Algorithms for replacing tools on multifunctional metal-cutting equipment

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Abstract. The results of the work aimed at reducing organizational downtime of equipment associated with the readjustment of machines during the transition to the manufacture of another type of product are presented. A set of measures is proposed, which includes the formalization of the technological process in a matrix way, which allows describing the processing from the point of view of the cutting tool and machine tools used. After formalization, various methods of cluster analysis were applied to determine the sequence of starting parts into processing, at which the equipment readjustment time would be minimal. For the study, equipment having a block layout was selected. A key place in the article is given to the problem of determining the procedure for replacing equipment in machine blocks with a built-up sequence of starting parts for processing. Several algorithms are proposed, among which the best one in terms of the number of necessary replacements in the equipment blocks has been selected.

In modern mechanical engineering, machine tools with numerical control (CNC) are widely used. As this equipment developed, more and more advanced models appeared, such as turning and milling machining centers, precision longitudinal turning machines, etc. This equipment is multifunctional, i.e. can perform operations of turning, drilling, milling, boring, etc. It allows machining with high cutting speeds and feeds, using several spindles and tool blocks simultaneously, using several, up to ten, control axes, using automatic interception or support of the workpiece. Since their frequent changes lead to a loss of productivity, they usually use this equipment in large-scale production. However, such machines are now increasingly used in small-scale production, which is associated with the ability to obtain surface parts with high accuracy (of the order of 5-6 quality) and cleanliness up to grade 12 when processing, which in most cases avoids grinding and lapping operations.

One of the main tasks is to increase the utilization of equipment, i.e. reduce time spent on organizational and technical procedures, reduce downtime associated with the reconfiguration of machines during the transition to the manufacture of another type of product, etc.

To solve the problem in [1], an integrated approach to the development of technological processes (TP) for manufacturing products was proposed. This approach is based on the matrix method for describing the manufacturing processes of products described in [2]. In this case, the production process is represented by a vector in a multidimensional space of attributes. Attributes may be quantitative or qualitative.
For example, the technological process of processing five parts described by the matrix method, the characteristics of which are represented by the set of tools and devices used, has the following form (table 1).

| Part name/feature name | Part №1 | Part №2 | Part №3 | Part №4 | Part №5 |
|------------------------|---------|---------|---------|---------|---------|
| Tool №1                | 1       | 1       | 0       | 0       | 1       |
| Tool №2                | 1       | 1       | 0       | 0       | 1       |
| Tool №3                | 0       | 1       | 1       | 0       | 1       |
| Device №1              | 1       | 1       | 1       | 0       | 1       |
| Device №2              | 1       | 0       | 0       | 0       | 0       |
| Device №3              | 0       | 1       | 0       | 1       | 0       |

In the binary system, the presence of “1” in the table means the use of a tool or device, “0” - not use. Depending on the degree of detail, the process can be described in more detail, considering the characteristics of each tool, i.e. not just divide the tool by type of processing and name, but also by geometry of cutting edges, type of coating, type of chipbreaker, etc.

In [3], within the framework of an integrated approach, the application of cluster analysis methods to determine the optimal sequence for launching parts into processing is presented. In this case, the main objective was to reduce the number of readjustments of equipment when processing a certain batch of parts.

As an example, TP processing on CNC longitudinal turning machines was chosen. The selected equipment has 5 tool blocks, spindle, lynette units, a workpiece feed device (barfeeder), and also an anti-spindle unit (figure 1). Thus, in total, the machine has 9 reconfigurable blocks.

![Figure 1. Block structure of a CNC longitudinal turning machine.](image)

Replaceable elements during readjustment are respectively the cutting tool, spindle collets (TsH), lance collets (TsL), barfeide collets (CB) of the counter-spindle chuck (TsPShP). In the first five blocks, a different cutting tool is installed depending on the functional purpose, for example, in the block 1, passage, groove, threaded, and cutting tools are fixed; in block 2 - centering drills, drills, mills, etc. The tool installed in block 2 can also be installed in blocks 4 and 5. Similarly, collets installed in the spindle can also be installed in the counter spindle.

