Advances in Economics, Business and Management Research, volume 119
1st International Conference on Emerging Trends and Challenges in the Management Theory and Practice (ETCMTP 2019)

Formation of Robotized Structures at Innovation-Oriented Clusters' Enterprises in Terms of Digital Manufacturing

Irina V. Baranova
Institute of Business Studies
The Russian Presidential Academy of National Economy and Public Administration
Moscow, Russia
yar.baranow@gmail.com

Oleg V. Korobchenko
Korib Group of Companies
Naberezhnye Chelny, Republic of Tatarstan, Russia
okulakov@korib.ru

Sergey V. Mayorov
Mechanical Engineering Cluster of the Republic of Tatarstan
Naberezhnye Chelny, Republic of Tatarstan, Russia
mayorov@chelny-invest.ru

Vyacheslav V. Baranov
Institute of Business Studies
The Russian Presidential Academy of National Economy and Public Administration
Moscow, Russia
professor_baranow@icloud.com

Marina M. Batova
Department of Informatics and Management
Military University of the Ministry of Defense of the Russian Federation
Moscow, Russia
batova_m_m@mail.ru

Abstract– **A mathematical tool for modeling the optimal set of the robotic elements at the cluster member enterprise is proposed. The necessary and sufficient conditions of the robot-assisted technological equipment with the minimal resource idle time are formulated. The problem of minimizing technological downtime while robotic services a parallel working technological equipment is solved. The mathematical apparatus is proposed for calculating the duration of technological equipment servicing by robotic for proportional operations. At the stage of robotic elements design and operation the problem of organizing was solved for the cluster-member enterprises. At the design stage the problem solution consists in finding the best option of the technological equipment deployment in the robotic elements sectors so that the only one robot services each element. The features of the solution problems using manipulator-type robotics are detected. At the stage of robotic elements operation, the problem solution involves the development of optimal option if the set operations for the designed elements. Algorithms for solving combinatorial problems of design and operation robotic elements are developed for a cluster-member enterprise. The computational mechanism of creating and using robotic elements allowing reduce time needed to obtain combinatorial problems solutions is proposed for a cluster-member enterprise. In this mechanism, the task of splitting a given set of equipment into robotic elements is replaced by the task of sequentially extracting elements from the set of equipment in the production system of a cluster-member enterprise. The developed methods form the basis of the software package supporting solutions in the scope of robotic elements design and using for an engineering cluster enterprise**.

Keywords: digital manufacturing, innovation-oriented cluster, high-tech enterprise, mathematical model

I. Introduction

In the context of the digitalization of Russian industry and its transition to innovative development factors, high-tech enterprises are becoming one of the key elements of the macroeconomic system. They use highly automated equipment, robotics, and information systems implementing new technologies (process innovations), produce products with a high share of intellectual labor costs. At the same time new technologies acquiring the form of technological capital of high-tech capital give an impetus to the development of innovative processes, in particular, the processes of new organizational and production structures formation. High-tech enterprises create strong relationships with resource suppliers and product consumers.

To ensure conditions for the efficient operation of high-tech enterprises, Government implements various forms of organizational and financial support. At the regional level territorial innovation-oriented cluster structures are such a form. One of the regions of Russia in which innovation-oriented cluster structures are successfully created is the Republic of Tatarstan. Currently such world-class clusters are the engineering cluster and the Kama innovative territorial-production cluster. They have been created in Tatarstan. For example, the engineering cluster of the Republic of Tatarstan is the largest engineering cluster in the Russian Federation. The cluster unites 142 enterprises, which employ more than 27 thousand people.

The enterprises of the engineering cluster of the equipment with number j on the entire set of equipment included in the robotic production element.

The problem statement of modeling the optimal set Republic of Tatarstan in the course of their activities use production systems oriented to flexible automation of production, and produce products that are competitive on the world market. Technological capital created in an innovation-oriented cluster structure generates the ability of cluster-member enterprises to use rational methods of organizing production processes.

II. The Problem Statement of Modeling the optimal Set of Robotic Production Elements of a Cluster-member Enterprise

Given the importance of the innovative subsystem and the technological capital formed on its basis a number of problems arise in the mathematical modeling of innovative activity processes [1, 3, 5]. One of these problems is related to the formation of production elements of a cluster-member enterprise and the choice of their optimal set. The formation of such elements involves the introduction of highly automated equipment and industrial robots that perform the functions of handling machineries [11, 12]. As a result of the design the production potential of a high-tech cluster enterprise is created. This potential, covering the summation of fixed and intangible assets, intellectual resources and a number of other elements, is characterized by the value of production capacities which characterizes the maximum ability of robotic elements to fulfill a given production program.

