Improving the efficiency of CNC machine tools with multi-pallet systems in machine-building manufacturing

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Abstract. The paper discussed the problems of effective machining of workpieces in small batches on CNC machines with multi-pallet systems, combined into flexible manufacturing cells (FMC). In the paper was reviewed timeline of such manufacturing cells. It is shown that in order to increase the efficiency of the CNC machines with multi-pallet systems into each flexible manufacturing cell is necessary to pick up different workpieces to be machined, based on the duration of their machining cycles and installation in pallets. It allows providing machines downtime minimization. To calculate the machining cycles of workpieces in a flexible manufacturing cell, it is proposed to use the graph-analytical method, which gives an enlarged estimate, and the method of simulation of manufacturing processes, which allows obtaining a refined decision.

1. Introduction.

At present, various software and hardware for the execution of technological operations are widely introduced at domestic machine-building enterprises.

Increasing the level of technological processes automation leads to the stability of product quality, reduce the time of technological cycles of manufacturing products, and improve the efficiency of production in general [1].

Despite the great potential of using flexible manufacturing cells in technological processes, the effectiveness of their application in practice is not enough [2].

As a rule, technical problems of FMC application are mostly solved. Organizational issues are considered to a lesser extent. The effectiveness of FMC using is largely determined by the organization and maintenance factors [3].

In this paper, has been investigated an integrated approach for determining the composition of automation devices and the interaction of elements within FMC in the context of the designing of manufacturing systems.

2. Initial data for the analysis of the machines with multi-pallet systems effectiveness and statement of the problem.
As an example of a manufacturing system, a workshop of small-scale production with CNC machines equipped with multi-pallet systems and automatic pallet changers (APC) has been selected. This solution for the automation of flexible manufacturing cells involves the completion of machines with pallet magazines and automatic feeders and pallet changers. Within the same cell can be machines equipped with APC, and without APC. Data are given for the milling operations of this workshop.

The composition of the equipment and the automation devices been used are shown in Table 1.

### Table 1. Composition of milling machines

| №  | Type of equipment | Symbol | Automation devices |
|----|-------------------|--------|-------------------|
| 1  | 3-axis Milling machines designed for roughing | M3 «R» | 1) CNC system. |
| 2  | 3-axis Milling machines designed for basic finishing, equipped with APC | M3 «F» + APC | 2) Tool magazine and devices for automatic change of cutting tools |
| 3  | 5-axis Milling machines (3-axis + discrete machining on 2 additional axis) | M5 «3+2axis» | 3) Devices for automatic measurement of the actual tool dimensions and correction of the control program (automatic binding devices). |
| 4  | 5-axis Milling machines (3-axis + discrete machining on 2 additional axis) equipped with APC | M5 «3+2axis» + APC | 4) Devices (probes) for automatic measurement of the workpiece being machined |
| 5  | 5-axis Milling machines models "S" (synchronous machining on 5-axis axes) | M5 + «S» | 5) The device of light signaling about a condition of the machine tool (a three-color traffic light). 6) Automatic pallet changer with a part in the working area of the machine with a pallet magazine. Storage capacity - 7 pallets, for item 2 and item 4. |

Based on these types of equipment and automation devices, and on preliminary calculations of the number and types of the necessary machines, flexible manufacturing cells are formed, the structure of which is shown in Table 2. Figure 3 shows a fragment of the workshop plan with the placement of 4 units of FMC 3 (4 machines per cell with one operator) of the FMC of the milling operation.

### Table 2. Structure of the flexible manufacturing cell of the milling section (basic version)

| №  | Types of FMC | Quantity of FMC | Composition of FMC |
|----|--------------|----------------|--------------------|
| 1  | FMC 1        | 2              | M3 «R» CNC machine operator |
| 2  | FMC 2        | 4              | M3 «F» + APC CNC machine operator |
| 3  | FMC 3        | 4              | M3 «F» + APC CNC machine operator |
| 4  | FMC 4        | 4              | M5 «3+2axis» CNC machine operator |
| 5  | FMC 5        | 4              | M5 «3+2axis» CNC machine operator |
| 6  | FMC 6        | 2              | M5 + «S» CNC machine operator |

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It is required to determine the composition and structure of the FMC taking into account the specification of the workpieces to be machined:

1) the optimal composition of the components of each FMC included in the flexible manufacturing system (FMS): the number of machines in the cell; number of machines equipped with APC;

2) distribution of the workpieces to be machined in the FMC.