For each tool block, a catalog-dictionary of attributes is compiled, and the dimension of the catalogs is $m_1, m_2, m_3 \ldots M_9$, respectively (table 2).
Table 2. Catalogs-dictionaries of features-characteristics for each block.

| Catalog dictionary of block 1 | Catalog dictionary of block 2 | Catalog dictionary of block 3 | ... | Catalog dictionary of block 9 |
|-------------------------------|-------------------------------|-------------------------------|-----|-------------------------------|
| 1st Block tool 1              | 1st Block tool 2              | 1st block tool 3              | ...| TsPShP1                       |
| 2-nd Block tool 1             | 2-nd Block tool 2             | 2-nd Block tool 3             | ...| TsPShP2                       |
| ...                           | ...                           | ...                           | ...| ...                           |
| \( m_1 \)                     | \( m_2 \)                     | \( m_3 \)                     | ...| \( m_9 \)                     |

Similarly, inside each block, the tool should be ordered according to its functional purpose, i.e. by type of instrument. For example, in block 1, first the cutters are recorded, then cutting, grooving and threaded. An example of a matrix description of a manufacturing process for manufacturing 5 parts for block 1 is presented in table 3. Similarly, a description of the characteristic features for other blocks of the machine.

Table 3. Matrix description of 5 parts TP manufacturing.

| Tool block number → | BLOCK1 |
|---------------------|--------|
| Tool type →         |        |
| Part name / tool name | Through cutters | Cutting tools | Grooving tools | Threaded tools |
| Part 1              | Cuter I1 | Cuter I2 | Cuter I3 | Cuter I4 | Cuter I5 | Cuter I6 | Cuter I7 | Cuter O1 | Cuter O2 | Cuter O3 | Cuter O4 | Cuter K1 | Cuter K2 | Cuter K3 | Cuter P1 | Cuter P2 | Cuter P3 | Cuter P4 | Cuter P5 | Cuter P6 |
| Part 2              | 0       | 1       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| Part 3              | 0       | 0       | 1       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| Part 4              | 0       | 0       | 1       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       |
| Part 5              | 0       | 0       | 0       | 1       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 0       | 1       | 0       | 0       | 0       |

In table 3, the through cutter is designated Cutter P1, the second - Cutter P2, etc. Five parts from table 4 are part of the sample on which the study was conducted; the total sample size is 30 parts.

In [3], to determine the sequence of starting parts into processing, various cluster analysis methods were used: the single-linking method (single-linking method), the fully-linking method (full-linking method), weighted average linkage, unweighted average linkage, unweighted centroid method (centroid), the weighted centroid method (median), the Ward method for different metrics [4, 5]. According to the results of applying this or that method, the corresponding dendrograms were built (figure 2).

Thus, according to the obtained results, the sequence of starting the parts into processing was built. The use of various methods and metrics led to the construction of various sequences. To select the most suitable method and metric, the number of equipment readjustments was calculated. For this, the following algorithm was developed (algorithm No. 1).
Figure 2. Dendrogram combining 30 objects. Weighted Centroid Method. Squared Euclidean distance.

The algorithm is built according to the following principle. If the value in the previous row of the matrix column in question is equal to one, and the value in the current row is zero or one, then this tool was used to process the previous part, and is not used or is used when processing the current part. In this case, there is no installation of a new tool, that is, there is no readjustment. If the value in the previous row of the column in question is equal to zero, and in the current row is equal to one, this means that the tool in question was not used in the processing of the previous part, but is used in the processing of the current part, thus, equipment is readjusted.

According to this algorithm, the number of readjustments was calculated for all sequences obtained using cluster analysis methods. The data are summarized in table 4.