In the robotic systems created at the enterprise level of the cluster, the problem arises of minimizing the downtime of equipment and maximizing the rate of robot use servicing this equipment. This task is most relevant for a situation when the robot serves several units of technological equipment that work in parallel.

There is a number of the introduced assumptions for the convenience of mathematical modeling:

- Considering equipment that performs machining operations at the enterprise of an engineering cluster;
- Assuming that the equipment number and the number of the technological operation performed on this equipment are the same;
- Each unit of equipment for a certain time interval is assigned to perform one operation.

The number of technological equipment in the robotic production element is denoted by the index j. For each unit of equipment with number j, the variables necessary to create the model are introduced:

- robot servicing time – t_j^s;
- automatic operation time of the equipment – t_j^a;
- operative execution time of operation with number j – t_j^{op},

The total value of the in-process time during maintenance of all units of equipment during the maintenance cycle will be T^b. This value will be equal to the sum of the robot servicing times for each unit of of a robotic production system:

- Using available technological equipment on a cluster-member enterprise a set of the robotic production elements is required to create. Moreover, for each element it is necessary to select such a number technological equipment units so that during the automatic operation of any unit of equipment the robot can serve all other units included in the formed element.

The results of the organizational design of robotic elements should provide a minimum downtime of equipment in the element at maximum operating time of the robot.

The mathematical apparatus for solving the problem of modeling the optimal set of robotic production elements

That statement of the problem assumes that for any technological operation j performed in a robotic production element:

- first the operative execution time of operation with number j is:

$$t_j^{op} = t_j^a + t_j^s \quad (1)$$

- second the total in-process time of equipment maintenance cycle by robot should satisfy the following relation:

$$T^b \leq t_j^{op} \quad (2)$$

A necessary, but not sufficient, condition for the operation of technological equipment included in the robotic production element with minimal downtime (and ideally with a complete absence of downtime) is a high rate of robotic use when it is servicing this equipment. In order to have a sufficient condition for the functioning of a robotic production element with minimal downtime, it is necessary to form restrictions on the values of the operating time for each operation with number j (t_j^{op}).

It is assumed that initially at the cluster-member enterprise a production system is used, from the parts of which robotic production links are formed. Moreover in the basic production system proportional operations are performed. For each operation with number j, the operational time on the whole set of such operations obeys the relation:

$$t_j^{op} = A_j d \quad (3)$$

where: A_j - are natural numbers;

d – the minimum value of operational time from the entire set of operations performed by equipment included in the formed robotic element.

Since the robotic production elements created for the cluster enterprise are formed on the basis of its basic production system the equipment of these elements will also perform proportional operations. In this case it is possible to analytically determine the value of the minimum time interval during which the maintenance of all units of the technological equipment included in the robotic element is repeated in the same order.

For each robotic production element, this time interval will be called the cycle of servicing the element technological equipment by the robotic. If proportional

the symbol $K^{lf}{}_j$.

Then, when solving the problem of optimizing the composition of robotic production units by dividing the

operations are performed in the element, then the duration of this cycle will be::

$$T_s = Q d \quad (4)$$

where: Q – least common multiple of coefficients A_j.

During the time amounting to the duration of the cycle of the robot servicing the technological equipment of the robotic production element, the operation with number j will be performed Q/A_j times. At the same time servicing equipment with number j in the robotic production unit that performs the operation with the same number, the robot spends time t_j^s. Therefore the rate of robotic use is:

$$k^{lf}_r = 1/d\,[\sum(t_j^s / A_j)] \quad (5)$$

Using the results of organizing a highly automated production process consisting of proportional operations, it can be constructed a number of approximate algorithms for creating robotic production elements for a cluster-member enterprise. The necessity of developing such algorithms is shown in [2, 4].

III. Target setting for organizing Robotic Productions Cluster at a Cluster-member Enterprise

The task of organizing the maintenance by a robotic of technological equipment during the design of robotic production elements and during the operation of these elements is formulated in different ways. However, in any case, it will be considered elements of technological equipment that are interchangeable with respect to the operations being performed. If this condition is not met for all units of the production system, then the task of optimizing the set of robotic production elements should be addressed in relation to each of the groups of interchangeable equipment separately.

IV. Statement of the Problem at the Design Stage of Robotic Production Elements

In this case the task of creating robotic production elements is formulated as follows:

- find the best option for distributing a variety of technological equipment of the base production system of the cluster-member enterprise to robotic production elements, so that each of these elements is served by one robot.

