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**Article**

**Keywords:**

**Posted Date:** November 24th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-11755881/v1

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**Additional Declarations:** No competing interests reported.

# A Methodology for Designing Grinding Operations Based on Predicting the Tool Life Using an Acoustic Indicator

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**Abstract**

This article proposes a new methodology for designing grinding operations based on predicting the tool life using an acoustic indicator. The methodology is based on a comprehensive model correlating the acoustic characteristics of the grinding process with the quality parameters of the machined workpiece surface under specific process conditions. The article discusses the main methods for implementing this methodology, which improves the efficiency of grinding operations by predicting the tool life using an acoustic criterion.

**Keywords:** grinding, multinomenclature production, designing grinding operations, regime and tool equipment, grinding wheel redress life, acoustic criterion of grinding, production planning.

## 1 Introduction

The efficiency of grinding operations is estimated at the design stage primarily aimed to determine the rational characteristics of the grinding wheel and machining conditions. There are several main approaches to solving this problem.

The most common and accessible approach to ensuring the production of high-quality and competitive products relies on the use of reference materials and general

engineering standards. Their development is based on the statistical analysis of large volumes of empirical data gathered from production experience. Such recommendations are characterized by a high degree of generalization, low universality, and several assumptions. The use of general engineering standards is most effective for mass and large-scale production. In other conditions, their effectiveness can be significantly reduced or even eliminated.

Multinomenclature production is undergoing intensive development [1] due to the shift away from traditional mass production towards the creation of customized high-tech products tailored to meet the specific needs of individual customers. In the multinomenclature production environment, standard guidelines are taken into account, but they are not always strictly followed when designing grinding operations. A limited range of grinding wheels is used in practice to machine large volumes of frequently changed batches of workpieces. A specialized tool is used to machine each batch of parts, which can reduce productivity.

Another approach to designing grinding operations involves predictive modeling [2]. Production planning requires evaluating the performance of a selected tool for the assigned machining conditions. To this end, a grinding wheel performance criterion is defined and a predictive model is developed to evaluate it. This criterion is represented by one or a set of grinding process parameters: grinding force components [3–5]; metal removal rate [6]; machined surface roughness [7]; grinding zone temperature [3, 8], etc.

A common drawback of using modeling results is the high labor intensity of the calculation procedure. Furthermore, any model includes many assumptions and neglects many secondary (according to the developer) process aspects, which, taken together, can affect the calculation accuracy and reduce the reliability of the results. Model customization to meet established process conditions and its application requires sufficient user expertise and significant time investment, which limits their use in production environments. Operating models and implementing modeling results are beyond the scope of the process engineer's expertise.

Engineering system monitoring serves as a tool for automation and production management, as well as a source of data for calculating and/or making adjustments when determining process performance characteristics. The implementation of monitoring systems can significantly reduce equipment downtime, enhance machining accuracy, and lower maintenance costs [9, 10].

The implementation of monitoring systems requires the use of a quantitative or qualitative indicator to assess the technical status of a process system and monitor the compliance of process parameters with specified requirements. Availability, versatility, and informativeness are important when selecting such a parameter. The following criteria are used to monitor the grinding process: cutting force components [11, 12]; spindle and machine axis drive loads [9–11]; temperature in the cutting zone [8]; vibration and acoustic parameters [10, 12, 13, 14,], etc. Acoustic signal monitoring offers several significant advantages over other criteria. Information contained in the acoustic signal on the equipment or tool status, machining quality, and emerging defects facilitates rapid assessment of the technical status of the system [15–17]. Monitoring systems based on recording and analyzing acoustic signals do not require significant equipment retuning, making them simple and cost-effective to implement.

An approach combining monitoring and computer simulation of acoustic process parameters, taking into account machining quality requirements, seems promising for designing grinding operations. Simulation modeling during production planning allows for selecting rational grinding wheel characteristics and machining modes, while process monitoring enables controlling the current technical status of the tool based on an indirect acoustic indicator related to machining quality requirements.