| Method / Metric          | Euclidean distance | Euclidean distance Square | “First” power distance | “Second” power distance | Percentage of disagreement | Measure based on correlation |
|--------------------------|--------------------|---------------------------|------------------------|-------------------------|---------------------------|-----------------------------|
| Single link Method       | 175                | 180                       | 183                    | 178                     | 172                       | 173                         |
| Full link method         | 162                | 162                       | 162                    | 162                     | 162                       | 162                         |
| Weighted Average Link Method | 163   | 160                       | 163                    | 163                     | 160                       | 160                         |
| Unweighted average link method | 161 | 158                       | 161                    | 161                     | 158                       | 163                         |
| Median                   | 157                | 156                       | 152                    | 152                     | 156                       | 158                         |
| Centroid                 | 176                | 169                       | 176                    | 176                     | 169                       | 169                         |
| Ward Method              | 162                | 163                       | 162                    | 162                     | 164                       | 162                         |
The following algorithm was developed (algorithm No. 2) to check a possible variant of the sequence of starting parts without using cluster analysis methods, which at the same time gives high indicators of the number of readjustments. The smallest number of readjustments (152) was obtained using the median method (weighted centroid method) from the “first” and “second” power distances, taken as a metric. This suggests that this method and metrics are most suitable for solving the minimization of the number of readjustments; therefore, this method and the metric “first” power distance were taken as a basis when developing the following algorithm.

The sequence of starting parts using the selected method is shown in the dendrogram (figure 2), from which it can be seen that the sequence begins to form from part No. 1, to which part No. 21 is closest and part No. 5 is closest. By proximity is meant multidimensional distance feature space, which are elements of the integrated catalog of features-characteristics.

To determine the start-up sequence of parts, for which the number of readjustments will be the largest, it is necessary to line up choosing the first part from the received dendrogram The second part should be least close one behind it. Next, the line describing the first part in the queue is removed from the original matrix, and again the cluster analysis procedure is performed using the same method and metric. Based on the received dendrogram, the part that is the closest to the second is found and added to the sequence, then the row describing the second part is removed from the adjusted matrix, and the cluster analysis procedure is performed again and so on until the last part in the queue is determined.

According to algorithm No. 2, the start sequence was built from the sample of parts under consideration. The number of readjustments in this sequence was determined according to algorithm No. 1, as a result, a value of 241 was obtained. Thus, it can be argued that when using cluster analysis methods the smallest number of readjustments is 152, and if not used, 241, on average we can get 197 readjustments. This example illustrates a situation in which the start sequence is determined by the line manager of the site without using any method or algorithm, and the number of readjustments will be equal to 197 on average. Thus, the application of cluster analysis methods to determine the start sequence of parts is relevant.

As mentioned earlier, the equipment in question was presented as a set of nine blocks. Each unit has its own capacity. This suggests that when processing parts, part of the cells of a block may be free or occupied by a tool that was used to process the previous part, but is not used to process the current one. However, at the same time, the same tool can be used when processing any part from the sample under consideration in the future. Thus, the task arises of determining the optimal sequence of replacing elements in block cells constructed using cluster analysis of the start-up sequence of parts. To solve this problem, the corresponding algorithms were developed (No. 3, No. 4, No. 5).

The capacity of the equipment units is as follows: unit 1–5 cells, unit 2–5, unit 3–4, unit 4–4, unit 5–4, spindle, lunar, anti-spindle and barfider unit –1.

The source matrix is a dimension matrix $n \times m$, where $n$ is the number of details considered, $m = 1 \ldots m_9$ is the number of characteristics, characteristics is an ordered set of dictionary directories for all blocks. Moreover, the signs are divided according to the following principle. For block 1, the columns of the combined matrix-row of features-characteristics B are used for which $j = 1 \ldots m_1$. For block 2, columns are used for which $j = (m_1 + 1) \ldots m_2$ and so on.

The algorithms are based on a sequential review of each block .. At the beginning of the algorithm, the readjustment counter is 0, i.e. it is understood that there are no installed elements in the machine blocks (hereinafter the tool and accessories are elements). The first row of the matrix is considered ($i = 1$). The amount of the used tool and equipment for processing the first part is calculated by summing the elements of all the columns of the first row $= \sum_{j=1}^{m_1} a_{1j}$. This value is entered in the changeover counter. Since the amount of equipment needed to process the first part has already been determined, a transition is made to the consideration of the next line, starting with the second ($i = i + 1$).

If the number of elements necessary for processing the previous and considered part does not exceed the block capacity, then the elements necessary for processing the current part are installed in free cells. When considering the following lines, this procedure is repeated until the number of elements exceeds
the block capacity. When this condition occurs, it is necessary to solve the problem of which tool to remove from the block.