When setting the task of optimizing the composition of robotic production elements we took into account that some types of robotics are stationary and do not have freedom of movement. Therefore, for stationary robotics, a restriction should be introduced on the number of technological equipment located in the service area of the robot.

Thus, when using stationary robots, the task of optimizing the set of robotic production elements is complicated. This is due to the fact that the planned output volume for some operations may not ensure a full load of equipment. Therefore, for each technological operation with number j, in addition to the values of the operational time to complete the operation (t_j^{op}) and the time the robot serviced the equipment engaged in performing this operation with number j. Denote this coefficient by

interchangeable equipment of the base production system of the cluster-member enterprise into robotic elements at the design stage, it is necessary to take into account a number of additional data:

- first the number of technological equipment units of the base production system of the cluster-member enterprise (M) should be known;
- second for each operation with number j assigned to equipment with the same number, the values of the operational time of the operation (t_j^{op}), the time the robot serviced the equipment engaged in the operation (t_j^s) and the planned load factor of the equipment should be known performing an operation (K^{lf}_j);
- third the maximum allowable amount of equipment that can be in the service area of each robot - r_{max} - must be determined. We assume that r = M for a robot with an unlimited service area.

As a result of solving the problem, it is necessary to find an option for the distribution of a given set of equipment of the basic production system of the cluster-member enterprise among robotic production elements. This option should provide the optimum of the selected objective function. A similar optimum is determined provided that the actual load factor of a piece of equipment with number j (k^{lf}_j) when working in a robotic production element satisfies an inequality of the following form:

$$K^{lf}_j \le k^{lf}_j \le K^{lf}_j + \Sigma \quad (6)$$

1. where: Σ - the set value of the deviation of the actual load factor (k^{lf}_j) from the planned value (K^{lf}_j).

Assessing the effectiveness of the decisions made it is necessary to formulate the objective function, as well as have a set of indicators and criteria for their assessment [9]. In this case, it is advisable to choose a function that provides the maximum Net Present Value (NPV) or Internal Rate of Return (IRR) for the project life cycle interval as the objective efficiency function. The duration of this cycle should cover the stages of the creation of robotic production elements and their operation.

In addition to these functions it is possible to use a minimum of the totality of integrated costs (investment and current) on the interval of the life cycle of the project. These costs are associated with the acquisition and use of elements of the designed production elements (equipment, robotics, distributed information systems, transport and storage devices).

V. Statement of the Problem at the Stage of Operation of Robotic Production Elements

During the operation of the formed robotic production elements the formulation of the task of the planned load factor of the equipment performing the operation (K^{lf}_j);

organizing the maintenance of industrial equipment by an industrial robot takes a different form. The solution to the problem of organizing the maintenance of industrial equipment by an industrial robot is preceded by the formation of an array of source data:

- first the number of generated robotic production elements must be known;
- second the number of technological equipment and operations performed in the planning period should be determined;

- third each of operations with number j is characterized by the values of the operational time of the operation (t_j^{op}), the time the robot serviced the equipment engaged in this operation (t_j^s), and the planned load factor of the equipment performing the operation ($K^{lf}{}_j$).

As a result of solving this problem it is required to develop an option for optimal consolidation of operations for designed robotic elements for a planned period of time. The proposed option of securing operations for robotic production elements should provide a minimum of current costs for the maintenance and operation of the formed elements. At the same time the requirements for the value of the actual load factor of a piece of equipment performing an operation with number j ($k^{lf}{}_j$) remain the same as in the case of solving the design problem of robotic production elements. These requirements formalize the conditions for the compulsory implementation of the planned production program by the cluster-member enterprise.

VI. Algorithms for Creating Robotic Production Elements

The formulated options of the problems solved in the framework of organizing robotic production and optimizing the set of robotic elements are combinatorial problems [6, 9]. The exact solution to this class of problems can be obtained in two ways. The first method involves a complete search of possible options for including equipment in robotic production elements. The second way is associated with the design of possible options for securing operations for the technological equipment of the elements created.

With a sufficiently large number of technological equipment that is part of the production system such tasks belong to the class of combinatorial tasks. Solving such problems takes considerable time. Therefore, for the management of a cluster-member enterprise, the development of approximate solution methods is of practical interest. We propose one of these methods.

First, a set of source data is formed:

- for the production system of the cluster-member enterprise is determined by the number of operations performed - M;
- each operation with number j is characterized by the values of the operational time of the operation (t_j^{op}), the time the robot serviced the equipment engaged in the operation (t_j^s), and
- permissible excess of the actual load factor of technological equipment ($k^{lf}{}_j$) of the planned value of this coefficient ($K^{lf}{}_j$) – Σ.

