Operational Management of Flexible Production of Machine-Building Enterprises Using the Analytical Method for Optimizing Work Order Planning Services

Lubov Mikhailova[1]

[1] Moscow Aviation Institute (National Research University), Moscow, Russian Federation

Correspondence: Lubov Mikhailova, Moscow Aviation Institute (National Research University), Moscow, 4, Volokolamskoe Highway, 125993, Russian Federation. Tel: 7-963-753-7110. E-mail: lubov999999@mail.ru, danonik92@mail.ru

Abstract

The analytic method of optimization of production process models is developed in this article. The purpose is the optimization of work schedule based on using mathematic methods in operational management of operational processes of flexible production systems in machine-building enterprises. The task of constructing an optimal production schedule for jobs is being considered (work modules or centers), which is the systems of operational management of flexible production' core. The author offers a model of the dynamics of the intellectual potential of the enterprise, which will improve the efficiency of its use and can be used as a tool for analysis and management of the company's intellectual capital in the process of innovative development. Theoretical and methodological base of researching the problem is the mathematic modeling and systematic approach, on the basis of which the specific features of interrelated factors are analyzed, which define the complex nature of flexible engineering, which are essential for development and realization the effective system of operational management. The proposed method can be used in improving operational management systems during the organization of flexible production and in the process of its functioning under various external and internal changes.

Keywords: modeling of the production process, operational management, flexible production, optimization of the schedule, model of the dynamics of intellectual potential

1. Introduction

The impending global economic crisis caused by the pandemic of the coronavirus Covid-19, according to forecasts of economists from all over the world, will lead the world economy to a deep recession. The International Monetary Fund predicts a record global slowdown by the end of 2020. According to the analysis conducted by the international insurance company Euler Hermes, such a global industry as mechanical engineering faces the greatest risk (Usman & Mikhailova, 2020). Serious risks arise due to the unstable situation in many end markets around the world and emerging problems on the demand and offer. This is because machine-building complex is the basic industry of developed countries' economy that provide a progressive development of all industries of the world economy that play an important role in providing defensive potentialities of their countries, including aerospace industry, fuel and energy complex, metallurgy, etc. (Kanashchenkov, Novikov & Veas Iniesta, 2019).

The fourth world industrial revolution that has begun (Schwab, 2016) assumes further development of technological platform, when the leading companies of the world actively use in their activity high-tech machines and high-tech equipment, innovative and information and communication technologies that provide digitalization and international economic integration. Moreover, in a pandemic, the speed of digitalization of the economy exists.

The effective use of intellectual potential as an important resource of enterprises determines the efficiency and competitiveness of enterprises (Mikhailova, 2006). According to the World Intellectual Property Organization (WIPO), intangible assets, including intellectual property, account for more than 90% of the added value of high-tech products, for which a significant part of the value is created during R&D.

The proposed model of the dynamics of the intellectual potential of an enterprise will improve the mechanism for the efficient use and management of intellectual resources.

Evaluation and determination of opportunities for the development of intellectual cooperation can significantly increase the value of the company, increase the effectiveness of innovative projects and the speed and flexibility of business processes.

This makes it possible to increase the efficiency of using the production capacities of modern machine-building enterprises. The proposed work is devoted to the urgent problem of using mathematical modeling in the management of production processes and should ask questions about where and when parts, assembled equipment and finished products should be processed. The task of modeling and optimization of production processes was solved in the division of Russian Aircraft Corporation MiG, including the Lukhovitsky Aviation Plant named after P.A. Voronin.

The basics of operational management of production resources are jobs (work modules, centers) in order to be able to use resources or provide production facilities (Chase, Aquilano & Jacobs, 1998).

The purpose of optimization the models of production processes often comes down to the choice of optimal order of processing parts and building a work schedule, i.e. to sequentially determining the time of the start of each batch of parts for processing and the completion of its processing at each workplace (module) of a flexible management system (FMS).

The methods used in practice for the formation of an optimal work schedule (vector optimization methods, linear and dynamic programming, combinatorial discrete programming methods, heuristic methods, Monte Carlo method, etc.) have a number of disadvantages: they are of limited use due to rapid growth sizes of models in connection with the growth of the scheduling task, require multivariate enumeration, not excluding a complete enumeration of all possible options, or give conflicting results and do not guarantee the achievement of a mathematical optimum. Eliminating these shortcomings and creating an effective operational-calendar FMS work plan will allow the use of an analytical method to optimize work order planning, which in turn will minimize the amount of resources consumed, work in progress, losses and comply with the established terms for production and delivery of products to consumers in specific production conditions.

At an enterprise, Workflow is equivalent to Cash Flow, and a calendar plan controls the Workflow. Therefore, a rational schedule of work is a prerequisite for successful business at all stages of the modern enterprise.

2. Features of the Development of Machine-Building Enterprises Based on Flexible Production Systems Using Intellectual Cooperation

The analysis of engineering industry development allowed revealing the following specific features and directions of development of modern engineering production that is essential for development and realization of effective system of operation production management:

1. Competition in all segments of the engineering products market is becoming more acute.

2. Wide automation and robotization of production processes.

3. Mass introduction of flexible production systems and automation design systems.

4. Intellectualization of production in the terms of the development of platform technologies, such as Internet of Things (IoT), Big Data, Mobility, cloud technologies, and additive technologies.

