrological validation as a risk-reduction tool rather than merely a formal compliance requirement, highlighting its contribution to achieving reliable industrial deployment of automated coordinate measuring systems.

A key contribution of this work lies in structuring and formalizing the integration of established engineering practices within a lifecycle-based framework for automated CMM deployment.

Rather than introducing new metrological concepts, the proposed approach focuses on the consistent integration of design, validation, and production considerations in real production environments.

5.2. Relevance for Automated Manufacturing Systems

The results of this work indicate that successful deployment of CMMs in automated manufacturing environments depends not only on nominal metrological accuracy but also on operational continuity, predictable system behavior, and effective integration with production equipment. In this context, CMMs operate as integral components of automated manufacturing systems rather than solely as inspection devices.

Machine design decisions, including architectural configuration, sensor selection, and consideration of environmental influences, are as critical as the metrological requirements themselves. The proposed methodology aligns these decisions with the requirements of industrial automation and structured risk management.

This perspective is particularly relevant in sectors such as the automotive industry, where high production rates and stringent manufacturing tolerances require measurement

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systems capable of operating reliably in real industrial environments without compromising product quality or process efficiency.

Although the case study focuses on a near-line automotive application, the principles described may be extended to other manufacturing sectors. However, the proposed methodology is illustrated through a representative industrial case study, and further validation across additional scenarios would be beneficial to assess its broader applicability.

5.3. Future Directions: Artificial Intelligence, Digital Twins, and In-Line Metrology

Current trends in smart manufacturing point toward an even deeper integration of metrology within automated systems. In this context, the application of artificial intelligence (AI) techniques offers significant opportunities to optimize measurement strategies, detect deviations in system behavior, and anticipate maintenance needs through the analysis of metrological and environmental data. These techniques can be further applied during the series production phase to analyze metrological and environmental data, enabling predictive maintenance strategies and early detection of performance drift in measurement systems.

The development of digital twins [21,22] for CMMs and associated measurement systems enables the simulation of design alternatives, environmental variations, and production process changes, allowing their impact on system performance to be assessed in advance. From the perspective of the proposed lifecycle framework, digital twins can support the project phase by enabling simulation-based evaluation of alternative CMM configurations, environmental conditions, and measurement strategies prior to physical deployment.

This development reinforces the lifecycle-based design approach and supports the transition toward in-line metrology solutions that are fully integrated into the production flow. As a result, CMMs are expected to play an increasingly important role as decision-making nodes within automated manufacturing systems.

Taken together, these developments reinforce the lifecycle-based framework proposed in this work and highlight its potential extension toward data-driven and digitally integrated metrology systems.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
CMM	Coordinate Measuring Machine
DFMEA	Design Failure Mode and Effects Analysis
ISO	International Organization for Standardization
KPI	Key Performance Indicator
MPE	Maximum Permissible Error
PFMEA	Process Failure Mode and Effects Analysis
ZDM	Zero-Defect Manufacturing