It is required to distribute a given number of operations among robotic production elements. The distribution of operations option must satisfy a number of conditions. First, at each element, equipment maintenance should be performed without downtime. Second, the actual load factors of each piece of equipment with number j ($k^{lf}{}_j$) should be no less than the planned load factors ($K^{lf}{}_j$), differing from them no more than by a predetermined value (Σ).

We propose an algorithm for distributing a given number of operations among robotic production elements. The algorithm includes a series of steps performed sequentially. First, for each operation with number j, the repeat period is calculated. Let denote it by the symbol τ_j. This is the time interval at which the load factor of the equipment performing the operation with number j (accurate to rounding the division result) is $K^{lf}{}_j$ The determination of the repeatability period involves the analysis of the values of the operational time of the operation (t_j^{op}) and the allocation of the integer part for each operation with number j. From the set of repeatability period values thus determined, the minimum value (d) is selected.

Then, the actual load factor of equipment with number j ($k^{lf}{}_j$), that performs the operation with the same number is calculated:

$$k^{lf}{}_j = t_j^{op} / (A_j\, d) \qquad (7)$$

In this formula, the value of A_j is selected as the integer part of the ratio of the repeatability period calculated for equipment with number j (τ_j), to the minimum value of the period set for the entire set of operations performed in the robotic element (d). It should be considered that the technological operation with number j can be performed in the formed robotic elements, provided that the actual load factor of a piece of equipment with number j ($k^{lf}{}_j$) is within the permissible deviation from the value of the planned load factor ($K^{lf}{}_j$).

Next, a final check of the feasibility of choosing a set of equipment for a robotic production element is performed. Verification consists in monitoring the basic conditions for organizing equipment maintenance without downtime. This means that the duration of the cycle of the robot servicing the technological equipment of the robotic production element (T_s) should be a multiple of the minimum value of the operational time from the whole set of operations performed by the equipment included in the formed unit (d).

According to the results of the check, the number of pieces of equipment included in the robotic production unit is corrected. The correction involves reducing the number of units of equipment that is part of the robotic production unit, and is carried out if the number of elements acts as a limitation on the amount of this equipment located in the service area of the robot.

The quasi-optimal option is selected from the set of process equipment in the unit exceeds the allowable number of units of equipment that may be in the robot service area.

VII. The Computational Mechanism for the Implementation of Algorithms for the Creating and Use of Robotic Production Elements

To implement the algorithm, we proposed, an appropriate computational mechanism was developed. When creating such a mechanism the task of splitting a given set of technological equipment into robotic production units is replaced by the task of sequentially isolating these elements from the entire set of equipment that is part of the basic production system of the cluster – member enterprise. This mechanism is implemented as follows.

For each operation with number j, the period of its repetition (τ_j) is calculated. Technological operations are ordered in accordance with the increase in the repeatability period. Then the process of forming robotic production elements is implemented. When they are formed the value of the transmission of its repeatability for the first operation in the sequence is taken as parameter d. Then other operations are added to the selected operation. When forming the set of operations included in the structure of robotic production elements, a number of factors are taken into account, including:

- fulfilling the condition of proportionality of operations;
- admissibility of the actual load factor of equipment performing operation with number j (k^{lf}_{j});
- restrictions on the number of technological equipment that may be in the service area of the robot.

It is obvious that the formation of many operations performed on equipment included in the composition of robotic production elements is affected by a fairly large number of factors. One of such factors is the deviation of the actual load factor of equipment unit with number j (k^{lf}_{j}) from the value of the planned load factor of the same equipment (K^{lf}_{j}). By changing this parameter within certain limits admissible from the point of view of the given design conditions, it can be obtained various options for organizing robotic production elements.

Each of the obtained options will provide a value of the objective efficiency function close to the optimal value. Therefore, the approximate method we propose is for dividing the set of equipment of the production system of a cluster -member enterprise into robotic production elements, although it is quasi-optimal, but it allows for high accuracy of calculations.

The algorithm for solving the task of securing operations for technological equipment during the operation of robotic production elements is similar to the considered algorithm used at the design stage of these elements. The actual number of units of technological equipment included in various robotic production feasible solutions. The totality of such decisions is generated by varying the deviation of the actual load factor of an equipment unit with number j (k^{lf}_{j}) from the value of the planned load factor (K^{lf}_{j}). The change in the deviation is in the range from 0 to the maximum allowable value set by the developer.