5. Most of the industry's main products belong to the high-tech and knowledge-intensive categories.

6. Loyalty of customers to companies directly depends on the innovativeness of the manufactured products of a wide range and types of the provided services.

7. High capital intensity of the engineering industry.

8. Significant increase in the importance of research and development (R&D) and the share of intangible components in the potential, resources, and products of enterprises.

9. For the development of FMS machine-building enterprises, intellectual capital is becoming more significant than physical.

All this imposes appropriate demands both to production systems and to systems of their management (Novikov & Veas Iniesta, 2019).

Flexible technologies and robotics are one of the basic (strategic) breakthrough innovations (Keisner, Raffo & Wunsch-Vincent, 2016). The flexibility of production system includes the following components:

1. Machine flexibility as an opportunity of automatic equipment changeovers for manufacture of new products of arbitrary nomenclature within the technical capabilities of equipment;

2. Technological flexibility as an opportunity of modification of the used technology;

3. Structural flexibility as an opportunity of modification of structure flexible production modules and/or flexible production cells;

4. Production flexibility as an ability of system to continue working in case of failures of individual components;

5. Route flexibility as an opportunity of changing the order of operations without redevelopment of equipment;

6. Nomenclature flexibility as an ability of system to produce a wide range of production and change it;

7. Volume flexibility as an ability of system to function effectively while changing production volumes;

8. Organizational flexibility as an adaptability of management and personnel system that is ready to promote innovation and expand its skills.

Over the past 30 years, a large number of systems have been created at machine-building enterprises of Russia, which developers consider to be flexible production systems. They are operated in various types of production: most on the machining of bodies of revolution and body parts, but also on automatic welding lines, hot and cold stamping, assembly, painting, etc. In Russia, among the high-tech machine-building enterprises that have achieved the greatest success in introducing integrated flexible production systems that include various types of processing: JSC Sukhoi Company, Russian Aircraft Corporation MiG, JSC Tupolev and other holding companies and aircraft repair enterprises of PJSC United Aircraft Corporation. FMS can be a flexible production complex on the level of workplace (site) or a whole production system made of several technological modules, connected together with transport, warehouse, instrumentation, and auxiliary modules (Novikov, 2019). FMS allows combining the advantages small batch and mass production (Heizer & Render, 1999). Wherein the flexible and economic production is made, mobility of production, growth in labor productivity, high quality of made production agreement with the following basic principles:

1. Consistency;

2. Specialization;

3. Proportionality;

4. Flexibility of technique, technology, and organization;

5. Modularity;

6. Effectiveness;

7. Hierarchy;

8. Integration of FMS with other systems: make an integrated production complex, i.e. full consolidation and harmonization of business-processes in order to optimize them (Nogueira Bastos, 2018).

Wherein the decision of the whole complex of management tasks, because information volumes are minimized on the basis of a broad unification of all elements of the production process and automation of production processes and management processes.

The effective functioning and innovative development of machine-building enterprises is determined by the high share of the intellectual component in their structure, as well as the effective use of intangible assets and intellectual capital (Zinchenko, Mikhailova & Sazonov, 2018). For example, while designing innovative production of JSC Sukhoi Company the share of intellectual resources is much higher than material and financial resources and has a tendency to further expanding. In these conditions, the implementation of effective intellectual capital management is highly relevant, which is a form of capitalization of intellectual potential. That is why for solving this problem there was made a model that is shown on the Figure 1, which illustrates the development of intellectual potential (PI) in time (T) referred to conditional object.

Let us show points Z on the graphics: special points that correspond to moments of change in the nature of the development of potential. Let us say, that in a moment $T_i=0$ the opening of a new object is made, for example, a material. The previous knowledge about this object is absent, therefore: PI=0, when $T_i=0$. Earlier the fundamental research of this new object was made. There is an increase of value PI. Line that goes through points $0 - Z_1 - Z_{12} - Z_{13} - Z_{14}$ characterizes the dynamics of the fundamental research in a period T_0-T_4. If we draw a perpendicular to the time axis T, for example, in a moment of time T_4, we get the segment $Z_{14} - T_4$. Let us call this segment a cluster of fundamental research. Let us agree that this cluster includes the results of all basic research

concerning the selected object, which is made in a period of time T_0-T_4.
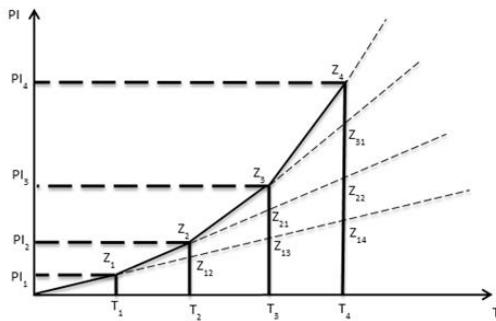

Figure 1. Dynamics model of intellectual potential in time

Let it be, that in the moment of time T_1 it gets clear, that usage of this object may has a practical application. And along with basic research, applied research begins. The cluster of applied research is set up. In the Figure the cluster of applied research is depicted for time T_4 by the segment $Z_{22} - Z_{14}$. In this cluster, the results of all applied research are concentrated, carried out in relation to the selected object until the time T_4. From the moment T_2 the stage of development begins, all development work is made, connected with the application of the object, in addition new products are being designed using this facility. A cluster of development work is being created, where the results of the design preparation of production are concentrated. This cluster with T_4 in the Figure is shown as a segment Z_{31}-Z_{22}. With T_i=T_3 begins the designing of object's production technology and products with its usage. Similarly to the previous stage, the cluster is created, where the results of the technological preparation of production are collected. In the Figure for time T_4, it is shown as a segment of line Z_4-Z_{31}. For the following stages of the life cycle of an object and products with its application, the schedule can be continued. The multi-user database created in this way will allow increasing the effectiveness of innovative activity of the company, saving and increasing scientific and technical experience.