3. Description of the methods used in the development of project solutions.
Frequently, it is not possible to use the traditional methods of calculation, because:

1) Algorithms of a FMS components interaction can differ significantly; therefore general used equations give an incorrect result. For example, the principle of forming a machining floor-to-floor time involves the sequential execution of of the machine adjustment for the machining of workpieces. It is mean that during the adjustment the machine does not machining of the workpiece. The time loss factor caused by organizational reasons is usually assigned based on statistical data for analogues of manufacturing systems.

2) The traditionally performed calculation of the complex coefficient (the ratio of the machine operating time to the working time of the worker) does not take into account the organizational losses of time and gives the theoretical marginal productivity of the cell.

To improve this situation it is proposed to use the following methods [4]:

1) method of graphical designing of cycle diagrams (graph-analytical method) of the FMC operation for a relatively small time interval - for analyzing the operation of a multi-station flexible manufacturing cell (Figure 1);

2) method of simulation to analyze the joint work of flexible manufacturing cells in a flexible manufacturing system for a long period of time. It is realized after the definition of strategies for forming the structure of the FMC and fixing the appropriate machining parts. It is necessary to analyze the work of the FMC for a long period of time, as well as to analyze their joint work taking into account possible deviations from the established norms of time. Based on the complexity of the manufacturing under consideration, due to the large number of elements of the manufacturing system and a wide range of logics of their interaction, the simulation model must have more flexibility, which can be realized with the help of agent or hybrid simulation techniques [5].

4. Practical implementation of the proposed integrated method for evaluating design solutions when creating flexible manufacturing systems.
Method 1
First, using the graph-analytical method, the efficiency of individual FMC is analyzed depending on the composition of cells and the type of workpieces delivered to them. Figure 1 shows a cycle diagram of parts "A" machining (conditionally medium cycle parts, processing time 7 min.) and "B" (conditionally short cycle parts, processing time 3 min.) of the selected types of parts on the milling operation in a flexible manufacturing cell consisting of two machines.

![Cycle Diagram](image_url)
Figure 1. Graph-analytical method: a) a cycle diagram of operation of two-machine FMC while machining of parts "A" and "B"; b) the parameters of the production operations used in the cycle diagram

We perform a comparative analysis of FMC configurations. In this analysis the quantities of batches of parts are taken to be the same.

Figure 2 shows the cycle diagram for the machining of parts "A" and "B", built for a comparative analysis of the efficiency of various options for the composition of the FMC components, use of APC for each of the machines: two-machine FMC (view "a"), three-machine FMC (view "b"), four-machine FMC (view "c").

Figure 2. Cycle diagrams of the FMC operation for the machining of parts "A" and "B" using each machines with APC: a) two-machine FMC, b) three-machine FMC; c) four-machine FMC; d) the parameters used in the cycle diagrams.

From the diagrams shown in figure 2, one can see that the four machines FMC has the highest productivity - 0.36 parts per minute. For the machining of a minimum batch of 50 parts "A" and 50 parts "B" will take about 278 minutes. In this case, the shutdown time of the machine tools adjustment will be about 30 minutes. Parallel to this, loading of pallets into the shop of APC (28 minutes) and assembly of the tool magazine of the machine tool is carried out. Thus, the processing time is almost greater than the machine's shutdown time for setup.