Algorithm No. 3 works according to the following principle. Elements are found that are not used in the processing of the considered part in sequence. Among these elements for removal from the block, one that has the lowest priority of use is selected. An element that will participate in the processing of subsequent parts earlier has a higher priority. Comparison is made start with the lowest priority of use is selected. An element that will participate in the processing of

An example of the operation of algorithm No. 3 within the framework of one block for pass-through and cutting tools is presented in table 5. As a source data, the start sequence obtained using the weighted centroid method of cluster analysis using the “first” power distance metric was chosen. In the matrix, white color indicates the elements that are necessary for manufacturing TP, dark gray (red in the color version) - which are installed or removed from the block, light gray (yellow in the color version) - which remain in the block, but are not used during processing. Counting the number of readjustments is carried out separately for each line, and then summed up.

Table 5. An example of the operation of algorithm No. 3.

| Tool block number → | BLOCK 1 | Changeovers |
|---------------------|---------|-------------|
| Type of tool →      | Through cutters | Cutting tools |
| Part name / tool name | PI1  | PI2  | PI3  | PI4  | PI5  | PI6  | PI7  | PO1  | PO2  | PO3  | PO4  |
| Part1               | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 2     |
| Part 21             | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     |
| Part 16             | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     |
| Part 20             | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     |
| Part 19             | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     |
| Part 2              | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     |
| Part 11             | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     |
| Part 22             | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     | 0     | 1     | 0     |
| Part 9              | 0     | 1     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 10             | 0     | 1     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 27             | 0     | 1     | 0     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 1     |
| Part 18             | 0     | 1     | 0     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 1     |
| Part 8              | 0     | 1     | 0     | 0     | 1     | 0     | 0     | 0     | 1     | 0     | 1     |
| Part 12             | 0     | 1     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 13             | 0     | 1     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 23             | 0     | 1     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 25             | 0     | 1     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 24             | 0     | 1     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 15             | 0     | 1     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 17             | 0     | 1     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 28             | 0     | 1     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 7              | 0     | 1     | 1     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 14             | 0     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 4              | 0     | 0     | 0     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 29             | 0     | 1     | 0     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 3              | 1     | 0     | 1     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 26             | 1     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
| Part 6              | 1     | 1     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 1     |
According to algorithm No. 3, the number of readjustments was calculated for all sequences obtained using the methods of cluster analysis, as well as algorithm No. 2. The data are summarized in table 6.

Table 6. The results of algorithm No. 3.

| Method / Metric | Euclidean distance | Euclidean distance Square | “First” power distance | “Second” power distance | Percentage of disagreement | Measure based on correlation |
|-----------------|--------------------|----------------------------|-----------------------|-------------------------|---------------------------|----------------------------|
| Single link Method | 136                | 142                        | 141                   | 135                     | 139                       | 130                        |
| Full link method | 127                | 132                        | 131                   | 128                     | 131                       | 129                        |
| Weighted Average Link Method | 129 | 128 | 129 | 128 | 127 | 128 |
| Unweighted Average link Method | 128 | 129 | 128 | 128 | 130 | 134 |
| Median | 126 | 125 | 124 | 125 | 125 | 126 |
| Centroid | 137 | 129 | 139 | 139 | 132 | 133 |
| Ward Method | 133 | 134 | 134 | 134 | 134 | 128 |
| No. 2 Algorithm | 191 |                |                          |                          |                           |                           |

It is seen from table 6 that the smallest number of readjustments corresponds to the sequence obtained using the method of cluster analysis of the median by the metric “first” power distance, which confirms the results presented in table 4.

Algorithm No. 4 works according to the following principle. Elements are found that are not used in the processing of the considered part in sequence. The sum of the elements in each column is found starting from the row next to the one under consideration. The element with the smallest sum is deleted from the block, i.e. the applicability, which is less when processing the sample in question.

Algorithm No. 4 calculated the number of readjustments for all sequences obtained using cluster analysis methods, as well as algorithm No. 2. The data are summarized in table 7.