The suggested model of development of intellectual potential gives an opportunity to point out and to evaluate individual levels of company intellectual capital management and can be built for any innovative process, during which products are created.

3. Analytical Method for Optimizing the Planning of the Work Sequence of Flexible Manufacturing Modules (FMM) of Machine-Building Enterprises

In the terms of medium and small batch multi-item production, whose specific weight is currently approximately 80% of the whole global engineering production. The main type of scheduling in these terms is detail-complete one. Planning unit is a part or assembly unit, for which time of launch of batches (series) in production and release time is determined. In significantly short assembly cycle, which is not more than one month, the shown model of planning is used, i.e., in fact, in this case the company manufactures products in batches periodically, or by consumers' orders, or for making and inventory replenishment (Chase, Aquilano & Jacobs, 1998). In this case, the planning and accounting unit of the assembly shops is an order for making one or some products, for processing and procurement workshops is a complex of details or blanks for order.

Making an optimal schedule plan is an actual task of operational management of flexible automatic production, which algorithmically comes to the choice of optimal sequence of launching batches of parts into production (Ford, 2015).

As an optimization criterion, it is better to accept the minimum of the duration of the whole production cycle (T_{pc}→min), because this one of the most important indicators reflects the quality of modeling and organization of the production processes (Mikhailova, 2005). Its optimization allows minimizing the volumes of the unfinished production, helps to fasten the turnover of working capital, makes premises for fast responding to changing consumer preferences (Ford, 2015), i.e., in fact, it indirectly takes into account most of the indicators that reflect the effectiveness of the production process.

For definiteness, we solve the problem of modeling and optimizing production processes for parts machining workshops of Lukhovitsky Aviation Plant named after P.A. Voronin, one of the branches of Russian Aircraft

Corporation MiG.

The most adequate form of the process organization in time is the model, which is built on the principle of parallel-sequential operations (Mikhailova, 2004).

The foundation of the operational production management automation is building of the production process model (Mikhailova, 2004), which comes to a description of the movement in time of the entire range of details by workplaces (modules), based on the nomenclature plan of start-up details in terms of flexible production systems.

Organizational and economic essence of the algorithm for calculating displacements on technologically connected pairs of workplaces (modules) of flexible production system consists of linking the process of processing batches of parts in such way that the beginning and the ending fulfillment of the next operations in the technological process would not be ahead of their beginning and ending on all previous operations, ensuring the fulfillment of the condition: $T_{pc} \rightarrow$min.

Wherein as a displacement in technologically related workplaces (modules) it is considered to be the time interval between the starting of processing parts at the transmitting workplaces (modules) and the beginning of the processing parts at the receiving workplace (module) of FMS.

That is why the following dependence can be taken to basis of calculating lead-time, which is shown as a formula (1).

$$b_i = \max \left\{ \begin{matrix} \sum_{i=1}^{i-1} t_i - \sum_{i=1}^{i-1} t_i \\ \sum_{i=1}^{i} t_i - \sum_{i=1}^{i} t_i \end{matrix} \right\} \tag{1}$$

where b_i is the value of the offset component (lead) of the launch of the i-th batch of parts;

t_i, t_i is processing time at the transmitting and receiving parts workplaces (modules) of the consignment of parts of the i-th stage, respectively.

During the derivation of formulas the following convention is used: while calculating values of the offset of launching the batch of parts in processing, the combination of points of beginning ($\sum_{i=1}^{i-1} t_i - \sum_{i=1}^{i-1} t_i$) or the ending one ($\sum_{i=1}^{i} t_i - \sum_{i=1}^{i} t_i$) of the process of the batch of parts with the same names on a technologically related pair of workplaces (modules). For deleting this dependence then to the found meaning we have to add the time of parts transfer processing (c_i), i.e., launch batch parts that are made for simultaneous intermodular transportation and continuous intramodular manufacturing. Construction features and characteristics of details and equipment determine the optimal size of the transfer batch. Finding of the optimal variant is made by methods of imitative modeling.

As a result, value b_i turns into the common meaning of offset (a_i), as it is shown in the following formula (2):

$$a_i = b_i + c_i. \tag{2}$$

While modeling real production system, using formula (1), the amount of knowledge bi is determined, which is equal to the amount of item names on every technologically connected pair of workplaces (modules). Because the desired offset has to be unequivocal, you have to choose the maximal value from all. Therefore, bj for any connected pair of workplaces (modules) has to be determined by the formula (3).

$$b_j = max\{b_1, b_2, \ldots, b_i, \ldots, b_k\} \tag{3}$$

Here b_1, b_2,…,b_i,…, b_k are the components of displacement (advance) of the start of a batch of parts that are determined the inequality of time for processing parts on a couple of workplaces (modules), which are determined by the details 1,2,…,i,…k-th queues of launching their batches into processing.