Analysis of the cycle diagrams (see Figure 2) showed:
1) if it is not possible to provide external adjustment of tools, as well as loading control programs into the machine, setting up pallets, the tool by one worker, the time for stopping the machines will be commensurate with the machining time. In this case, the gain from increasing the productivity due to the application of the APC systems is offset by the increased time for setting up the cell, i.e. the cost of more expensive equipment is not justified;
2) the maximum theoretical performance of the FMC is obtained for the 4-machine configuration of the cell (Figure 2 "c"), the same option is most beneficial from the point of view of the minimum requirements in human resources;
3) the 4-machine configuration of the cell (Figure 2 "c") will be difficult to implement in practice, since the operator will not be able to work without intervals for a long time, besides, in this case, there are no reserves for smoothing the inevitable deviations from the established time. As a result, equipment in such a cell will be idle due to the operator's employment with the maintenance of other machines;

4) rational organizational and technological solutions for the formation of the FMC are:
- three machine configuration of the FMC provided that two machines are loaded with "A" type parts (with a longer machining cycle) and the remaining one with "B" type parts,
- two machine configuration of the FMC, in which both machines are engaged in processing short-cycle parts of type "B". The final composition of the FMC in the flexible manufacturing system (FMS) will be determined by the ratio of the output quantities of the "A" and "B" type parts.

Currently, methods of external adjustment of tools have been worked out and successfully used, the interfaces of CNC systems have become much simpler, and operational control systems have appeared [6].

This allows implementing the above-mentioned techniques for increasing the efficiency of the multi-step FMC and make recommendations for organizing the work of the cell:
1) during the machining of parts, the CNC machine operator keeps track of the machines. At this time other worker prepares the tools;
2) during the re-adjustment of machine for new part, the service personnel, workers and operators are involved, while simultaneously loading the tool, devices, programs;
3) using of group technologies in small-scale production also significantly reduces the amount and laboriousness of the equipment readjustment.

Method 2
To analyze the joint work of the components of flexible manufacturing cells, as well as to analyze the joint work of the FMC itself, a simulation model of the mechanical workshop of the multiproduct small-batch production was developed. A fragment of the simulation model's plan of FMC 3 (see table 2) is shown in Figure 3. According to the results of the method 1, for FMC 3 a 4-machine FMC layout was selected (Figure 2 "c").

It is required to determine the optimum composition of the FMC, namely: the optimal number of workers for this flexible manufacturing cell; the optimal number of automation tools is APC.

![Figure 3](image-url)

**Figure 3.** Fragment of the simulation model of the workshop for FMC 3. Shown: four-machine FMC 3; indication of machines status, machines utilization; indication of APCs for machines; material flow indication.

The agents of the simulation model are the following elements of the manufacturing system of the workshop: parts, technological equipment (CNC machines, thermal furnaces, workbenches, etc.),
buffers (storage tanks), automatic pallet changers, operators, etc. Each of the agents has its own logic of functioning and interaction with other agents of the model. Also in the model there are: the schedules of the elements of the manufacturing system, the schedules of repair and maintenance of equipment, the probability of equipment failure, the parts machining, the schedules of the operators, multi-stop service and other.

Based on the results of the cycle diagrams of operation of the FMC of the first stage of the analysis (see Figure 2), the following logic is adopted for the operation of a multi-cell with APC.

When a batch of N parts arrives for machining, they are loaded into the APC free equipment store until the magazine of the M capacity is fully loaded (7 positions in the case under consideration). If N < M, then the whole batch of N parts or the remainder of the batch with the volume L is loaded into the store - the number of unhandled parts from the lot N, where L < M.

Further, in the automatic mode, the parts loaded into the store are machined to the full exhaustion of raw parts, after which an operator is called on the signal lamp to unload the finished parts from the APC drive and load the next batch of new parts. Thus, for the case under consideration, the operator with the APC is deliberately excluded when the machine is running, which is done to avoid mistakes made by the operator, the probability of which increases many times when mixing short-cycle parts from different batches within the same processing cycle.

