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Development of Control and Measurement Procedures for Geometrically Complex Surfaces

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Abstract

This study aims to develop and automate control and measurement procedures for parts with complex geometric surfaces under multiproduct manufacturing conditions. By integrating combinatorial analysis, statistical testing, and probe trajectory optimization into a unified framework, the proposed methodology formalizes measurement planning within an automated system. The actual dimensional characteristics of each workpiece are determined at the design stage, enabling the adaptation of the technological process to specific components. Experimental validation was performed on a FARO 9 ARM coordinate measuring machine using six types of complex parts, and statistical testing was performed to identify the optimal number of control points (108) with a minimum measurement time of 72 min per part. The methodology achieved a defect rate reduction of 5% and demonstrated an annual cost savings of 641,172 Rubles. This study integrates control point selection, probe trajectory planning, and measuring instrument choice into a single automated system that adapts to actual workpiece geometry, advancing Metrology 4.0 principles. The proposed approach significantly improves performance compared with conventional methods, reducing metrological preparation time by 76%, lowering defect rates by 50%, and decreasing the number of measurement operations by over 40%. These results confirm the potential of the methodology for enhancing productivity and economic efficiency in digital manufacturing environments.

Keywords:

Control and Measurement Procedures;
Multiproduct Manufacturing;
Production Optimization;
Production Planning;
Technological Process.

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1- Introduction

Modern multiproduct manufacturing of parts with geometrically complex surfaces faces critical challenges in technological preparation and quality control. The high labor intensity of manufacturing such parts, increased requirements for geometric parameter accuracy, and the need to minimize production costs require fundamentally new approaches to the organization of the control and measurement procedures. Traditional measurement planning methods based on generalized workpiece parameters and subjective allowance assignments do not provide the required efficiency in the context of digital production and Industry 4.0 concepts [1, 2]. An analysis of the current state of research in automated measurement planning (AMP) reveals several critical gaps. In Industry 4.0, the development of inspection planning systems based on coordinate measuring machines (CMMs) to support smart metrology demonstrates the application of artificial intelligence, engineering ontology, and genetic algorithms to optimize measurement paths and probe configurations, which reduces the measurement trajectory length [3]. However, these approaches solve the problem of measuring probe path planning without determining the optimal number and placement of control points based on the actual geometric characteristics of specific workpieces.

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A key problem in modern systems is the lack of methods for the adaptive placement of measurement points, considering the actual parameters of the parts. Generative models for point-sampling strategies on complex surfaces can reduce the number of measurement points while maintaining the surface error reconstruction accuracy, transforming the task into an image super-resolution problem [4]. Adaptive sampling methods for the precise measurement of aircraft engine blades have improved the accuracy of assessing the geometric complexity of surfaces [5]. However, existing sampling strategies are not integrated with automated process planning systems and require pre-programming for each part type using generalized parameters instead of actual workpiece dimensional characteristics.

The integration of metrology systems into Industry 4.0 is becoming a key direction in modern manufacturing development. Smart metrology, a revised metrology function that uses artificial intelligence techniques to make informed decisions, necessitates comprehensive measurement models and cyber-physical measurement systems [6]. Integrating metrology with smart manufacturing concepts provides higher product quality, improved productivity, and energy efficiency through the use of smart sensors, robotic platforms, and data monitoring systems [7]. However, the practical implementation of such systems faces challenges in managing large volumes of measurement data and requires significant investments in IT infrastructure.

In this context, the problem of forming a rational set of measuring instruments for multiproduct manufacturing is particularly relevant. Modern approaches to planning machining processes do not include automated methods for selecting control and measuring instruments based on the technical characteristics of the measured surfaces [8]. The lack of formalized procedures for selecting measuring instruments leads to the excessive use of measuring instruments and an increase in the time required for the metrological preparation of production.

A critical analysis of the literature shows that existing methods address the tasks of determining the number of control points, their placement, and planning the trajectory of the measuring probe as independent problems without providing a comprehensive solution. To date, there are no quantitative assessments of the economic efficiency of introducing automated systems for planning control and measurement procedures in actual multiproduct manufacturing to determine specific indicators for reducing defects and time expenditures [9].

This study aims to fill the identified gaps by developing a comprehensive methodology for the automated planning of control and measurement procedures for multiproduct manufacturing of parts with complex surfaces. The scientific novelty of this study lies in the integration of determining the optimal number of control points based on the actual dimensions of the workpieces, their placement using combinatorial analysis methods, and the formation of a rational set of measuring instruments into a single automated system.

Experimental testing on a FARO 9 ARM coordinate measuring machine demonstrated the quantitative advantages of the methodology: a 76% reduction in metrological preparation time, a decrease in the proportion of defective products from 10% to 5%, and a reduction in the number of measurement operations by more than 40%, which significantly exceeded the results of existing solutions in individual areas of optimization. Thus, the methodology ensures conceptual novelty through the systematic integration of measurement procedures within the Metrology 4.0 context, as well as a significant improvement in the production efficiency of multiproduct manufacturing of parts with geometrically complex surfaces. The developed methodology ensures the adaptation of the technological process to the actual geometry of specific workpieces, eliminates the subjectivity of technological allowances, significantly reduces the time required for the metrological preparation of production, reduces the proportion of technological defects, and increases the overall production efficiency in the context of the digitalization of multiproduct manufacturing.

The Literature Review section presents a critical analysis of current research in the field of AMP, identifying key gaps in existing methodologies. The developed methodology is described in the Materials and Methods section, including the formation of sets of control and measurement procedures and instruments and the determination of the optimal number and distribution of control points. The Results section presents the results of the methodology's experimental testing on a FARO9 ARM coordinate measuring machine with a quantitative assessment of its economic efficiency. The Discussion section compares the results obtained with those of existing approaches and presents a systematic analysis of the proposed methodology's advantages. The conclusion section presents the main conclusions of the study, its theoretical and practical significance, and directions for further research.

2- Literature Review

The integration of automated measurement planning systems with the concepts of Industry 4.0 and smart manufacturing is becoming a key development area in modern metrology. The development of approaches to plan measurement trajectories for 5-axis coordinate measuring machines (CMMs) with consideration for path reuse proposes an inspection planning methodology for multi-station production of complex parts, such as engine cylinder blocks. Zhao et al. [9] developed a rapidly exploring random tree with multi-root node (RRT-MRNC) algorithm to optimize the measurement of probe trajectories, including the reuse of paths without additional obstacle avoidance points. This reduced the total planning time by 41.4%–55.2% compared with the traditional methods. The methodology involves classifying measurement points based on coverage criteria and using a genetic algorithm to solve the generalized traveling salesman problem for global path planning. However, the proposed approach focuses on predefined groups of measurement points and does not adapt to the actual dimensional characteristics of specific workpieces, limiting its application under multiproduct manufacturing conditions with variable part parameters [10].

Yan et al. [11] developed two-module methodologies for automated scanning measurement planning for complex surfaces. This study proposes an approach that combines automatic trajectory planning with the optimization of scanning parameters to ensure high accuracy and productivity of measurements on CMMs. The time required to prepare measurement programs is significantly reduced and their reliability is increased. However, this methodology does not consider the actual geometric characteristics of specific workpieces and requires preprogramming for each part type, which limits its application in multiproduct manufacturing conditions. Urban et al. [12] discussed issues related to the optimization of economic indicators and environmental impact when planning CMM measurements. They showed that the proper optimization of measurement plans can significantly reduce the time and energy consumption of measuring equipment without compromising the control accuracy. However, the proposed algorithms are not integrated with automated process planning systems and do not adapt to the actual workpiece dimensional characteristics.

Modern studies have focused on the application of optical measurement methods in digital manufacturing. Catalucci et al. [13] and Hall [14] provided a comprehensive overview of optical metrology methods for digital manufacturing, emphasizing the advantages of non-contact measurement technologies for increasing measurement cycle rates and integrating them into automated production systems. However, optical methods have limitations when measuring complex geometries with multiple elements or curved surfaces, which require the use of contact measurement methods to achieve the required accuracy [15]. The development of specialized metrological approaches is becoming a critical task in additive manufacturing (AM). A comprehensive review of metrology in AM and 3D printing technologies [16, 17] shows that traditional measurement methods require significant adaptation to control geometrically complex products manufactured layer by layer. The authors emphasize the need to develop new metrology standards and measurement procedures dedicated to AM technologies. Existing approaches do not provide effective planning of measurement procedures that consider the specific defects of AM and require considerable time to set up the measuring equipment.

Archenti et al. [18] investigated integrated metrology approaches in advanced manufacturing. This study demonstrates the transition from autonomous metrology systems to integrated solutions that provide continuous quality control at all stages of the manufacturing process. This approach is particularly relevant for the multiproduct manufacturing of parts with complex geometric surfaces. However, to modernize existing systems, this integration requires significant planning and investment, and managing large volumes of measurement data requires a reliable information technology (IT) infrastructure. Mohammad et al. [19] developed methods for assessing measurement uncertainty in CMMs using reference step gauges. The authors propose a new measurement model and modified uncertainty analysis for verifying the characteristics of CMMs, which provides a more accurate assessment of the measuring equipment's metrological characteristics. However, CMMs require significant investment in equipment and skilled operators, and improper use can lead to damage and high equipment repair costs.