If now to the found meaning b_j we add time of part batch processing time that limits meaning b_j, than the previously accepted convention is not taken into consideration, the desired offset value (a_j) for any technologically connected pair of workplaces (modules) can be determined by the formula (4).

$$a_j = b_j + c_j. \tag{4}$$

Therein in real production terms the last workplace cannot coincide with all parts of the produced batches and start and finish not on the first and last workplaces (modules), but on any intermediate. That is why the calculation of the duration of the total production cycle (T_{pc}) will be made by the formula (5), but calculation of the duration of the production cycle of processing batches of parts of each i-th item (T_{ci}) by the formula (6).

$$T_{pc} = \max\left\{\sum_{j=1}^{j} a_j + \sum_{i=1}^{q} t_{ki} \times n\right\}, \tag{5}$$

$$T_{ci} = T_{pc} - \left(\sum_{j=1}^{j} a_j + \sum_{i=1}^{i-1} t_{ji} + \sum_{i+1}^{q} t_{ki}\right), \tag{6}$$

where: $\sum_{j=1}^{j} a_j$ is the amount of displacement (lead) of the start of a batch of parts at the j-th workplace (module),

which begins the process of processing a batch of parts of this name;

$\sum_{i=1}^{q} t_{ki}$ is the total time for performing operations of technological processes of manufacturing parts at the workplaces (module) that completes the processing process;

$\sum_{i=1}^{i-1} t_{ji}$ is the time of manufacture of a batch of parts, the launch of which precedes the given i-th batch of parts at the workplaces (module) that begins its processing;

$\sum_{i+1}^{q} t_{ki}$ is the time of manufacture of a batch of parts, the start of which for processing follows the completion of processing a batch of parts of the given i-th item at the workplace (module) that completes its processing;

q is the number of items processed by the system;

n is the batch launch parts;

k is the number of the workplace (module) at which the process of processing the details of this batch ends.

The calculation of the lasting of the production cycle of processing the r-th group of parts (T_{cr}) is made by the formula (7), and the calculation of the duration of the production cycle of processing the i-th batch of parts of each item from this r-th group of parts (T_{cri}) by the formula (8).

$$T_{cr} = T_{pc} - \left(\sum_{j=1}^{\lambda} a_j + \sum_{r=1}^{r-1} T_{\lambda r} + \sum_{r+1}^{m} T_{kr}\right), \tag{7}$$

$$T_{cri} = T_{pc} - \left(\sum_{j=1}^{\lambda} a_j + \sum_{r=1}^{r-1} T_{\lambda r} + \sum_{i=1}^{i-1} t_{\lambda ri} + \sum_{r+1}^{m} T_{kr} + \sum_{i+1}^{p} t_{kri}\right), \tag{8}$$

where: $\sum_{j=1}^{\lambda} a_j$ is the number of displacements at the j-th workplace (module), at which the process of processing a batch of parts of this item begins;

$\sum_{r=1}^{r-1} T_{\lambda r}$ is the processing time of parts of all groups of parts preceding the r-th group, which includes the i-th batch of parts at the workplace (module), which begins the processing process;

$\sum_{i=1}^{i-1} t_{\lambda ri}$ is the processing time of parts preceding this batch of parts of the i-th item at the workplace (module) that starts the processing;

$\sum_{r+1}^{m} T_{kr}$ is the processing time of the groups of parts following the processing of the r-th group of parts, which includes the i-th batch of parts at the workplace (module) that completes the processing process;

$\sum_{i+1}^{p} t_{kri}$ is the processing time of the parts, the processing of which follows the processing of this batch of parts of the i-th item at the workplace (module) that completes the processing;

λ, k is the number of the workplace (module) that starts and ends the process of processing parts of this group accordingly;

r is the number of the details group, for which the duration of the production cycle is calculated;

p is the number of names of parts in the r-th group;

m is the number of groups of parts.

In the foundation of the method, there is an assumption that the production cannot be fully synchronized: there are always work centers (modules), which limit the bandwidth ("narrow places"). For example, the production in the conditions of the FMS of Lukhovitsky Aviation Plant named after P.A. Voronin of each new batch of parts involves a readjustment of equipment and a set of necessary preparatory work. Downtimes for technical reasons may include the elimination of failures of certain types of equipment, work to prevent marriage, etc. The changing production terms lead to modification of the algorithms for calculating the duration of the production and aggregate production cycles. Therein, depending on technical processes of FMS downtimes can be formed firstly after processing groups of parts and secondly after processing batches of parts.