Taken together, this will enable predicting key tool performance indicators, selecting rational operating conditions, and monitoring actual parameters in real time to control machining quality, reduce resource consumption, and improve productivity and overall production efficiency.

Thus, the goal of this article is to develop a methodology for designing grinding operations to implement simulation modeling of the acoustic signal generated by grinding wheel vibrations during machining and acoustic process monitoring.

# 2 Methods

The practical significance of the methodology for designing grinding operations based on the use of acoustic indicators lies in the ability to identify rational operational conditions during production planning and to control the process directly during machining.

Figure 1 illustrates the structural diagram of the methodology. The relevant performance of a grinding wheel is described by a set of current values of the process conditions that meet the specified quality requirements for the produced parts (Fig. 1, block 1).

Various grinding process parameters related to process and time factors can be predicted based on their sufficiently accurate mathematical description. The models of grinding quality parameters determine the time period during which a grinding wheel remains operable, while acoustic signal models determine the characteristics of the sound signal accompanying the machining process (Fig. 1, block 2).

Coupling the modeling results allows using an indirect acoustic indicator to estimate the current values of machining quality parameters (Fig. 1, block 3). Such coupling provides for the use of models in which the same process parameters serve as the function arguments. Time and machining mode are the most appropriate arguments to ensure accurate prediction and process control. Coupling results in a comprehensive model that establishes a relationship between the quality parameter values and acoustic parameters for similar process conditions.

The design of grinding operations is based on regime and tool equipment for the machining process, taking into account the acoustic indicator of the process. Modeling in the "grinding mode-time" coordinate plane predicts the defect-free operating range of the grinding wheel that meets machining quality requirements. The boundaries of the defect-free operating range are determined based on established quality requirements for specific process conditions, in the form of a defect-free tool operation prediction map. This allows using a rationalization approach for determining the most productive machining modes and grinding wheel characteristics, while ensuring compliance with product quality requirements (Fig. 1, block 4).

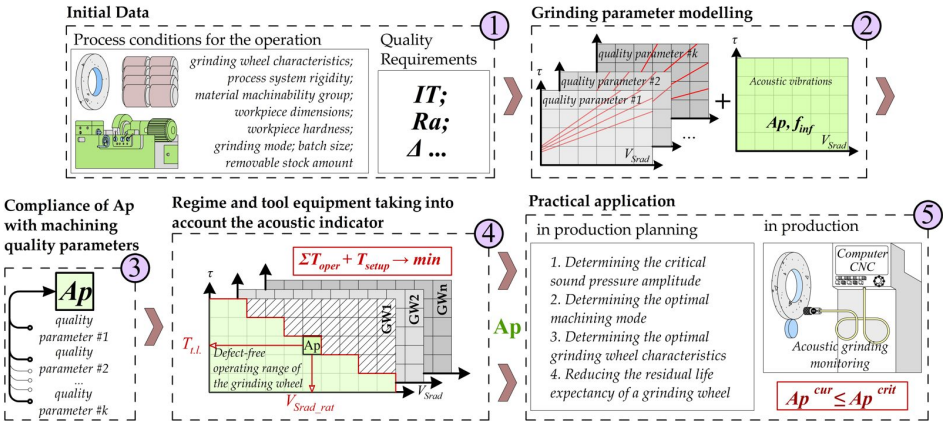


**Figure 1** Diagram of the methodology for designing grinding operations using an acoustic indicator

Monitoring the acoustic signal accompanying the grinding process allows for an indirect assessment of current quality indicators during production without interrupting the process. The continuous comparison of the current sound pressure amplitude with its predetermined critical value enables monitoring the technical status of the grinding wheel (Fig. 1, block 5).