Table 7. The results of the operation of algorithm No. 4.

| Method / Metric | Euclidean distance | Euclidean distance Square | “First” power distance | “Second” power distance | Percentage of disagreement | Measure based on correlation |
|-----------------|--------------------|----------------------------|-----------------------|-------------------------|---------------------------|----------------------------|
| Single link method | 138 | 145 | 145 | 141 | 140 | 136 |
| Full link method | 130 | 135 | 133 | 131 | 134 | 133 |
| Weighted average link method | 131 | 131 | 130 | 130 | 131 | 132 |
| Unweighted Average link Method | 132 | 132 | 133 | 131 | 132 | 138 |
Algorithm No. 5 works similarly to algorithm No. 4, but the element with the largest sum is deleted from the block, i.e. one whose applicability in processing the sample in question is greater.

According to algorithm No. 5, the number of changeovers was calculated for all sequences obtained using the methods of cluster analysis, as well as algorithm No. 2. The data are summarized in table 8.

**Table 8. The results of the operation of algorithm No. 5.**

| Method / Metric | Euclidean distance | Euclidean distance “First” power distance | Euclidean distance “Second” power distance | Percentage of disagreement | Measure based on correlation |
|-----------------|--------------------|------------------------------------------|-------------------------------------------|-----------------------------|-----------------------------|
| Single link Method | 141                | 147                                      | 147                                       | 145                         | 143                         | 138                         |
| Full link method | 132                | 137                                      | 135                                       | 134                         | 136                         | 136                         |
| Weighted Average link Method | 134           | 136                                      | 133                                       | 133                         | 132                         | 132                         |
| Unweighted average link method | 135           | 134                                      | 134                                       | 135                         | 136                         | 138                         |
| Median          | 133                | 133                                      | 128                                       | 130                         | 131                         | 132                         |
| Centroid        | 138                | 135                                      | 145                                       | 145                         | 137                         | 138                         |
| Ward Method     | 139                | 142                                      | 142                                       | 142                         | 142                         | 133                         |

Tables 6,7,8 show that the best result was obtained using algorithm No. 3 (124 readjustments). To check the effectiveness of the application of algorithm No. 3, algorithm No. 6 was developed, which allows one to calculate the number of readjustments in the non-optimal variant of replacing elements in block cells. Algorithm No. 6 is similar to algorithm No. 3 except for the situation when the number of elements necessary for processing the previous and current parts exceeds the capacity of the block. In algorithm No. 6, the element that has the highest priority of use is removed from the block.

Using the described algorithm No. 6, the number of readjustments was calculated when processing the sequence of parts obtained using the median cluster analysis method according to the “first” power distance metric, as well as the sequence obtained using algorithm No. 2. For comparison with the results obtained by algorithm No. 3, the data are summarized in table 9.

**Table 9. Comparison of the results of algorithms No. 3 and No. 6.**

| The method of obtaining the sequence / calculation algorithm | Algorithm No. 6 | Algorithm No. 3 |
|------------------------------------------------------------|-----------------|-----------------|
| Algorithm No. 2                                           | 223             | 191             |
| Median (“first power distance”)                            | 141             | 124             |
Thus, we can draw the following conclusions:

1. When determining the sequence according to algorithm No. 2 (a possible variant of the sequence determined by the line manager), when using algorithm No. 3, the number of changeovers is 191, when using algorithm No. 6, it is 223. This indicates the necessity and relevance of applying cluster analysis methods to determine the sequence of launching parts into processing.

2. Algorithm No. 3 gives the number of changeovers significantly less than algorithm No. 6 (a possible option for replacing elements in unit cells determined by the machine operator). For a sequence determined using cluster analysis, 124 and 141, respectively; in the sequence determined using algorithm No. 2, the number of changeovers is 191 and 223, respectively. This indicates the rationality and the need to use algorithm No. 3 to determine the sequence of tool replacement in block cells.

3. By choosing the minimum number of changeovers (median - “first” power distance - algorithm No. 3) equal to 124 and the maximum (algorithm No. 2 - algorithm No. 4) equal to 223, you can calculate the average number of changeovers equal to about 174. This number of changeovers can be on average obtained by determining the sequence of starting parts by a linear manager, and the sequence of changing elements in cell blocks by the machine operator. Thus, comparing the obtained average value (174) with the minimum (124), we obtain a difference of approximately 50 changeovers for a given sample of parts. This once again testifies to the relevance of applying the methods of cluster analysis and algorithm No. 3 to determine the sequence of starting parts into processing and changing elements in the cells of the machine blocks.

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