In the first case calculating of the duration of the total production cycle is made by the formula (9), calculation of the duration of the production cycle of processing each r-th group of parts by the formula (10), and the calculation of the duration of the production cycle of processing a batch of parts of each i-th phase of the launch in these conditions by the formula (11).

$$T_{pc} = max\left\{\sum_{j=1}^{j} a_j + \sum_{r=1}^{m} T_{kr} + \sum_{r=1}^{m-1} T_{Dkr}\right\}, \tag{9}$$

$$T_{cr} = T_{pc} - \left(\sum_{j=1}^{\lambda} a_j + \sum_{r=1}^{r-1} T_{\lambda r} + \sum_{r=1}^{r-1} T_{D\lambda r} + \sum_{r+1}^{m} T_{kr} + \sum_{r}^{m-1} T_{Dkr}\right), \tag{10}$$

$$T_{cri} = T_{pc} - \left(\sum_{j}^{\lambda} a_j + \sum_{r=1}^{r-1} T_{\lambda r} + \sum_{r=1}^{r-1} T_{D\lambda r} + \sum_{i=1}^{i-1} t_{\lambda ri} + \sum_{I+1}^{p} t_{kri} + \sum_{r+1}^{m} T_{kr} + \sum_{r}^{m-1} T_{Dkt}\right), \tag{11}$$

where Tλr, T$_{kr}$ is the processing time of the r-th group of parts at workplaces (modules) λ and k accordingly;

T$_{D}$ $_{\lambda}$ $_{r, TDkr}$ is the idle time of workplaces (modules) λ and k after processing the r-th group of parts accordingly;

T λ ri, t$_{kri}$ is the processing time of the i-th batch of parts of this r-th group at workplaces (modules) λ and k accordingly.

For the second case, when the downtimes' formation is made after the batch processing, corresponding calculation algorithms can differ and the formulas (9), (10) and (11) convert into the formulas (12), (13) and (14).

$$T_{pc} = max\left\{\sum_{j=1}^{j} a_j + \sum_{r=1}^{m} T_{kr} + \sum_{r=1,i=1}^{m,(p-1)} t_{Dkr}\right\}, \tag{12}$$

$$T_{cr} = T_{pc} - \left(\sum_{j=1}^{\lambda} a_j + \sum_{r=1}^{r-1} T_{\lambda r} + \sum_{r=1,i=1}^{(r-1),p} t_{D\lambda r} + \sum_{r+1}^{m} T_{kr} + \sum_{r+1,i=1}^{m,(p-1)} t_{Dkr}\right), \tag{13}$$

$$T_{cri} = T_{pc} - \left(\sum_{j=1}^{\lambda} a_j + \sum_{r=1}^{r-1} T_{\lambda r} + \sum_{r=1,i=1}^{(r-1),p} t_{D\lambda r} + \sum_{i=1}^{i-1} t_{\lambda ri} + \sum_{i=1}^{i-1} t_{D\lambda r} + \sum_{i+1}^{p} t_{kri} + \sum_{i}^{p-1} t_{Dkr} + \sum_{r+1}^{m} T_{kr} + \sum_{r+1,i=1}^{m.(p-1)} t_{Dkr}\right), \tag{14}$$

where $t_{D\lambda r}$, t$_{Dkr}$ is the idle time of workplaces (modules) λ and k after processing the i-th batch of parts included in the r-th group of parts accordingly.

The method of searching the optimal sequence of starting batches of parts for processing is offered, which is supposed to have such criterion as a base: $\sum_{j=1}^{j} a_j \rightarrow min$, because time for operations of technological processes does not depend on the order of processing batches of parts. Wherein, in order to determine the batch of parts that will be the first to be launched in processing, values are calculated $\sum_{j=1}^{j} a_j$ is isolated outside of the processing of the entire set of parts. The minimal values of the found will show which batch of parts hat to be launched in the first place. On the next iteration, there is the displacement calculation $\sum_{j=1}^{j} a_j$ for the sets of batches of parts, the order of which is not determined yet, with each of the remaining ones. On any iteration that batch of parts is launched into processing, for which $\sum_{j=1}^{j} a_j \rightarrow min$. As a result on the last iteration the production process model is formed, in which the sequence of starting batches of parts in processing is determined, the offset values are counted $\sum_{j=1}^{j} a_j$ on the whole set of technologically connected pairs of workplaces (modules) of the system and a work schedule has been built. Wherein, the searching of the minimal offset on every iteration must be accompanied by an analysis of the operational differences in the processing times of parts on technologically connected pairs of workplaces (modules) of the system: (t$_i$-t$_i$). In order to determine the minimal value $\sum_{j=1}^{j} a_j$ you have to take into consideration all possible combinations of calculated differences (t$_i$-t$_i$). For this you have to take into account the matrix building that has information on the operational differences in machining times (t$_i$-t$_i$) of each batch for all technological connections (rows of the matrix) for all names of parts (columns of the matrix). The formed matrix is the essential

element of the calculation of the time of displacement of the processing of parts.

There are possible four types of combining differences (t_i-t_i) of processing of parts on each pair of technologically related workplaces (modules) FMS.

The first case are the difference values (t_i-t_i) on this pair of technologically connected workplaces (modules) details of the i-th processing queue have a negative value and the detail (i+1)-th processing queue has a positive.