The degree of efficiency in manufacturing a particular product largely depends on the quality of each production operation's creation and organization. Production planning faces several technical and organizational challenges. The efficiency of performing these tasks largely determines each manufactured product's quality, including its technical and economic characteristics, which are established during the design stage. In this case, increasing productivity and production profitability and minimizing the main and additional costs associated with the production of each part are essential. The proper organization of TP, planning, and execution of each production operation must use modern management techniques. Simultaneously, the quality of the design of a future conditional part will largely determine the obtained results, as discussed in [20–22].

Modern approaches to automating the planning of measurement procedures using CMMs rely on integrating computer-aided design (CAD) models with offline programming modules to automatically generate probing trajectories. Studies on hierarchical planning have shown that the use of heuristics and multidimensional knowledge bases formalizes the procedures for converting geometric information about a part into coordinate measuring machines (CMMs). This significantly reduces the preparation time and minimizes the human factor in the measurement setup process [23]. Studies on the organization of automated planning based on ontologies and semantic models demonstrated an increase in system flexibility when supporting various types of surfaces and CMM tool configurations, which is essential for multiproduct manufacturing (MPM) [24].

Optimizing the measurement sequence and trajectory of the measuring head is a key task for improving the control and measurement procedures' productivity and accuracy. Reducing the task to a traveling salesman problem with restrictions on permissible spatial movements makes it possible to use genetic algorithms to determine a practically optimal path for traversing selected points on the part surface. This reduces the measurement cycle time without significantly reducing the accuracy of the geometric characteristics measurement [25]. However, CMM bottlenecks are often caused by a large volume of work, leading to an increase in measurement cycles and costs to ensure the proper level of production quality.

When designing measuring points for geometrically complex or freely shaped surfaces, the uniform distribution of control points and their significance should be given special attention. In conjunction with Poisson disk sampling algorithms, optimal experimental design methods that combine D-, G-, and A-optimality criteria allow for the formation of a set of points that is both maximally informative and uniformly covers the measurement area. The integration of "greedy" point selection with subsequent improvement of the solution using genetic algorithms demonstrates high stability and applicability in actual industrial scenarios [26, 27].

The concepts of smart manufacturing and Metrology 4.0 focus on the digital interconnection of the measurement data planning, collection, and analysis systems. Developments based on the integration of Computer-Aided Design/Computer-Aided Manufacturing/Computer-Aided Engineering (CAD/CAM/CAE) models, service-oriented architecture, and optimization algorithms (including heuristic and genetic algorithms) create platforms capable of adapting to the requirements of mass customization while maintaining high levels of flexibility and measurement quality. Automated measurement plan generation is a key module in such systems that reduces the cost of metrological preparation and increases the efficiency of controlling geometrically complex parts [3, 28]. However, speed and data processing bottlenecks associated with software and hardware solutions, as well as difficulties arising from variations in the size, shape, and texture of manufactured products, remain problematic.

An analysis of the current state of studies revealed critical gaps in the planning methodology for control and measurement procedures for multiproduct manufacturing of parts with geometrically complex surfaces. Modern optimization methods consider the tasks of determining the number of control points, their placement, and planning the measuring probe's trajectory as independent problems without providing a comprehensive solution.

Modern methodologies do not consider the actual geometric characteristics of specific workpieces and use generalized parameters when programming CMMs. Trajectory optimization studies consider the problem of planning the path of the measuring probe separately from determining the optimal number and placement of the control points. Studies on automated measurement planning are not integrated with process planning systems and require preprogramming for each part type. No methodologies exist for the automated formation of a set of measuring instruments based on the criteria for compliance with the technical characteristics of surfaces. Quantitative assessments of the economic efficiency of introducing such systems into actual multiproduct manufacturing, with the determination of specific indicators for reducing defects and time costs, are proposed.

3- Material and Methods

Figure 1 shows the flowchart of this study. The development of a method for control measurement operations for automated design systems of TP for machining is a variation in the formation of fundamentally new approaches to product planning, which enables the achievement of the required accuracy indicators for all surfaces of the future product against the backdrop of rapidly changing conditions of modern software products (SP).

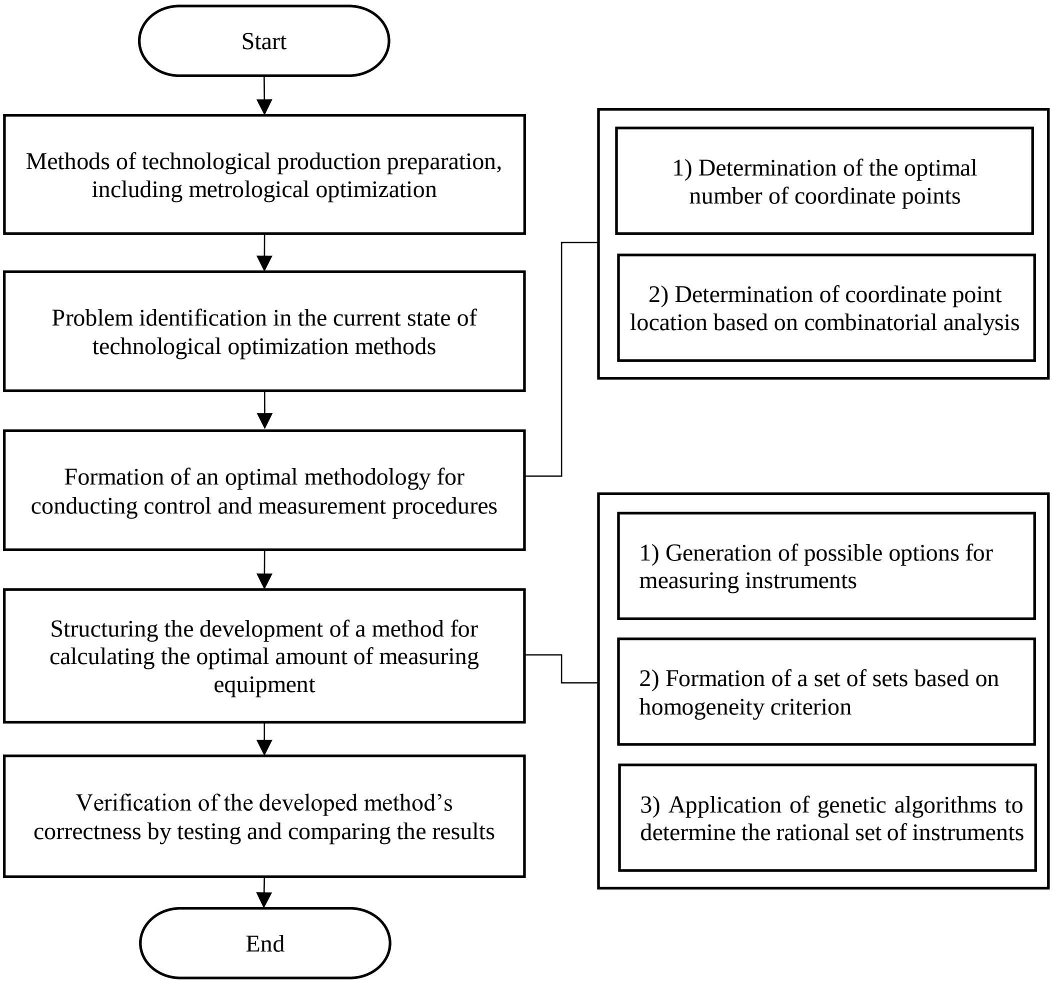

Figure 1. Flowchart of the study

3-1- Development of a Control and Measurement Procedure Set

To create the most efficient method for implementing each control measurement procedure under the current conditions, the following is necessary.

- Creation of methods that allow the measurement of the dimensions of each surface of the future product. The interrelationship between these dimensions and the workpieces of the manufactured products, which are structural components of the TP, must be considered.
- Systematization of each production operation expected by the project, including measurement, will help to form an optimal list of measuring instruments covering all control MIs necessary to measure the product surfaces.

The proposed system differs in that it has a distinct interconnection between several components: the final technological decision-making, the actual dimensions of all planes of the workpiece under inspection, and the current state of production. Owing to this interconnection, a reserve that optimizes the machining TP design can be formed,, as shown in Figure 2.