This algorithm has a significant difference from the previously considered algorithm. This difference is that since the number of robotic production elements is predetermined, the set of feasible solutions may be empty. A similar situation can arise even if the number of operations performed (M) is less than the number of units of technological equipment (J). Then the possibility of obtaining at least one feasible solution to the problem will be associated with a change in the source data. This change may concern a number of parameters, including the set of technological operations, the production program (cluster-member enterprise portfolio), the planned load factor of equipment, etc.

VIII. Software Package for the Implementation of Algorithms for Creating and Using Robotic Production Elements

The software package is developed for implementation of the proposed algorithms. This software package covers:

- basic naturally developed imperative language, which is a high-level programming language;
- source code development environment in this programming language.

The created language implements the fundamental concepts of the information technology industry, including paradigms such as concatenative, object-oriented, functional and the latest trends in the development of high-level languages (multi-valued logic, functional purity, pattern matching, transparent multithreading, parameter guards). These features of the programming language are organically combined within the framework of an intuitive and concise syntax.

The breadboard implementation of our proposed algorithm in a high-level programming language demonstrates the high robustness of this model. This reduces the quality requirements of the source data when designing robotic production elements. This feature is important from the aspects of the method practical implementation within the framework of existing and developed resource management systems of cluster structures high-tech enterprises. A developed high-level language is characterized by a combination of postfix and infix notations. This optimally corresponds to the streaming nature of the computing process in the proposed model.

IX. Conclusion

The result of modeling robotic production elements is the optimal set of the created element, including both the main (technological) and auxiliary (robotics) equipment. Besides the scope of a cluster-member enterprise innovation system is expanding. Along with product and process innovations organizational and management innovations appear in this system. Such innovations, embodying the processes of organizing and managing robotic production, act as a component of technological capital. By automating the computational processes of choosing the set of robotic production units, the cluster-member enterprise forms intellectual information assets and capital [7]. All these components reflected in the business reputation of the cluster-member enterprise increase its fundamental value.

In this case at the cluster-member enterprise level, the task of linking various information systems into an integrated software and information complex is emerged. It is necessary to create a single information space of the cluster-member enterprise for the practical implementation of the integration idea.

The concept of digital manufacturing is based on the idea of integrating various information systems, resources and capital into a single system. The basis of this concept is the development of an information model of high-tech production, covering technological, resource, organizational, management and other types of innovations, as well as tools and technologies for the information and communication support of this production [8]. Therefore, the embodiment of these models in the form of an information system for decision support is an important step towards the digital transformation of the cluster cluster-member enterprise.

REFERENCES

[1] Alpatov Yu.N. Mathematical modeling of production processes: Textbook. St. Petersburg: Lan, 2018. – 136 p.

[2] Andreev S.M. Development and computer modeling of automation system elements with the specifics of technological processes: Textbook. M.: Academia, 2017. – 360 p.

[3] Afonin V.V., Fedosin S.A. Modeling systems: a training manual. M.: Intuit, 2016. – 231 p.

[4] Baksansky O.E. Modeling in Science: Cognitive Models and Intelligence. M.: Lenand, 2019. – 304 p.

[5] Vlasov M.P., Shimko P.D. Modeling Economic Systems and Processes: A Training Manual. M.: Infra-M, 2018. – 320 p.

[6] Innovative Design of Digital Production in Mechanical Engineering: A Training Manual. / S.G. Selivanov, A.F. Shaykhuloeva, S.N. Poezhzhalova A.I. Yakhin. M.: Innovative engineering, 2016. – 264 p.

[7] Intelligence modern enterprise / S.D. Nikolaev, A.V. Zaitsev, V.V. Baranov, J. Kraft. M.: Publishing House "Komsomolskaya Pravda", 2010. – 252 p.

[8] Information Systems and Technologies: Scientific Edition. / Ed. Yu.F. Telnova. M.: UNITI, 2016. – 303 p.

[9] Mathematical methods of decision-making in the economy: Textbook / Under the editorship of V.A. Kolemaeva - 3rd edition, revised and enlarged. M.: Finstatinform, 2014. – 647 p.

[10] Ovechkin G.V. Computer Modeling: A Textbook. M.: Academy, 2018. – 432 p.

[11] Tolkachev S.A., Kulakov A.D. Robotization as a direction of neo-industrialization (on the example of the USA). // World of the new economy. 2016. № 2. – pp. 79 - 87.

[12] Ford Martin. Robots are advancing. Technology development and the future without work. M.: Alpina non-fiction, 2016. – 430 p.