Table 1. First case of a combination of the quantities (t_i-t_i)

Workplaces (Work modules)	Details	
	A	B
1	2n	5n
2	3n	2n
$(t_i- t_i)$	-1n	+3n

The analysis of the operational differences of the times of production operations at technologically related workplaces (work modules) (W) shows that in this case the negative difference (t_i-t_i) of the i-th processing queue (A) acts as a compensator, i.e. can compensate the positive difference (t_i-t_i) of the details of the next processing queues (in this example it is B). For the first case, the compensator designated by Eq_A is 1n (Figure 2).
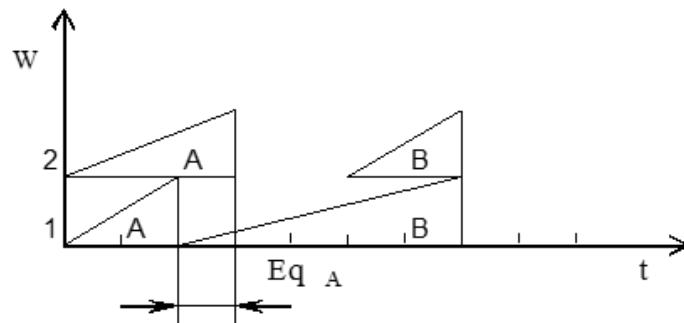

Figure 2. Scheme of the first case of the processing of batches (parts A and B)

The second case of the difference (t_i-t_i) of the i-th processing queue have a positive value and the detail of the (i+1)-th processing queue on technologically connected workplaces (modules) have negative value (Table 2). In this case, there is no compensator (Figure 3).

Table 2. Second case of a combination of the quantities (t_i-t_i)

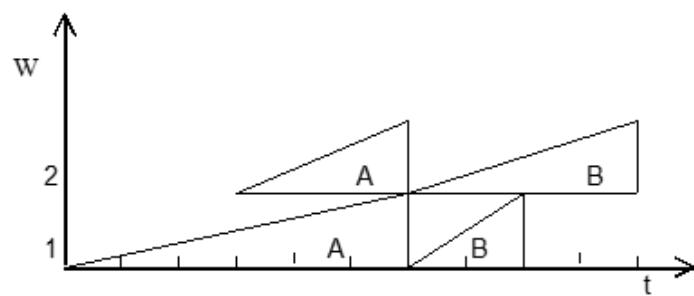| Workplaces (Work modules)	Details	
	A	B
1	6n	2n
2	3n	4n
$(t_i- t_i)$	+3n	-2n

Figure 3. Scheme of the second case of the processing of batches (parts A and B)

The third case of the difference (t_i-t_i) of the details of i-th and (i+1)-th processing queues on technologically connected workplaces (modules) have positive values (Table 3). In this case there is no compensator (Figure 4).

Table 3. Third case of a combination of the quantities (ti-ti)

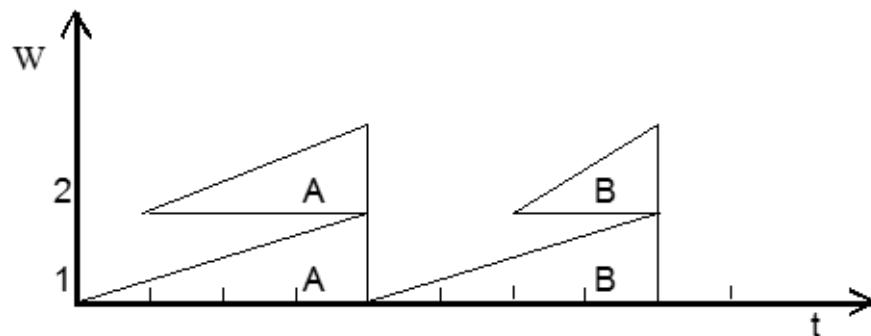| Workplaces (Work modules)	Details	
	A	B
1	4n	4n
2	3n	2n
$(t_i- t_i)$	+1n	+2n

Figure 4. Scheme of the third case of the processing of batches (parts A and B)

The fourth case of the difference (t_i-t_i) of these details of i-th and (i+1)-th processing queues on technologically connected workplaces (modules) have negative value (Table 4). This case is characterized not only by the presence of a compensator, but also by its accumulation. For the given example, the compensator (EqAB) is 3n (Figure 5).

Table 4. Fourth case of a combination of the quantities (t_i-t_i)

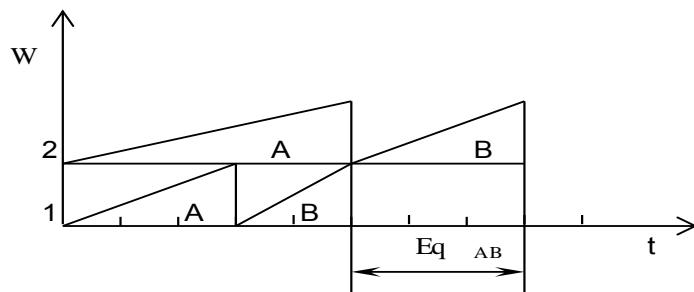| Workplaces (Work modules)	Details	
	A	B
1	3n	2n
2	5n	3n
(t_i-t_i)	-2n	-1n

Figure 5. Scheme of the fourth case of the processing of batches of parts A and B

Due to the analysis of the relation variants $(t_i\text{-}t_i)$ when optimizing the sequence of starting parts into processing by a computer program, there are performed actions, which are formed in the following four rules.