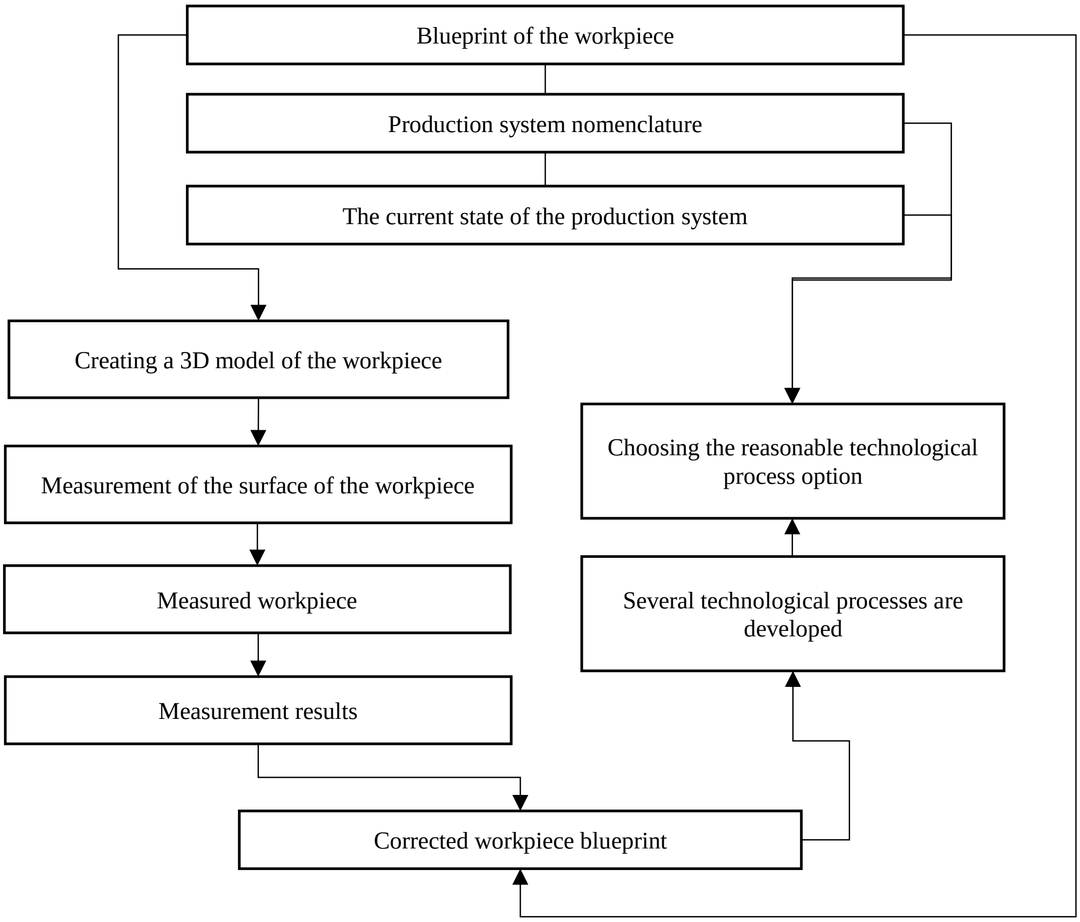

Figure 2. Organization of the implementation of a control measurement procedure system

The strength of the proposed method in creating TP products with sufficiently complex surfaces lies in the mandatory consideration of the actual dimensions of the future product blank, as opposed to the generalized conditions imposed on its quality parameters. As discussed by Leo Kumar [29], this advantage provides the required accuracy indicators for the final product and reduces the majority of its production costs.

During design, assessing the actual dimensions of each surface of conventional workpieces opens the possibility of controlling the formation of an appropriate processing technology for all products. It is also possible to compare the optimality of the current technological procedure with that of the primary TP, which is essential for understanding the specifics of the current SP design.

With the actual dimensions of all workpieces available, it is possible to develop a single TP for small-scale production, which requires universal measuring instruments such as CMMs. The automated measuring instrument capable of assessing the accuracy indicators of the product under test is the basis of the developed method for each control measurement procedure, which has geometrically complex surfaces and is technically complicated to measure, as discussed in more detail in Zhu et al. [30] and Pappas et al. [31].

Thus, CMMs, which represent the most promising type of measuring instrument, can help solve a variety of technically complex tasks related to assessing the quality of products with geometrically complex surfaces.

The use of CMMs in any control measurement procedure involves the creation of 3D models of workpieces based on drawings. The corresponding software was developed based on the 3D model of the workpiece to analyze the actual dimensions of each surface under study. This helps improve the initial structure of the workpieces and automatically generates working drawings that list all dimensional parameters for a given surface. The assessment of the working drawing allows the adoption of the most effective technological solution for the current conditions, such as the creation of a sheet for the implementation of the corresponding technological operation, selection of the optimal surface treatment method, base establishment, and choice of technological equipment and cutting tools.

The central task that control and measuring instruments must perform is to determine the influence of the measurement results of the specific workpiece surface on the characteristics of the TP creation (Table 1). Figure 3 shows the measurement results and the structural part of the automated multiproduct process planning system.

Table 1. Basic operations and product measurement indicators in the TP

Measurement of the workpiece surface parameters	Real surface parameters	Dimensional characteristics of the structural elements
		Dimensional relationships between the surfaces
	Deviated geometric shape	Deviations from the plane
		Deviations from the straightness
		Deviations from the roundness
		Deviations in longitudinal section profile
	Mutual arrangement of the surfaces	Misalignment
		Deviation from the symmetry
		Slope deviation
		Deviation from the intersection of the axes
		Deviation from the perpendicularity
		Positional location
Design procedures for the development of a technological process	Types of procedures	Choosing a Surface Treatment Method
		Development of a route for technological operations
		Choice of the basing schemes
		Formation of a set of technological equipment
		Development of the structure of technological operations

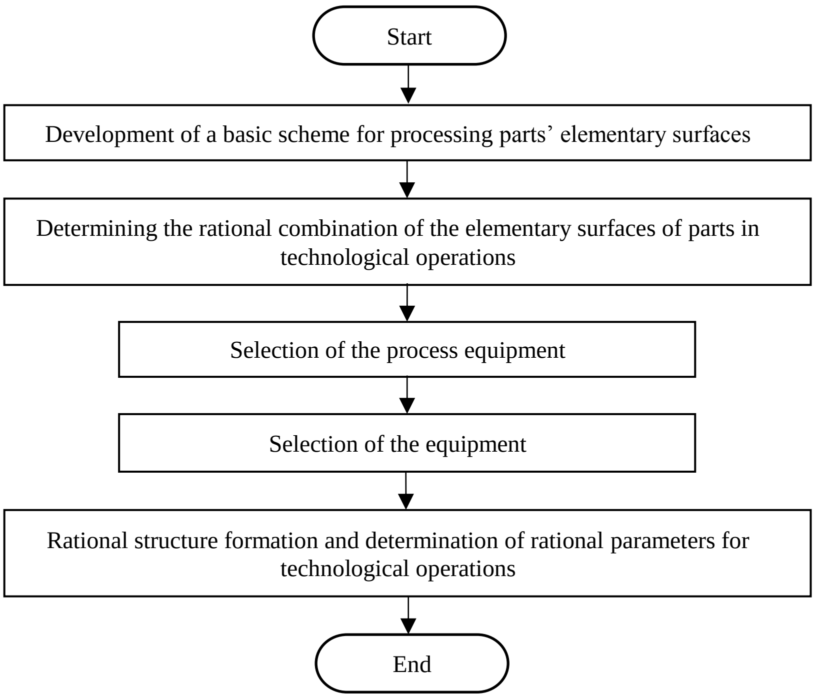

Figure 3. Structural part of automated systems capable of planning multi-product TP

Accordingly, information about the actual size of certain workpiece surfaces increases the efficiency of rational machining TPs for a product. This is essential, especially considering the specifics of production based on the automated planning of each TP, because it ensures the best placement of workpieces for the current conditions and the optimal sequence of ongoing processes, considering technological inheritance, tolerances for each surface, and other factors, as discussed in more detail in studies by Townsend et al. [32] Sushil et al. [33] Tao et al. [34] and Krolczyk et al. [35].

3-2- Formation and Distribution of the Optimal Control Point Number

The creation of a method capable of automatically measuring coordinates assesses the actual dimensions of each inspected workpiece surface, which is necessary for selecting the optimal processing technology for the current conditions.

The proposed measurement method helps determine the optimal number of positions for analysis on the surface under evaluation. The accumulation of information about such positions forms the specifics of the measurements and, in combination, creates a basis that increases the accuracy and productivity of all the measurements. This accumulation improves the productivity of the entire SP. Thus, information on all points that the user has accumulated can reduce the measurement duration and increase their effectiveness.

After analyzing all points N_{ras}, we can measure the dimensions of the surfaces of interest based on probability theory. After evaluating the dimensions of the workpiece surfaces (dimensions, diameters, radii, etc.), the maximum number of coordinates of the evaluated surfaces (N_m) was calculated as follows:

$$N_m = \frac{R_i}{k_{mt_{min}}} \tag{1}$$

where N_m is the maximum number of surface coordinates, R_i is a list of dimensions of the surfaces under investigation, i=1,2,3…r, r is the total number of all checked dimensions, and $k_{mt_{\min}}$ is the minimum dimension that the measuring device can check.