References

1. Hocken, R.J.; Pereira, P.H. *Coordinate Measuring Machines and Systems*; CRC Press: Boca Raton, FL, USA, 2012.
2. Weckenmann, A.; Estler, W.T.; Peggs, G.N.; McMurtry, D. Probing systems in dimensional metrology. *CIRP Ann.—Manuf. Technol.* **2004**, *53*, 657–684. [CrossRef]
3. Kusiak, A. Smart manufacturing must embrace big data. *Nature* **2017**, *544*, 23–25. [CrossRef] [PubMed]
4. Colledani, M.; Tolio, T.; Fischer, A.; Iung, B.; Lanza, G.; Schmitt, R.; Váncza, J. Design and management of manufacturing systems for production quality. *CIRP Ann.—Manuf. Technol.* **2014**, *63*, 773–796. [CrossRef]
5. Psarommatis, F.; Kiritsis, D. Identification of the inspection specifications for achieving zero defect manufacturing. In *IFIP Advances in Information and Communication Technology*; Springer New York LLC: New York, NY, USA, 2019; Volume 566, pp. 267–273. [CrossRef]
6. Flack, D. *CMM Measurement Strategies—Good Practice Guide No. 41*; National Physical Laboratory (NPL): Teddington, UK, 2011.
7. *ISO 1101:2017*; Geometrical Product Specifications (GPS)—Geometrical Tolerancing—Tolerances of Form, Orientation, Location and Run-Out. International Organization for Standardization: Geneva, Switzerland, 2017.
8. Majstorovic, V.D.; Durakbasa, N.; Takaya, Y.; Stojadinovic, S. Advanced Manufacturing Metrology in Context of Industry 4.0 Model. In *Proceedings of the 12th International Conference on Measurement and Quality Control—Cyber Physical Issue*; Majstorovic, V., Durakbasa, N., Eds.; IMEKOTC14 2019. Lecture Notes in Mechanical Engineering; Springer: Cham, Switzerland, 2019. [CrossRef]
9. Schwenke, H.; Schmitt, R.; Jatzkowski, P.; Warmann, C. On-the-fly calibration of linear and rotary axes of machine tools and CMMs using a tracking interferometer. *CIRP Ann.—Manuf. Technol.* **2009**, *58*, 477–480. [CrossRef]
10. *ISO 10360-1:2000*; Geometrical Product Specifications (GPS)—Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM)—Part 1: Vocabulary. International Organization for Standardization: Geneva, Switzerland, 2000.
11. *ISO 10360-2:2010*; Geometrical Product Specifications (GPS)—Acceptance and Reverification Tests for Coordinate Measuring Machines (CMM)—Part 2: CMMs Used for Measuring Linear Dimensions. International Organization for Standardization: Geneva, Switzerland, 2010.
12. *ISO 10360-3:2000*; Acceptance and Reverification Tests for Coordinate Measuring Machines—Part 3: CMMs with Rotary Tables. International Organization for Standardization: Geneva, Switzerland, 2000.
13. *ISO 10360-5:2020*; Acceptance and Reverification Tests for Coordinate Measuring Machines—Part 5: CMMs Using Multiple Probing Systems. International Organization for Standardization: Geneva, Switzerland, 2020.
14. Nafi, A.; Mayer, J.R.R.; Woźniak, A. Novel CMM-based implementation of the multi-step method for the separation of machine and probe errors. *Precis. Eng.* **2011**, *35*, 318–328. [CrossRef]
15. *ISO 14253-1:2017*; Geometrical Product Specifications (GPS)—Inspection by Measurement of Workpieces and Measuring Equipment—Part 1: Decision Rules for Proving Conformance or Non-Conformance. International Organization for Standardization: Geneva, Switzerland, 2017.
16. *ISO 15530-3:2011*; Geometrical Product Specifications (GPS)—Coordinate Measuring Machines (CMM): Technique for Determining the Uncertainty of Measurement—Part 3: Use of Calibrated Workpieces or Standards. International Organization for Standardization: Geneva, Switzerland, 2011.
17. *ISO 15530-4:2008*; Geometrical Product Specifications (GPS)—Coordinate Measuring Machines (CMM): Technique for Determining the Uncertainty of Measurement—Part 4: Evaluating Task-Specific Measurement Uncertainty Using Simulation. International Organization for Standardization: Geneva, Switzerland, 2008.
18. Calvo, R.; D'Amato, R.; Gómez, E.; Domingo, R. Integration of Error Compensation of Coordinate Measuring Machine into Feature Measurement: Part I—Model Development. *Sensors* **2016**, *16*, 1610. [CrossRef] [PubMed]
19. Magdziak, M. Estimating Time of Coordinate Measurements Based on the Adopted Measurement Strategy. *Sensors* **2022**, *22*, 7310. [CrossRef] [PubMed]
20. Vacharanukul, K.; Mekid, S. In-process dimensional inspection sensors. *Measurement* **2005**, *38*, 204–218. [CrossRef]

21. Lindqvist, R.P.; Strand, D.; Nilsson, M.; Collins, V.; Torstensson, J.; Kressin, J.; Spensieri, D.; Archenti, A. 3D Model-Based Large-Volume Metrology Supporting Smart Manufacturing and Digital Twin Concepts. *Metrology* **2023**, *3*, 29–64. [CrossRef]
22. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital twin in industry: State-of-the-art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415. [CrossRef]
23. Lu, Y.; Liu, C.; Wang, K.; Huang, H.; Xu, X. Digital twin-driven smart manufacturing. *J. Manuf. Syst.* **2020**, *54*, 12–28. [CrossRef]