Rule 1. If in the next iteration that determines the order of launching batches of parts in production it turns out that any detail has only positive differences $(t_i\text{-}t_i)$, for all technological connections (matrix column), than such batch of parts (or lots of parts, if there are several) should be launched last, because such detail does not have compensators (negative differences), which can compensate for positive differences $(t_i\text{-}t_i)$ of details of the next processing queues.

Rule 2. If in another iteration of all details on any technological difference $(t_i\text{-}t_i)$ (matrix row) have only positive values, in this case while choosing the batch of parts of i-th queue the found values $\sum_{j=1}^{j} a_j$ are adjusted to these differences, because such differences without adjusting fully fit in these last values.

Rule 3. If in another iteration of any detail on this connected pair of workplace (modules) the positive difference $(t_i\text{-}t_i)$ (matrix row) in absolute value greater than the negative sum of the differences $(t_i\text{-}t_i)$, in this case the found sum $\sum_{j=1}^{j} a_j$ is adjusted by taking into account in its value only the absolute value of all negative differences $(t_i\text{-}t_i)$ on this connected pair of workplaces (modules).

Rule 4. If in any iteration there appears two or more minimums of $\sum_{j=1}^{j} a_j$, than firstly you should launch into processing that batch of parts, whose sum of negative differences $(t_i\text{-}t_i)$ in absolute value more, because it has bigger importance of compensators that can compensate positive differences $(t_i\text{-}t_i)$ of batches of parts of the following processing queues.

Thus, if the difference $(t_i\text{-}t_i)$ is positive, it goes into displacement, and if it $(t_i\text{-}t_i)$ is negative, then it not only does not enter the offset, but also compensates for the positive differences in the batches of parts of the following processing queues.

Practical implementation of the algorithm, carried out in parts machining workshops of the integrated company Russian Aircraft Corporation "MiG", allows us to conclude that the improving rules for optimizing the order of machining parts can reduce the production cycle by an average of 50%. Therefore, the use of the proposed improvement rules significantly reduces the duration of the total cycle of processing parts, as well as the cycle of manufacturing parts of each item.

As for the practical application of the proposed method, it can be noted that when optimizing the duration of the production cycle of producing details of many groups for solution of the given problem you have to, firstly, determine the optimal sequence of starting processed batches of parts by calculating the displacement (Y_r), and, secondly, link processing of all r groups of parts due to the formula (15), having determined the order in which batches of parts are processed. With this offset f_j in the j-th workplace (module) will be determined by the formula (16).

$$f_r = Y_r + \left(\sum_{r=1}^{r-1} T_r' - \sum_{r=1}^{r-1} T_r'' \right), \tag{15}$$

where T'_r, T''_r is the processing time of parts of the r-th group of parts at the transmitting and receiving workplaces (modules) of FMS accordingly.

$$f_j = max\{f_1, f_2, f_3, \dots, f_r, \dots, f_m\}, \tag{16}$$

Calculation of the looked for offset a_j will be conducted by the formula (17) by adding a component c_j, which considers part batch processing time.

$$a_j = f_j + c_j, \tag{17}$$

Thereby there is the solution of the determined problem in dynamics. In this case, the results of calculating the total displacement at each next stage are taken as the initial data when solving the problem at the next one. Thus, there is a calculation and optimization of the total displacements of parts inside each group, groups of parts inside each launch option and options for launching parts into processing.

The result of modeling and optimization of the processing of parts or assembly of assembly units is the formation of optimal work schedules of workplaces (work modules, centers) for the adopted control step. A work shift, day, week, etc. can be taken as a management step. The choice of the management step is determined by the organizational level of the particular unit of the enterprise and irreversible processes that violate the stability of the FMS management do not occur during the step. The pitch may change over time. The more stable the production process, the more the control step can be taken. For the adopted management step, work schedules of FMS workplaces (work modules, centers) are formed. The initial basis for their formation is technological information, including the size of the launch lot and the time of the displacement of the launch of the parts into processing.

The formed work schedule is a detailed model of the production process, it determines for each workplace (work module, center) how many and when parts should be processed. Given the perfect execution of schedules and the implementation of the model, we could restrict ourselves to the formation of such schedules. However, in real production conditions, it is necessary to identify and take into account deviations in various parameters due to the influence of external and internal disturbances, which involves making changes to the database and correcting the original (base) model, which is performed according to the described algorithm for modeling the production process. Thus, the operational control loop of the object under consideration is closed. This circuit can be schematically represented as Figure 6.
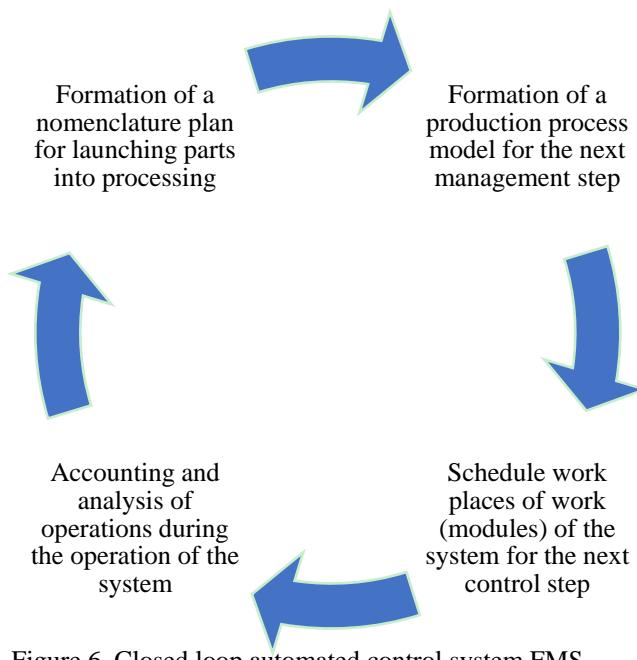