The quality of the measurement operations increases when measuring dimensional characteristics using the maximum number of coordinates; however, these operations become more labor-intensive. Therefore, it is essential to calculate the optimal number of coordinates for each measured surface, and its solution contributes to improving the measurement efficiency.

The optimal number of coordinates (N_{ras}) was calculated using statistical analysis. Based on their results, in this study, the actual size of the analyzed surfaces was refined using randomly selected points. Thereafter, the ratio of the frequency of the surface dimensional characteristics to the number of coordinates was calculated to ensure the accuracy of the measured precision characteristics, as shown in Figure 4. The optimal number of coordinates was determined using limited enumeration [36, 37].

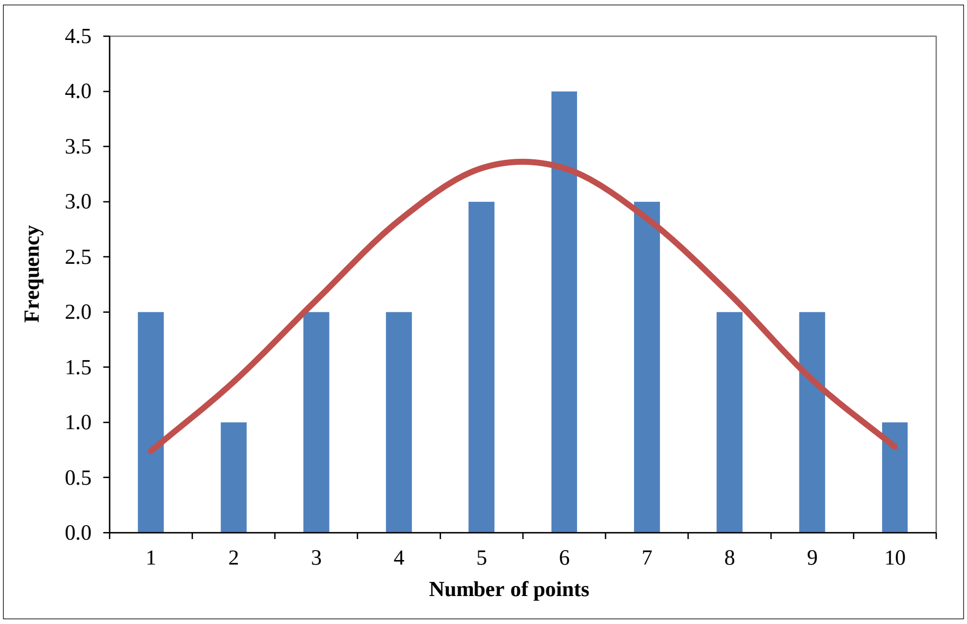

Figure 4. Optimal number of coordinates of measured product surfaces

The number of coordinates was determined to ensure that the final value was as accurately as possible. When measuring coordinates, following the recommendations regarding their correct placement is essential, as described by Magdziak [38]. Today, the method of uniform placement of coordinates on the measured surface is becoming increasingly popular because it allows for the high-precision recording of desired dimensions (for example, planes or workpiece edges). When analyzing a surface with a complex profile, such coordinate placement can indicate areas of concentration, which often increases the likelihood of errors.

Therefore, a combinatorial analysis was used to calculate the optimal placement of coordinates and their number N_{ras}, as described by Shai & Rubin [39]. The combinatorial analysis considered many options for the placement of coordinates (the optimal N_{ras}, calculated earlier) or coordinates placed unevenly (for example, along a twisted line, in a circle, etc.).

$$k=(N_0-1)! \tag{2}$$

where N_0 is the basic number of possible positions for placing coordinates. Considering the calculated number of coordinates, the option for their placement that best suits the current measurement operation (i.e., the maximum coverage of the measured surfaces by coordinates with the minimum measurement time) was selected as follows:

$$t_k = \frac{p(N_m)}{\vartheta} \to min \tag{3}$$

where $p(N_m)$ is a closed profile of the measured surfaces of conditional workpieces, ϑg is the time required for the operator to collect the desired coordinates (in our situation $\vartheta=const$), and t_k is the duration of surface assessment, considering the selected coordinate placement option.

As the next step, the resulting coordinate placement scheme must be applied on the measured surfaces $S_d(N_m,R)$ (the set of coordinates of the measured surfaces expresses the current k value) to select the best option for the given conditions for the placement of the coordinates of the surfaces under investigation with a constant transition time from the measurement of the current coordinate to the next one:

$$S_{N_{ras}}(n) = \sum_{i=1}^{N_{ras}\Sigma} \sum_{j=1}^{N_{ras}\Sigma} t_{ij} n_{ij} \to min$$

$$\begin{cases} \sum_{i=1}^{N_{ras}} n_{ij} = 1, \forall j = \overline{1, N_0} \\ \sum_{j=1}^{N_{ras}} n_{ij} = 1, \forall i = \overline{1, N_0} \\ n_{ik} \in (0,1) \end{cases} \tag{4}$$

where values of n_{ij} are determined by the inclusion or exclusion of MI in the set, $S_{N_{ras}}$ is the initial variant of the placement of the coordinates of the surfaces under investigation, $R \subseteq N_{ras} \times N_{ras}$ is all edges that connect the coordinates of the measured surfaces, thus forming a specific contour of the analyzed planes for the CMM measuring device, $N_{ras} = \{n_1, n_2, n_{3,\dots} n_k\}$ is the optimal number of coordinates of the examined plane, and t_{ij} is the time interval for the transition from the current contour edges to the next ones.

Therefore, a list of coordinates on the surfaces under study that best corresponds to the measurements' specifics is established. Calculating the optimal number of coordinates in a statistical test allows you to process all coordinate points checked during the measurements. Such a calculation is relatively simple, highly effective, and requires little effort to implement. As discussed by Zanini et al. [40], this is necessary to obtain the actual dimensional characteristics of the workpiece surface.

For the best distribution of production time, it is essential to use measuring equipment rationally. Therefore, it is necessary to select the optimal measuring instruments in the automated planning system to perform control measurements during the current TP.

3-3- Formation of a Control and Measuring Instrument Set

The distinctive feature of the proposed automated subsystem, which uses the MI list optimal for the current conditions and is on the general list of automated multiproduct process planning systems, is that the required data on the simulated TP of the future product processing in the automated planning system can be obtained based on the results of the previous processing stage. Figure 5 shows the specifics of selecting the optimal MI list.

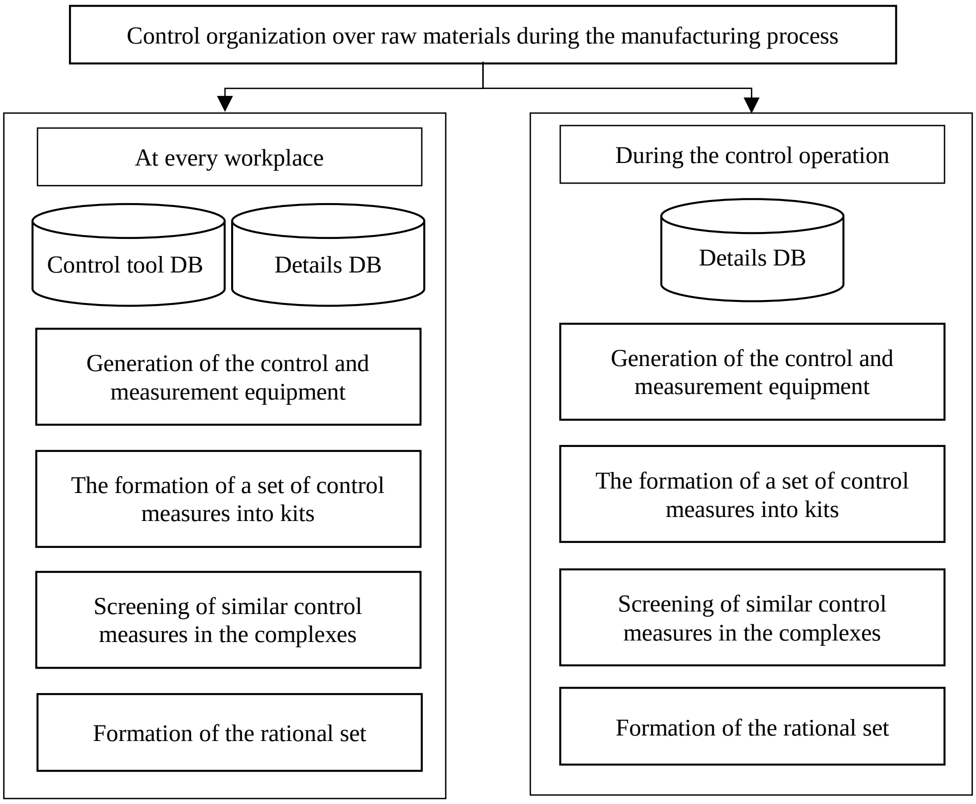

Figure 5. Specifics of selecting the optimal list of control MIs; DB stands for database

To generate probable variations of the MI list in the final kit for the simulated production system (PS), an apparatus based on set theory [41] was used. The following data were used as the initial data for generating the optimal MI list:

1) Possible combinations of planes to be measured.