# 3 Results and discussion

Let us consider four common production scenarios that offer potential for enhancing the efficiency of grinding operations through the application of the proposed methodology. Table 1 describes the conditions in which these scenarios arise (production type), the targets of the proposed improvements (objects of rationalization), and the parameters adopted as criteria for evaluating efficiency (efficiency indicators).

Implementing the methodology in each of these scenarios involves acoustic monitoring of the grinding process to assess the current condition of grinding wheels with different specifications under varying technological conditions, including machining parameters, workpiece material, stiffness, hardness, and other factors.

## 3.1 Determining the rational mode for machining workpiece batch with grinding wheels selected according to general engineering standards

We propose a method for determining the rational machining mode for large-scale and mass production, based on the use of an acoustic indicator of the grinding process. The criterion is the minimum total operational time ($\Sigma T_{\text{oper}} \rightarrow \min$), taking into account the total auxiliary time ($\Sigma T_{\text{aux}}$) spent on grinding wheel dressing (Fig. 2).

During production planning, we calculate the main time ($T_{\text{main}}$) spent on stock removal (z) for a range of feed rates. We determine the value and the number of workpieces (i) that can be machined before reaching this value. Thus, we can calculate the grinding wheel redress life based on the acoustic criterion.

**Table 1** Indicators for improving grinding efficiency through the methodology for designing grinding operations

| Type of production | Object of rationalization | Efficiency criterion |
|---|---|---|
| mass | Application of a rational grinding mode for a large batch of workpieces with a grinding wheel selected according to handbook recommendations. | $\Sigma T_{\text{oper}} = \Sigma T_{\text{main}} + \Sigma T_{\text{aux}} \rightarrow \min$ |
| serial | Use of one grinding wheel with a rational specification for machining several substantial batches of workpieces. | $\Sigma T_{\text{oper}} + \Sigma T_{\text{setup}} \rightarrow \min$ |
| multinomenclature | Use of a rational number of grinding wheels for machining many small batches of workpieces. | $\Sigma T_{\text{oper}} + \Sigma T_{\text{setup}} \rightarrow \min$ |
| multinomenclature | Machining many small batches of workpieces in a rational sequence. | $R_{\text{res}}/T_{\text{main}} \rightarrow \max$; $\Sigma R_{\text{res}} \rightarrow \min$ |

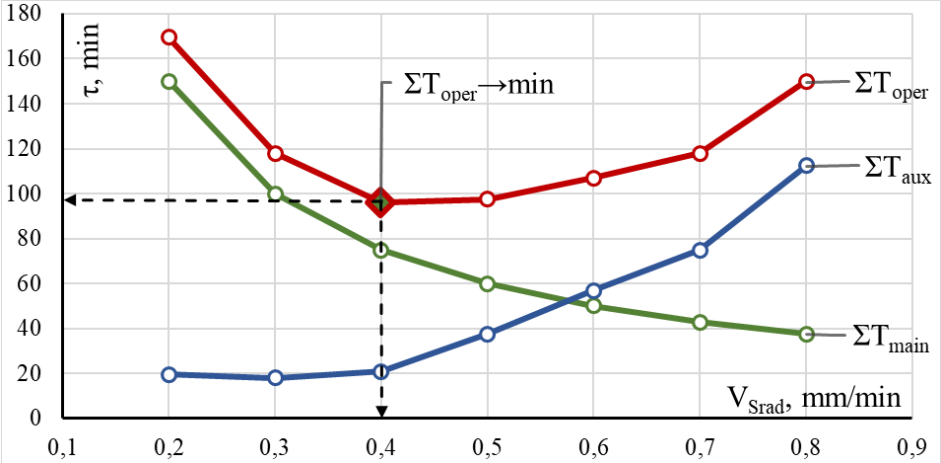


**Figure 2** Determining the rational machining mode using the recommended grinding wheel

The graph in Figure 2 shows how an increase in VSrad leads to an increase in $\Sigma T_{\text{aux}}$, as the number of grinding wheel dressings (m) required to maintain its performance grows. At the same time, $\Sigma T_{\text{main}}$ required to machine a batch of size N decreases with an increase in VSrad.