The plan of the experiment provides for the development of five modeling of the script (Table 3). Of the script 4, 5 are used the results of modeling the first three of the script.

| №  | Name of the script          | Characteristic of the script                                      | Purpose of the Script development                                      |
|----|----------------------------|------------------------------------------------------------------|------------------------------------------------------------------------|
| 1  | «Basic»                    | The initial FMS in the basic version of the FMC configurations    | Verification of the model, determination of the capabilities of the initial FMS for the execution of the production program |
| 2  | «Maximum»                  | Elimination of multi-stop service                                | Determination of the maximum performance of FMS                         |
| 3  | «Possible solution 1»      | The layout of the cells in accordance with the recommendations of the first stage of the analysis - FMC: 2 machines with APC | Determination of rational FMC layouts                                    |
| 4  | «Possible solution 2»      | Exclusion of APC with negligible effect according to scenario 3  | Optimization of the FMC and FMS structure                               |
| 5  | «Without automation devices»| The complete exclusion of APC systems                            | Determination of the effect of using automation devices                 |

Examples of output data for the analysis of the joint operation of the FMC components on the basis of experiments of the simulation model are shown in figures 4 and 5.
Figure 4. Cycle diagrams of the joint operation of the components of two-machines FMC during the simulation period from 300 to 800 hours. Machining of parts "A".

Figure 5. Real-time analytical reports for assessing the performance of an operator in two machine configurations of a FMC

5. The simulation results.
A comparative evaluation of the simulation results according to the developed scripts is shown in Table 4 (the results are shown for a FMC 3).

Table 4. Comparative characteristics of simulation results according to the developed scripts for a flexible manufacturing module of four 4-machine FMC 3

| Model scripts | Script 1 | Script 2 | Script 3 | Script 4 | Script 5 |
|---------------|----------|----------|----------|----------|----------|
|                | «Base»   | «Max»    | «Opt 1»  | «Opt 2»  | «W/o APC»|
| Components of FMC | M W A   | M W A    | M W A    | M W A    | M W A    |
|                |          |          |          |          |          |
As a result of the first script, it is established that the production program of the workshop cannot be performed due to low utilization of equipment, which was the result of the four-machine FMC.

To determine the maximum performance of the FMC and calculate the necessary machines for the production program, an experiment was conducted in the script 2, taking into account the recommendations of method 1 for fixing the selected types of parts type "A" and "B" for machines (see Table 4, line "Managing of material flow").

Taking into account the results of modeling the script 1 and 2, changes were made to the FMC structure. After that, simulation modeling of production processes of a FMC was carried out within the framework of the script 3.

For the manufacturing system under script 3, one of the possible design solutions was obtained, characterized by a significant reduction in the production cycle of manufacturing the entire volume of parts: 77.8 days against 119.5 in the “script 1” and an increase in machine utilization of 18.000%. Further optimization of the manufacturing system and its analysis within the framework of the script 4, make possible to reduce the number of operators and exclude inefficiently used automation devices with a slight increase in the production cycle (78.4 days). At the same time, inefficiently used APC were excluded from the FMC 5 (see Table 2, line "Changing the composition of other related FMC") associated with the FMC 3 with the general material flow.

For a comparative evaluation of the effect of the introduction of automation devices, the 5th series of experiments was performed with the complete exclusion of APC.

6. Conclusions

1) Using the proposed approach for sharing the graph-analytical method and the simulation method significantly improve the quality of design solutions, as well as to reduce the complexity and time for the design of the manufacturing system by means of:
   - simulation modelling of the joint operation of the FMC as part of a flexible manufacturing system;
   - a significant limitation of possible solutions to the flexible manufacturing system, by identifying possible FMC structures and processing strategies within the framework of graph-analytical analysis of the operation of individual FMC.
2) This allowed us to solve the following practical problems in the presented flexible manufacturing system:

- clarify the FMC structure, including: machine tools, operators, APC;
- determine the optimal ratio of the number of operators and other workers;
- to develop recommendations on fixing the parts for the corresponding FMC;
- to develop recommendations on the layout of the FMC.

3) The proposed approaches can also be used in the simulation of other production systems characterized by a complex interaction of its elements.

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