2) All MI combinations available to the automated planning system.

All K lists for all possible MI variations were formed based on an analysis of the characteristics of existing production, considering the dimensions of the future product $\{S_d\}$, the operating parameters of MI $\{w_i\}$, and possible variations in MI configuration $\{v_t\}$ for measurements as described by the following expression.

$$K = \{S_d\} \cap \{w_i\} \cap \{v_t\} \tag{5}$$

where all possible variations of K represent a set of separate lists with a unique set of MI, w and i are the aggregate parameters of the list, q is the basic properties of the list, and z is the total number of parameters of all sets.

The area where possible variations intersect forms a sector of probable solutions, i.e., a set of K covering all MI lists that best correspond to the current conditions. Figure 6 shows the formation of MI list variations.

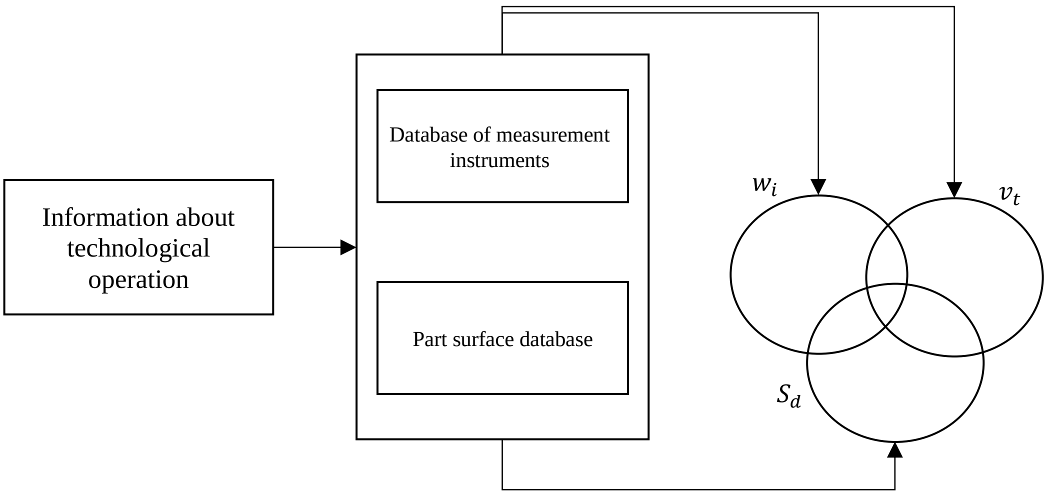

Figure 6. Formation of MI list variations considering PS characteristics

The selection of MI for specific lists considers that each measuring instrument in set K has specific parameters w_i corresponding to the measurement conditions. All created lists differ in terms of the technical and economic indicators considered when selecting the optimal MI list, but the measurement time using the selected MI was the shortest:

$$T_k = \sum t_k \rightarrow min$$

$$\begin{cases} P(K") = \sum_{m=1}^{z\Sigma} k_m * w_k \rightarrow max \\ \sum_{m=1}^{z} k_m * t_k \leq T_k \\ k_m \in \{0,1\}, m = \overline{1,z} \end{cases} \quad (6)$$

where values k_m are determined by either the inclusion or exclusion of MI into the final kit, $P(K")$is the optimal list of MI that best suits the specifics of existing production, $m = \overline{1,z}$, z is the total number of MI for performing a control measurement operation, w_k is a group of MI technical indicators, and T_k is the duration of use of a specific MI in a single operation.

In instances where the anticipated measurement efficiency proves unattainable, novel lists are developed based on the existing MI lists, which undergo cyclical updates over time. Concurrently, the duration of the methodology under consideration constrains each cycle. Upon completion of the methodology operation, several MIs meet the existing requirements; in other words, the result is an optimal MI list that can best perform the measurement operation under the current conditions. Several specialized methodologies were developed when selecting the optimal MI list and guided by the specifics of the automated planning system (Figure 7), which significantly reduced the time required for each measurement.

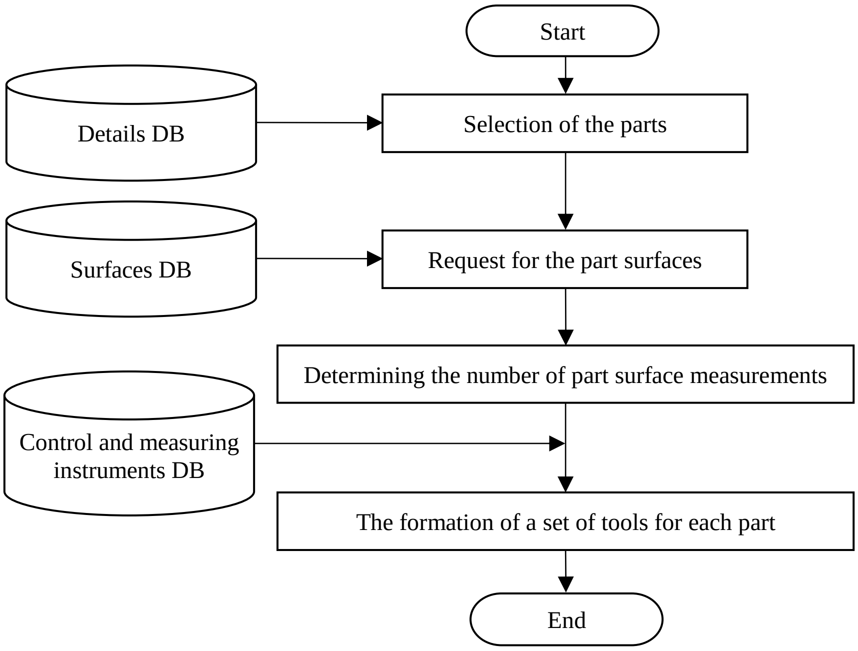

Figure 7. Schematic of the methodology for generating measurement instrument sets

Using these methodologies, requests can be generated to the information array that stores most of the technological parameters of MI. This array covers:

- Type of the measured surfaces;
- Surface accuracy;
- Dimensions of the measured surfaces;
- Accuracy level of MI;
- Spectrum within which MI can perform the measurements;
- Name of the MI.

Enumeration is used to form all possible variations of the MI configuration. The selection of the formation order of the following list of measuring instruments depends on the number of enumeration variations and calculation duration. Here, it is essential to organize the optimal selection of MI for the current measurement while eliminating less suitable sizes of measuring instruments, for which the analyzed surface, its dimensions, the specified measurement accuracy, and other factors are considered. Thus, a complete range of MI variations is created, allowing for the surface measurement of the processed workpieces.

The methodology and programs that eliminate ineffective variations must consider uniformity as a criterion, i.e., the selected MIs must be interchangeable. The dimensions of the analyzed surfaces and the MIs are used as the measurement operation's initial data. In the subsequent stage of the process, instruments capable of measuring the maximum number of planes of the conditional product are selected. The elimination of ineffective variations results in the generation of new MI list variations. The creation of an optimal MI list necessitated the development of a genetic methodology, as illustrated in Figure 8.