Taking into account the batch size, the grinding wheel redress life, the required number of dressing operations, and the number of workpieces that can be machined between dressing operations, we can determine the most rational mode to ensure the lowest time loss. This mode of machining is accompanied by acoustic monitoring for the indirect control of machining quality parameters and determining the grinding

wheel redress life. When the sound pressure amplitude approaches its critical value, the operator or the automated machine control system dresses the grinding wheel to restore its cutting performance.

## 3.2 Determining the rational mode for machining workpiece batches with a grinding wheel of specific characteristics

The conventional approach to designing grinding operations involves using a grinding wheel with specified characteristics under particular machining conditions. This approach is suitable for mass and large-scale production, where setup and finishing time is distributed across a large batch of parts. However, these production types are becoming less dominant, while batches of varying sizes must increasingly be processed with frequent changeovers, as is typical of multinomenclature production. Under these circumstances, frequent replacement of the grinding wheel, including the necessary balancing and dressing operations, substantially increases resource consumption, raises manufacturing costs, and reduces the competitiveness of the enterprise.

The specific features of machining workpiece batches (Fig. 3: A, B, C) in a multinomenclature production environment include significant time losses on replacing grinding wheels and a wide range of required tools. The consumption of these resources can be reduced by using a single grinding wheel to machine multiple batches of workpieces. The productivity losses associated with the use of a tool not selected in pursuance of standard recommendations for machining a specific batch can be significantly less than the costs associated with frequent replacements of grinding wheels.

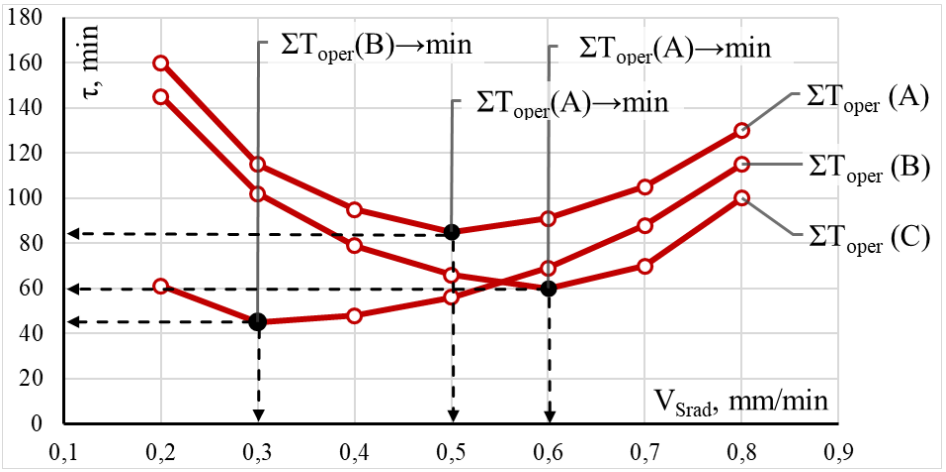


**Figure 3** Determining the rational modes for machining workpiece batches A, B, and C with a grinding wheel of a specific characteristic

A method similar to Production scenario 1 is used to determine the rational machining modes based on the criterion of minimum total operational time, taking into

account the reduction in the share of machine-setup time ($T_{\text{setup}}$) in its technical standard (Fig. 3). The established values of characteristic of each of the scheduled production batches allow machining in rational modes and ensure compliance with the specified quality requirements. During acoustic monitoring, the current value of the sound pressure amplitude Apcur is compared to its critical values characteristic of each batch: (A), (B), (C) to assess indirectly the machining quality parameters and determine the end of the redress life period for each "grinding wheel – machined workpiece batch" pair.