Figure 6. Closed loop automated control system FMS

4. Findings

Intellectual potential is a key innovative resource for the effective financial and economic activities of high-tech

enterprises in terms of functional and temporal characteristics. The resulting model of the dynamics of intellectual potential over time is universal in nature and can be used in managing intellectual resources on the scale of specific high-tech enterprises and the engineering industry as a whole, since it will contribute to enhancing the development of intellectual potential. The proposed model makes it possible to predict in the short term the direction of development of intellectual potential, taking into account the strategic priorities of innovatively active industrial enterprises.

The basis for the formation of a rational FMS operational management system is the production process model, which establishes the relationship between FMS resources, production process parameters and external control actions.

The analytical method for optimizing work order planning allows adequately displaying real FMS processes and generating optimal work schedules for the system's workplaces (modules) based on the developed production process model that takes into account the offset of the start times of processing batches of parts at the transmitting and receiving workplaces (modules) of the system. The experimental data obtained in the divisions of the integrated company MiG allow concluding that the proposed method is 2 times more effective than the one currently used.

General A closed loop of the operational management system for flexible production systems has been developed, which includes the following steps:

1. Forming of the nomenclature plan of launching parts into processing:
2. Forming of the production process module on another step of management;
3. Forming a schedule of operating of workplaces (modules) of the system for another step of management;
4. Accounting and analysis of operations with the functioning system.

5. Conclusions

In the result of the conducted research of modern features of engineering production, the author has worked out the model of the development of the enterprise's intellectual potential. The proposed model takes into account the stages of the life cycle of an innovative product, allows us to analyze in the process of time the creation of both the intellectual potential as a whole and its components. This model allows selecting the required intellectual resources on a competitive basis and increasing the effectiveness of the intellectual potential management of the company in the process of innovative development, which in modern conditions is an essential part of effective corporate management and ensuring strategic development and creating significant competitive advantages.

The proposed by the author analytical method of planning work order of FMS machine-building enterprises allows simultaneously with the calculation of priority to build the optimal work schedule, basing on the analytical modeling of the production process for different producing situations. The analytical method allows calculating the given problem, starting with any operating workplace (module). Determining the start time of each of the batches of parts for processing and the completion of its processing at each workstation (module) of FMS is carried out by analyzing and minimizing the displacement values under the considered conditions. Thus, in the model there is taking into account the mutual influence of operational times of machining parts, based on the analysis of all possible combinations, which in real production conditions formulated the relevant rules.

References

Chase, R. B., Aquilano, N. J., & Jacobs, F. R. (1998). *Production and operations management: manufacturing and services.* New York: McGraw Hill Series.

Ford, M. (2015). *Rise of the robots: Technology and the threat of a jobless future.* New York: Basic Books.

Groover, M. P. (2008). *Automation, Production Systems and Computer Integrated Manufacturing* (3rd ed.). London: Pearson Education.

Heizer, J., & Render, B. (1999). *Operations Management.* New York: Prentice Hall.

Kanashchenkov, A. I., Novikov, S. V., & Veas Iniesta, D. S. (2019). Technology formation of the mission of micro-level management enterprise in aviation. *IOP Conference Series: Materials Science and Engineering, 537*(4), 1-6.

Keisner, A., Raffo, J., & Wunsch-Vincent, S. (2016). Robotics: Breakthrough Technologies, Innovation, Intellectual Property. *Foresight and STI Governance, 10*(2), 7-27.

Mikhailova, L. V. (2004). Method of modeling production processes. *Organizer of Production, 1*(20), 11-14.

Mikhailova, L. V. (2005). Optimization of models of production processes. *Organizer of Production, 3*(26), 22-26.

Mikhailova, L. V. (2006). Some aspects of the innovative development of high-tech production of machine-building enterprises in Russia. *Scientific Works of the Free Economic Society of Russia, 74*, 211-225.

Nogueira Bastos, J. P. (2018). *Modular specification and design exploration for flexible manufacturing systems.* Eindhoven: Eindhoven University of Technology.

Novikov, S. V. (2019). Peculiarities of training of high-tech enterprise specialists under modern conditions. *IOP Conference Series: Materials Science and Engineering, 537*(4).

Novikov, S. V., & Veas Iniesta, D. S. (2019). Analysis of development trends in the innovation industry of the Russian Federation. *Amazonia Investiga, 8*(19), 298-307.

Schwab, K. (2016). *The fourth industrial revolution.* Geneva: World Economic Forum.

Usman, E. V., & Mikhailova, L. V. (2020). Risk assessment of investment projects of aviation industry enterprises using a comprehensive indicative approach. *Espacios, 41*(05), 28-38.

Zinchenko, A., Mikhailova, L., & Sazonov, A. (2018). Basic elements of the mechanism of management of the intellectual capital. *Bulletin of University, 10*, 23-27.