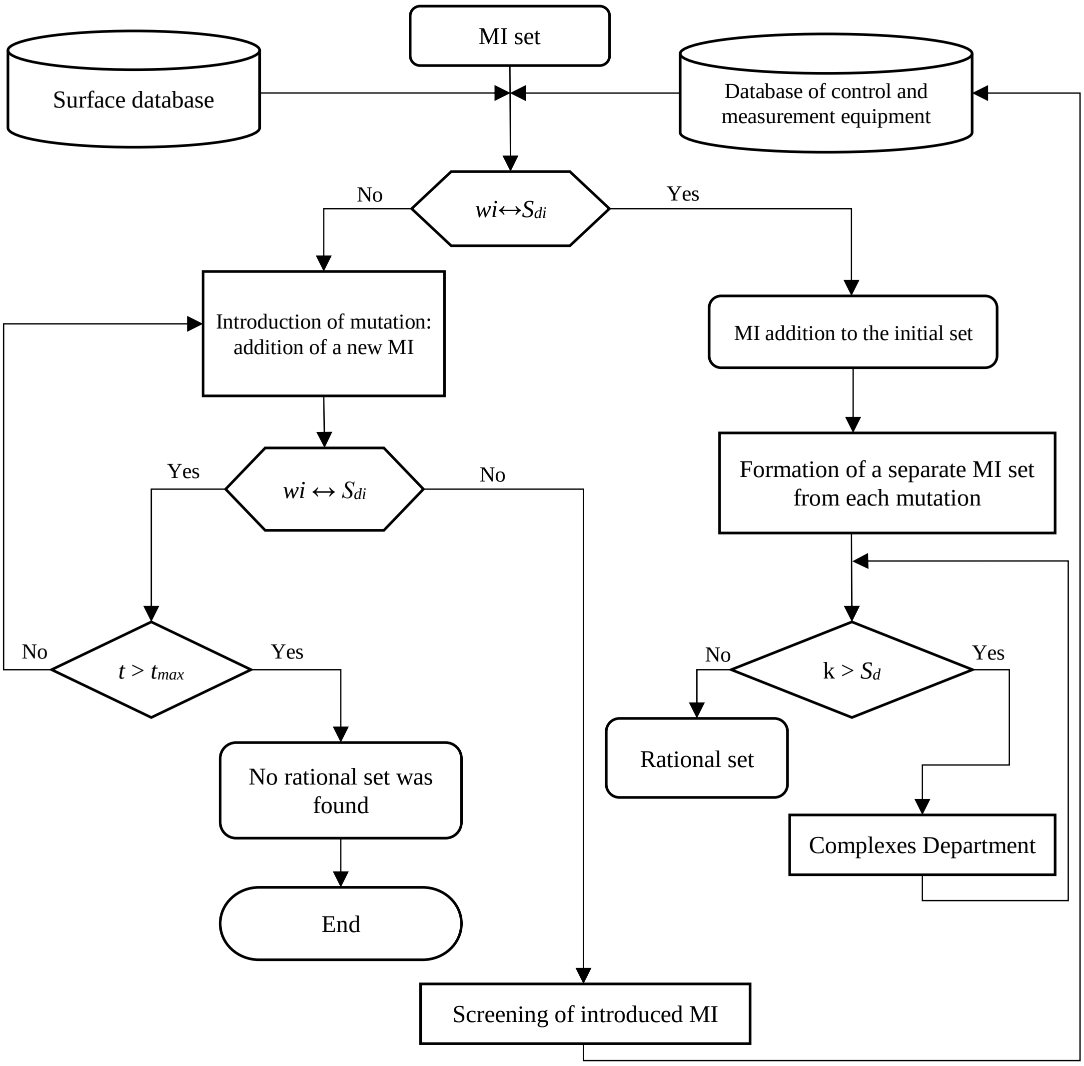

Figure 8. **Schematic representation of the purpose of a rational set of control and measuring instruments in a controlled planning system**

Previously created MI lists that combine measurement tools not entirely suitable for the current situation serve as initial data for creating an optimal MI list within the existing automated planning system. When selecting the optimal MI list that can meet requirements such as the shortest measurement time under given conditions and the ability to measure different types of surfaces, a new MI is added to the existing MI information array. The selection of a particular measuring instrument occurs according to previously created variations of MI sets, provided that it is available to reserve. The formed set is rechecked. The number of such checks is limited by the duration of the methodology operation. Upon completion, an updated MI set that meets the requirements is formed.

4- Results

The proposed methodology was tested on six types of parts with geometrically complex surfaces to verify its applicability in multiproduct manufacturing. However, the limited sample size implies the need for further validation when scaling the methodology for large-scale production with a more diverse range of geometric configurations. The computational efficiency of algorithms when processing thousands of different product sizes requires additional research and optimization of the combinatorial analysis procedures. The applicability of the developed approach to optical and hybrid coordinate measuring machines appears to be feasible. However, adaptation of calibration procedures is required owing to the specifics of non-contact measurement methods.

The economic efficiency of the created system of control measurement operations necessary for developing a multiproduct TP plan was assessed considering the following:

- Using an automated planning system, reduce technological defects in manufactured products
- The TP period is reduced by forming an optimal list of control MIs, thereby reducing the duration of each measurement operation and the total number of measuring instruments used.
- Increase the productivity of the automated planning system using a method that measures the workpiece surfaces, which makes it possible to obtain actual dimensional characteristics.

We conducted a series of experimental studies to analyze the results of the proposed method, which automatically measures the dimensions of surfaces, during which products with geometrically complex surfaces were examined. A FARO 9 ARM coordinate measuring machine was used for this purpose. Based on the research results, the number of coordinates was justified using different types of measured planes, observing the specified accuracy and the highest performance under the current conditions.

Figure 9 shows a graph of the dependence of the frequency of obtaining the dimension characteristics of the measured surfaces of the future product on the number of coordinates used in this assessment.

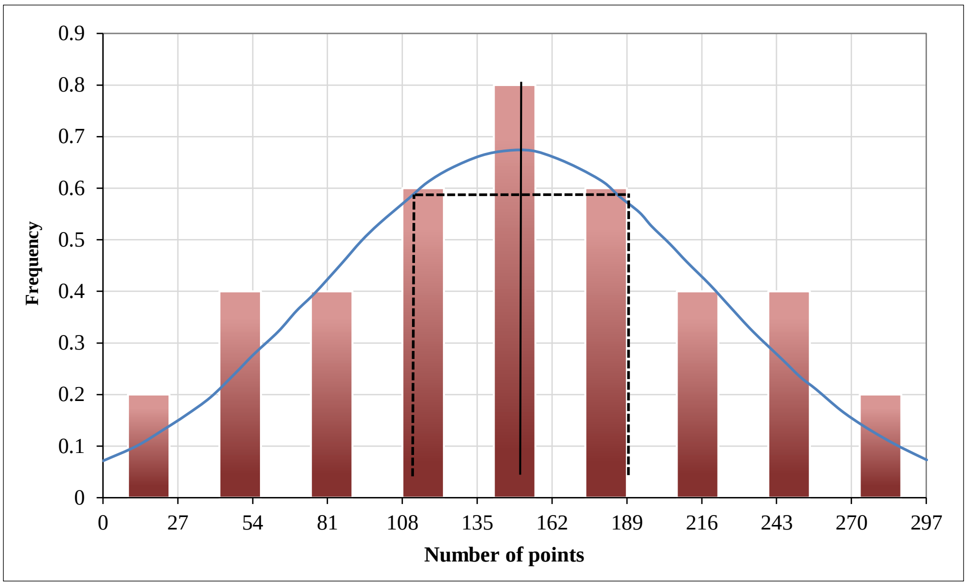

Figure 9. Calculation of the optimal number of coordinates

Consequently, we determined that the optimal number of coordinates is in segment $(N_p;N_m)$:$3 \leq N_{opt} \leq 190$ when N_{opt}= 108. The points' values are determined by the minimum boundary σ.

The methodology was experimentally verified on a FARO 9 ARM coordinate measuring machine for a set of typical parts with geometrically complex surfaces (base, support part, outer joint, expansion cam base, shaft with radial element, and bushing housing with spiral surfaces). Statistical testing revealed an optimal number of control points of 108, ensuring the required accuracy with a minimum measurement time of 72 min per part. The geometric characteristics of the parts determine the placement density requirements of the control points on the measured surfaces. The surface profile complexity, presence of transition areas, and radius elements require more coordinates for a reliable assessment of shape deviations, whereas a minimum number of points is sufficient for simple flat elements. Different deviation values from the geometric shape obtained during measurement introduce changes in the structure of the technological operation, namely, the selection of various technological equipment and different technological bases for installing the workpiece.

To reduce technological defects in the products manufactured by the automated planning system, we considered recommendations regarding technological tolerances based on the actual dimensional characteristics of the planes when creating this system for multiproduct technological processes. This helps make the most efficient technological decisions under current conditions, ensuring the specified accuracy indicators and reducing the time costs of implementing the SP.

The sample presented is relatively small. It comprises six types of products. Various products used have the following indices: 1 - Base; 2 - Support; 3 - External joint; 4 - Base of the expansion cam; 5 - Shaft with a radial element; 6 - Bushing housing with complex spiral contours on the side surface. Figure 10 shows the results of the analysis of how much the proposed method helps to reduce production costs.

The elimination of subjective assessments during the creation of the TP for processing parts, the utilization of measurements of the actual dimensions of the workpieces, and the formulation of specific recommendations regarding the technological tolerance values demonstrated a 50% reduction in the proportion of defective products. Consequently, the total defect rate was reduced to 5%.

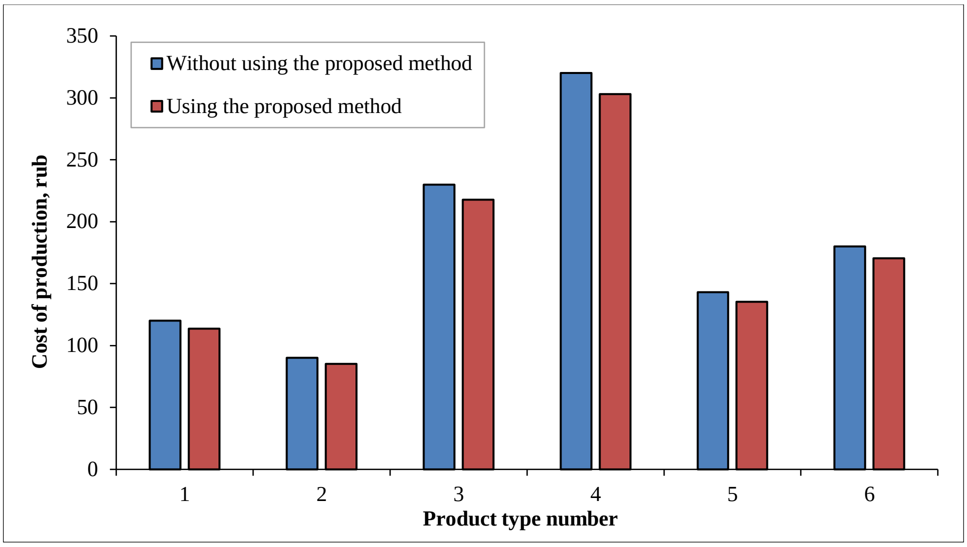

Figure 10. Economic efficiency of the proposed technological solution

Understanding these relationships will help develop adaptive control strategies for specific product ranges. Technologists can determine in advance the rational distribution of measurement resources between different types of part surfaces, thereby reducing the inspection time without compromising metrological accuracy. This reduces the preparation costs when developing new products and minimizes the risk of missing defects in critical areas of complex surfaces.