### 3.3 Determining the rational grinding wheel characteristics for machining workpiece batches

In this scenario, we need to select the minimum number of grinding wheels for machining the scheduled batches of workpieces in a multinomenclature production environment.

The tool redress life prediction based on the acoustic criterion and determining the rational machining mode (similar to production scenarios 1 and 2) are used to create a matrix of total operational times (Fig. 4) for the considered workpiece batches (A, B, C, D, E) and grinding wheels (1, 2, 3, 4, 5) recommended by the standards for machining each batch. The matrix cells contain the sums of the times spent on stock removal ($\Sigma T_{\text{main}}$) and tool dressing ($\Sigma T_{\text{aux}}$) for each batch. The cells on the main diagonal of the matrix indicate the times corresponding to the most productive modes recommended by general engineering standards. However, their use during the machining of each batch necessitates tool replacement when switching to the next batch, which significantly increases the share of $T_{\text{setup}}$ in the technical time standard.

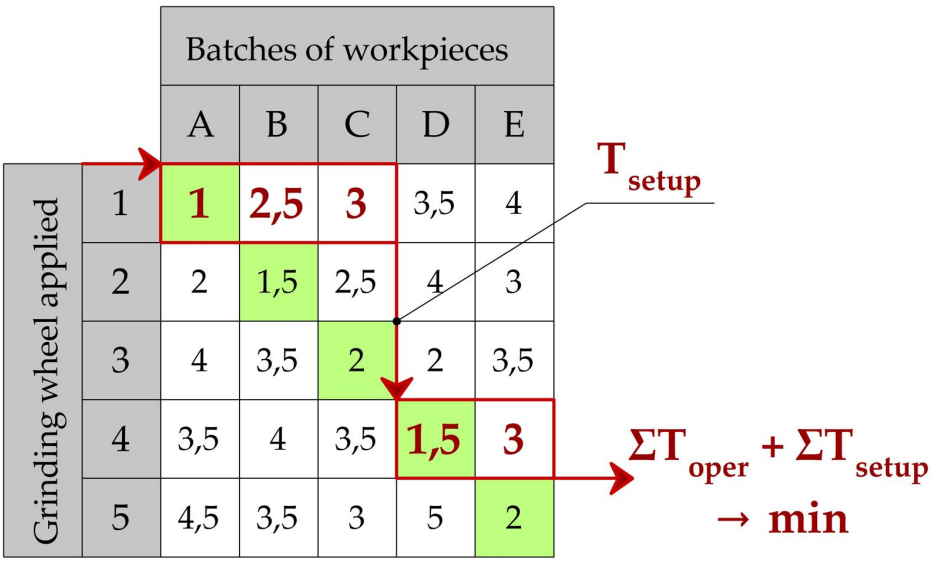


**Figure 4** Matrix of total operational times for machining batches A, B, C, D, E using grinding wheels 1, 2, 3, 4, 5 (min)

The complete enumeration method is used to determine the minimum range of grinding wheels required to reduce the technical time standard ($\Sigma T_{\text{oper}} + \Sigma T_{\text{setup}}$) for machining all workpiece batches. Subsequently, grinding operations are accompanied by acoustic process monitoring to track the Apcur value and compare it to the critical values of corresponding to the machining of specific workpiece batches with the actual tools.

## 3.4 Determining the rational sequence of workpiece delivery to the machine

The service life of grinding wheels is not always fully utilized during machining. The tool is often forced to be dressed, which increases its available volume and mass consumption. The residual service life (Rres) should be spent on stock removal by predicting the tool redress life, which is facilitated by the developed methodology for designing grinding operations taking into account the acoustic criterion. However, it can be challenging to determine the limits of the potential service life of grinding wheels when used under various process conditions.

To reduce the total residual service life $\Sigma R_{\text{res}}$, the number of tool dressings m, and the time spent on dressing $\Sigma T_{\text{aux}}$, we developed an algorithm for determining the workpiece batch that is most rational for machining with a tool at its current service life (Fig. 5).