To calculate the economic effect of reducing the preparation period, the total number of MIs used was reduced owing to the increased efficiency of the automated planning system's measurement operations. This objective was accomplished by employing automatic measuring instruments that analyze the accuracy characteristics of products with geometrically complex surfaces and reduce the measurement duration using an optimal list of MIs.

The following equation provides a quantitative representation of the reduction in MI usage achieved through automated system implementation:

$$E=(T_{na} - T_a)*S_c \quad (7)$$

where T_{na}, T_a is the duration of the measurement operation by non-automated and automated MI, h, S_c is the operator's salary servicing non-automated operations, Rubles/h, and E is the degree of economic efficiency.

The proposed methodology was tested to evaluate the optimal duration of product surface measurements. The test results were then compared and plotted on a Gantt chart, as illustrated in Figure 11, where T_{na} = 0.83 h and T_a = 3.53 h. Therefore, the savings calculated for 12 months using ratio (7) were 641,172 Rubles.

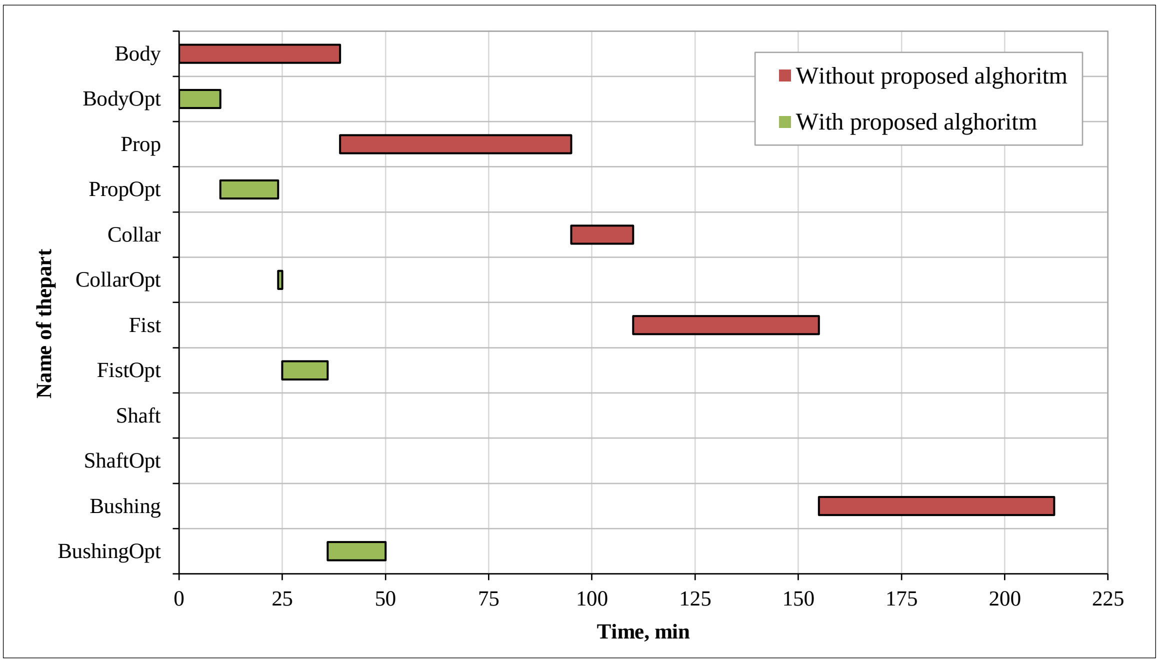

Figure 11. Duration of the measurement procedure

A comparative analysis of the duration of the measurement procedures showed a significant reduction in the cost of time. The Gantt chart demonstrated that the proposed method reduced the measurement process duration by 76% compared to non-automated operations, thus proving the high efficiency of the developed method.

The use of a software procedure for measuring part surfaces increases production system productivity by reducing measurement time. This method was based on the calculation of economic effect indicators using the software measurement procedure on a coordinate measuring machine. Equation 8 is also used to calculate the increase in labor productivity, which directly affects revenue, as a criterion for analyzing the economic gain obtained.

$$P = \frac{(T_a - T_{na})}{T_{na} - (T_a - T_{na})} \times 100\% \quad (8)$$

The calculation showed that measuring the actual dimensional parameters of workpieces using automated tools saved 3.825 hours and increased labor productivity by P = 43%.

5- Discussion

The developed comprehensive methodology for planning the control and measurement procedures for parts with geometrically complex surfaces combines the measurement of the actual parameters of workpieces with the optimization of measurement strategies. The actual dimensions of each part are determined during the design phase, adapting the technological process to a specific product and eliminating subjectivity when assigning tolerances. A combinatorial analysis of control point selection is applied, considering the analytical surface model and measurement costs. The probe trajectory is optimized as a closed loop with minimal transition time. The implementation of rigorous criteria for selecting MIs (type, range, and accuracy) eliminates ineffective tools, thereby reducing the total number of operations. This approach aligns with the principles of digital manufacturing and Metrology 4.0, enhancing the flexibility and reliability of production planning. Experimental testing on the FARO 9 ARM CMM demonstrated the proposed method's high efficiency. Generally, alternative hybrid control and measurement instruments with similar accuracy should yield the same results. The identified rational number of measurement points (108) enabled the achievement of the required accuracy with minimal measurement time. Despite the relatively small sample of parts used to test the proposed methodology, it is effective in large-scale production with various parts of different geometries.

A fundamental weakness of existing approaches [9, 20, 21, 26] is that they treat the tasks of determining the number of control points, their placement, and planning the measuring probe's trajectory as independent tasks. Stojadinovic et al. [3] demonstrated the use of genetic algorithms and engineering ontology to reduce the length of the measurement trajectory by 12.81-30.11%. However, the probe path optimization does not determine the optimal number of sampling points. Zhao et al. [10] achieved a 41.4-55.2% reduction in planning time using an RRT algorithm with path reuse for 5-axis CMM, but their method focuses on predefined groups of measurement points without adapting to the actual parameters of specific workpieces. Alexandrov et al. [20] developed a method for optimal path planning for free-form surfaces, which achieved a 28% reduction in inspection time. Their approach operates with nominal CAD geometry without considering actual workpiece dimensions.

The proposed methodology eliminates this fragmentation through an integrated approach that sequentially solves the tasks of determining the rational number of control points using statistical testing (108 points at 72 min per part), their optimal placement using combinatorial analysis, considering the closed contour of the bypass, and the formation of a rational set of measuring instruments based on strict compliance criteria. The synergistic effect of integration resulted in a 76% reduction in the time spent on metrological preparation, which is 20.8-47.2 percentage points higher than the best results of isolated optimizations (Figure 12).

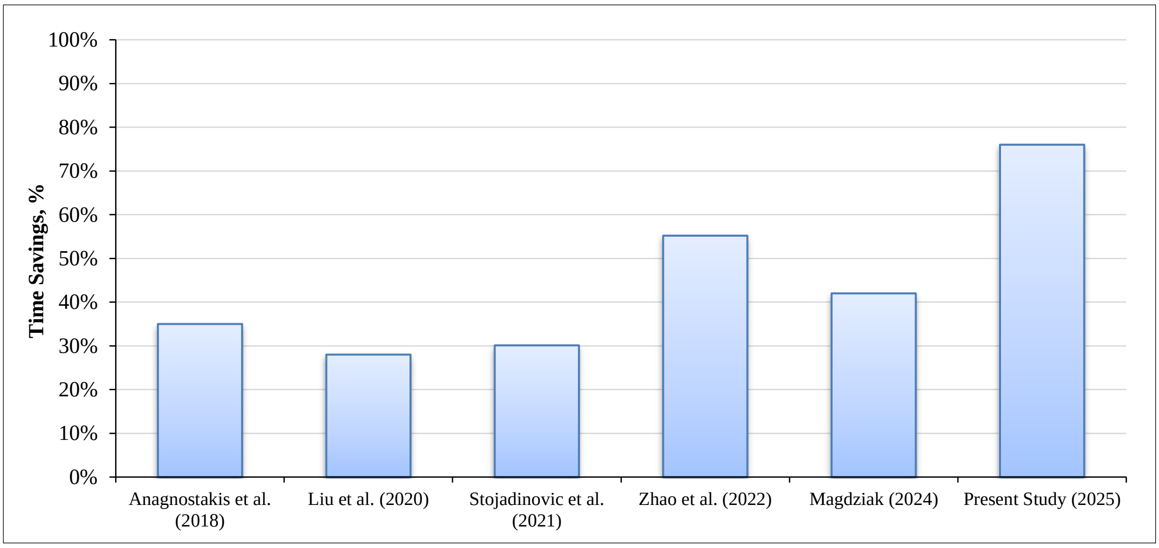

Figure 12. Comparison of time savings in metrological preparation

The use of generalized workpiece parameters when programming CMMs is one of the shortcomings of all the methods considered. Anagnostakis et al. [23] developed an expert system with hierarchical planning for offline CMM programming, which reduced program preparation time by 35%. However, the proposed system uses a knowledge base with predefined strategies for part families without considering individual dimensional characteristics. Urban et al [12] proposed a multicriteria optimization of measurement plans, resulting in an approximate 42% reduction in time and energy costs. Simultaneously, optimization is performed for existing CMM programs based on nominal dimensions. This approach requires preprogramming for each part type and is non-flexible in multiproduct manufacturing with variable workpiece parameters.

The developed methodology differs from others in that it determines each workpiece's actual dimensional characteristics at the design stage. This methodology adapts the individual technological processes to a particular part of the system. Measuring the actual dimensions of workpiece surfaces instead of using generalized parameters eliminates subjectivity in assigning technological allowances and ensures the formation of specific recommendations for material removal values. Table 2 presents a comparative analysis of CMM methodologies for parts with complex geometric surfaces.

Table 2. Systematic comparison of the CMM inspection planning methodologies for complex surface parts

Study	Anagnostakis et al. [23]	Liu et al. [22]	Stojadinovic et al. [3]	Zhao et al. [10]	Urban et al. [12]	Present Study
Method/Approach	Knowledge-Based Expert System with Hierarchical Planning for Offline CMM Programming	Optimal path planning for free-form surfaces using genetic algorithms	Artificial intelligence-based system with engineering ontology and genetic algorithms for Industry 4.0	RRT with Multi-Root Node Competition for the Reuse of 5-Axis CMM Paths	Multi-objective optimization of CMM measurement plans considering economic and environmental factors	Integrated automated methodology: statistical testing for optimal point quantity, combinatorial analysis for placement, and rational MI set formation based on actual blank dimensions
Adaptability to the Real Workpiece Geometry	Low: uses a predefined knowledge base without adaptation to specific blanks.	Average–considers surface complexity but not actual blank dimensions	Low: operates on predefined measurement point groups	Low–oriented to predetermined inspection groups	Average: Optimizes existing plans but does not adapt to specific workpiece variations.	High–adapts a single TP to a specific part using real dimensional characteristics measured at the design stage
Time Savings	35% reduction in program preparation time	28% reduction in inspection time	12.81-30.11% trajectory length reduction	41.4-55.2% planning time reduction	42% reduction in time and energy cost	76% of the metrological preparation time
Defect Reduction	Not reported	15% through better coverage	Not reported	8% through collision avoidance	12% throughput consistency	50% reduction (defect rate from 10% to 5%)
Integration with the TP Planning	Partial: manual input is required for each part family.	No: isolated optimization task	Partial –Modular architecture with no TP feedback	No–focuses solely on path planning	No. Optimization tool for existing CMM programs	Full–embedded in an automated multi-product TP planning system
Key research gaps	Limited to prismatic parts; requires no real-time geometry adaptation; manual knowledge capture	Path planning separated from measurement point selection; uses only CAD nominal geometry	Does not adapt to variable workpiece parameters in multi-product manufacturing	Isolated path optimization: no mechanism for determining the optimal point quantity	Not integrated with automated TP planning systems; operates on measurement strategies already defined	Limited experimental validation set (6 part types); requires CMM infrastructure; validated method for mechanical machining processes

The developed methodology was embedded in a fully integrated automated planning system for MPM processes. The results of measuring the actual dimensions of workpieces automatically generate working drawings containing the dimensional parameters of the surfaces. Technological decisions, such as the creation of operation cards, selection of processing methods, establishment of bases, selection of technological equipment, and cutting tools, are made based on them. Information about the actual dimensions ensures optimal workpiece positioning, a rational operation sequence considering technological heredity, and accurate allowance assignment.

Considering the ROI indicator, the high economic feasibility of implementing the proposed methodology can be identified. However, the ROI varies significantly depending on the production scale. For large enterprises with an annual volume of more than 1,000 parts with geometrically complex surfaces, the payback period is 2-3 years owing to the economic effect of reducing defects and metrological training. For small enterprises, the implementation of the methodology may not be economically feasible without the joint use of CMMs by several manufacturers or rental of measuring equipment. However, the use of existing CMMs at the enterprise can improve the ROI by eliminating the critical item of capital costs and reducing the payback period while maintaining all the methodology's advantages.

The proposed methodology provides a comprehensive solution for control and measurement procedure planning. It integrates the determination of the optimal number of control points, their rational placement, and the measuring probe trajectory planning into a single automated system. In contrast to existing approaches, which regard these tasks as separate issues, the developed methodology establishes an automated array of measuring instruments according to rigorous criteria for adherence to the measured surfaces' technical characteristics. This approach eliminates ineffective instruments and reduces the total number of operations while ensuring high accuracy in controlling geometrically complex parts. The use of machine learning algorithms (e.g., neural networks or support vector machines) to predict the optimal number and coordinates of control points based on a CAD model of a part could eliminate the need for repeated statistical tests for each new product type, maintaining metrological accuracy while reducing measurement preparation time.

Experimental testing on a FARO 9 ARM coordinate measuring machine confirmed the methodology's practical effectiveness for a set of typical parts of multiproduct manufacturing. The achieved reduction in technological defects to 5% and economic efficiency of 641,172 Rubles/year reveal the high potential of the developed methodology in the conditions of production digitalization and Metrology 4.0 concepts. The integration of the proposed methodology with automated planning systems of technological processes is of particular importance, which ensures the adoption of optimal technological solutions based on the actual dimensional characteristics of the workpieces and distinguishes it from isolated solutions for measurement optimization.

6- Conclusion

The development of the proposed methodology revealed and justified the need to develop a measurement operation system for products with geometrically complex surfaces. This system is essential for creating a multiproduct TP plan. A method was developed to measure the parameters of accuracy of such products. This method involves selecting the optimal number of coordinates for each measured plane, considering their location. The time costs of the existing automated planning system for each product are significantly reduced by 75%. The method for creating TP for the mechanical processing of products was improved. This method involves a system of measurement operations based on the adoption of a technological solution that is optimal for the current conditions, which considers the actual dimensions of the measured surface of the workpiece. The process of creating an optimal list of MI, which ensures the performance of each measurement operation of TP in product manufacturing, was streamlined. This ensured the specified accuracy characteristics and increased the overall production efficiency. The proposed methodology can also be integrated into existing computer-aided design/computer-aided manufacturing systems.

The theoretical significance of this study lies in the formalization of control and measurement procedures as a part of automated TP planning and the creation of a mathematical apparatus for optimizing measurement coordinates. Experiments have confirmed the practical significance of this study, which demonstrated a reduction in defects to 5%, savings of 3.8 h per year on metrological preparation, and an economic effect of 641,172 Rubles. The study's limitation lies in testing on a limited set of parts; however, the comprehensive approach and consideration of the actual dimensions of the workpieces ensure high efficiency. Further research should include expanding the experimental base, integrating the methodology with AI methods, and adapting it for use in AM. The integration of machine learning methods to predict the optimal number and placement of control points based on the geometric characteristics of the parts is a promising direction for further research, which could potentially reduce computational costs while maintaining metrological accuracy. Hybrid approaches that combine statistical tests for forming training samples with machine learning algorithms for optimizing measurement strategies can increase the effectiveness of the proposed methodology in mass customization of production.

7- Declarations

7-1- Author Contributions

Conceptualization, I.A.A. and N.I.; methodology, I.A.A. and A.L.,; software, N.K., A.L., and A.T.; validation, I.A.A.; formal analysis, N.I. and A.L.; investigation, N.K. and A.T.; resources, I.A.A.; data curation, N.I.; writing—original draft preparation, N.K. and A.T.; writing—review and editing, N.K. and A.T.; visualization, N.K., A.L., and A.T.; supervision, I.A.A. and N.I.; project administration, I.A.A.; funding acquisition, I.A.A. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

Data sharing is not applicable to this article.

7-3- Funding

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7-4- Institutional Review Board Statement

Not applicable.

7-5- Informed Consent Statement

Not applicable.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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