The rationality criteria include maximizing the number of workpieces that can be machined by using the residual tool life (Rres/$T_{\text{main}} \rightarrow$ max) and minimizing the total residual service life ($\Sigma R_{\text{res}} \rightarrow$ min) for the current batch. This means that if two batches are competing for the first position on the machine, under the current conditions, we should select the one that minimizes the residual service life of the grinding wheel after machining and maximizes the number of machined workpieces, assuming all other factors are equal.

Let us consider the machining of four scheduled workpiece batches – A, B, C, D. Based on the initial data (Fig. 5, block 2), we select the prediction maps of the defect-free tool operating range (Fig. 5, block 3), which are used to determine the critical values of the sound pressure amplitude corresponding to quality requirements: (A), (B), (C),(D) (Fig. 5, block 4). We then predict the possible periods of the grinding wheel redress life for each batch based on these values (Fig. 5, block 5), where are time intervals during which the specified quality requirements will be met during continuous machining. Using stock amounts and grinding modes, we can determine the number of workpieces in each batch that can be machined within one redress life period : iA, iB, iC, iD (Fig. 5, block 6) in compliance with the established quality requirements. This allows determining the actual periods of the grinding wheel redress life (Fig. 5, block 7), where are time intervals spent on machining the parts of a specific batch between dressing operations. Next, we determine the values of the residual service life ; ; ; (Fig. 5, block 8).

In blocks 9.1, 9.2, 9.3, 9.4, we calculate the integer number of parts in batches that can be machined within the residual service life of the grinding wheel, while maintaining quality requirements, based on the following conditions: Rres/$T_{\text{main}}\rightarrow$max; $\Sigma R_{\text{res}}\rightarrow$min.

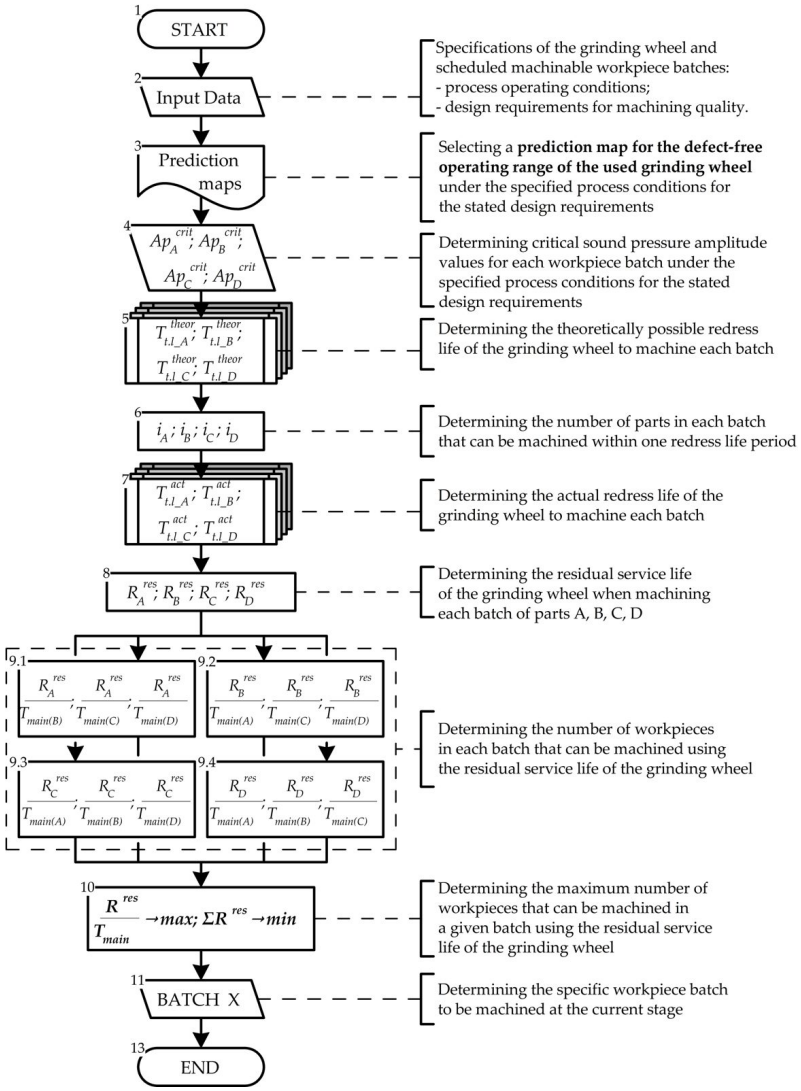


**Figure 5** Algorithm for determining the rational sequence of workpiece batch delivery to the machine

We then determine the maximum number of parts in a given batch, the machining time for which does not exceed the current value of the residual service life of the grinding wheel (Fig. 5, block 10).

Acoustic grinding monitoring allows for monitoring the current performance of the grinding wheel at each stage, especially during the transition from one workpiece batch to the next. Thus, the Ap value reached when the machining of a workpiece batch has been completed should be lower than corresponding to the machining of the batch of parts that entered the machine, by a multiple of $T_{\text{main}}$.

The described approach and implementation of the algorithm for determining the rational batch machining sequence (Fig. 5) enables more complete utilization of the total residual service life of the grinding wheel, reducing the number of tool dressing operations and the time spent on them by managing the sequence of workpiece batches entering the machine. In a multinomenclature production environment characterized by the need to machine a large number of small batches, the use of the methodology for designing grinding operations that ensures quality requirements through acoustic monitoring improves the overall efficiency of grinding operations.

# 4 Conclusion

1. We developed a methodology for designing grinding operations using an acoustic indicator, which can be practically applied in four typical production scenarios: determining the rational machining modes for recommended grinding wheels; determining the rational modes for machining multiple workpiece batches with a specific grinding wheel; determining the rational characteristics of grinding wheels for machining different workpiece batches; determining the rational sequence of machining workpiece batches.

2. The methodology for designing grinding operations using an acoustic indicator is implemented through the use of regime and tool equipment, which significantly reduces the overall operational time ($\Sigma T_{\text{oper}}$) and contributes to increased production efficiency.

3. The use of this methodology allows reducing the range of grinding wheels used in small-batch and multinomenclature production. The productivity losses associated with the use of a grinding wheel mounted on a machine with characteristics different from the recommended ones, when used in the rational modes, can be significantly lower than the losses caused by replacing the grinding wheel according to the recommendations.

4. The developed algorithm for managing the residual service life of a grinding wheel (Rres) enables setting the rational sequence of machining workpiece batches, ensuring the maximum utilization of the tool life, reducing the number of dressing operations (m), and, consequently, the total auxiliary time ($\Sigma T_{\text{aux}}$).

The practical significance of this research lies in the potential integration of the developed methodology for designing grinding operations into a knowledge-intensive production system as a tool for improving its efficiency through advanced automation. The most significant effect of this methodology is expected in multinomenclature production environments. This is because the developed methodology makes it possible to use an accessible and sufficiently accurate acoustic indicator of the grinding process as an indirect criterion for assessing the current condition of a grinding wheel across a wide range of combinations of technological conditions.

Consequently, at the production planning stage, it becomes possible to predict the grinding wheel redress life under different machining conditions and to determine a rational sequence for delivering workpiece batches to the machine according to the current condition of the grinding wheel.

## Funding

This work was funded by the Russian Science Foundation grant No. 25-29-20029, https://rscf.ru/en/project/25-29-20029/ (Aleksandr Zhukov and Dmitrii Ardashev). Co-authors – Nizami Yusubov and Heyran Abbasova took part in the study on their own initiative without funding.

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