Models and Software Tools for Assessing Efficiency of Industrial Company Production Activity in Connection with Digital Technology and Manufacturing Use

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Abstract. The article considers models and software tools for assessing the efficiency of industrial company production activity in connection with digital technology and manufacturing use. The method allows assessing and comparing a whole set of permitted alternative options of innovative solutions on the introduction of digital technology and manufacturing at the stages of product life cycle and production development. The method is based on a set of mathematical models used to form the tools for equipping manufacturing processes with digital technology and manufacturing components; forming a total of partial criteria to assess the efficiency of the company production activity as a result of digital technology and manufacturing introduction; searching for an optimal problem solution. In terms of the structure, the process of manufacturing re-equipment with digital technology and manufacturing use is presented in the form of the algorithm for the assessment of digital technology and manufacturing introduction efficiency within the already existing or being developed corporate information system consisting of nine stages. The automation of the developed method is conducted with software tools MS Excel, MS Access, MS Project, C#. The method industrial approbation demonstrates its operation efficiency for solving various problems of the comparative assessment of innovative solutions at the design stages of a life cycle of items and manufacturings.

1. Introduction

At present the level of technical and technology development of the companies as well as their competitiveness is significantly defined by the level of automation and information&communication support of manufacturing processes the use of which is rationalized by the application of digital technology and manufacturing (DTM) [1-5, 11, 15]. The analysis of various approaches used by the companies to improve the operating efficiency shows that achieving significant progress in the activity results is possible by the transition to digital manufacture [3-9, 12-14, 16-20].

The key peculiarity of such manufacturing types is integrated information exchange between all process stages organized in the digital form only.

The production management complexity in these cases consists in the necessity to identify and establish a larger number of complex interconnections between manufacturing process parameters,
means of manufacturing operation technique and parameters of assessing the efficiency of industrial company production activity with the account of dynamically changing factors of the company external and internal environment. A key task is the procedure of synthesizing the options of problem solution with a subsequent evaluation of options on the total of selected efficiency criteria and taking into account the assumed limitations.

The purpose of conducting such events on the introduction of digital manufacturing technology at industrial companies is increasing the economic efficiency of the companies’ operation and product quality, reducing the time of making and launching new samples of the products, optimizing the use of available companies’ resources, mobilization reserves of production capacities, provision of the competitiveness at global markets.

The tasks of production digitalization include the tasks of making and introducing modern integrated information systems and advanced production technologies at the companies. Such systems and technology will cover all business processes and subdivisions existing in the company as well as all the life cycle stages of the manufactured products.

Digitalization in operation stipulates for the informational support directed at increasing the efficiency of business processes of economic entities (organizations, integrated structures, etc.).

However, according to the data in the available references today the ratio of expenses and digitalization efficiency is low, has long payoff periods and high risks of process information safety [7, 10, 13, 21-26].

In this connection, the relevant problem is economic&mathematical simulation of the decision making on production process instrumentation with the use of digital manufacturing and technology.

The research purpose is providing the efficiency of design solution development in digital technology and manufacturing and, consequently, the automation and information&communication support for industrial processes and manufacturings by means of simulation and research of the industrial company production activity with the use of mathematical simulation methods allowing to synthesize multiple permitted design options and subsequent selection of the optimal solution by a total of identified criteria via the implementation of a set of economic&mathematical models [21-31].

To achieve the aforementioned purpose, the following research objectives are stated in the paper:
- develop an algorithm for assessing the efficiency of DTM introduction within the framework of the existing corporate information system of the system under development;
- provide a rationale for the selection of a set of criteria to assess the efficiency of the industrial company production activity in connection with digital technology and manufacturing use;
- develop a mathematical optimization model for selecting an optimal innovative solution.

2. Method of assessing efficiency of industrial company production activity in connection with digital technology and manufacturing use

The means of digital production implementation are based on digital information technology. It consists of two components, software and hardware ones.

The hardware component, in other words, material and technical support of digital manufacturing, includes manufacturing equipment of various intended uses, such as machines, industrial robots, 3D printers, etc.: computers and office appliances - electronic computing machines, communication tools, information processing tools, etc.

The software component includes software complexes implementing the algorithms for formation and management of all information flows and design and manufacturing processes as well as the processes of making, transition and storing of the generated information, etc. In this case software means virtually all the technologies of international standard which allow operating in the design, simulation and generation of advanced manufacturing technology and cooperating with any company in the world in any economic sector.

The DTM development programme shall define the concept of technical, HR, structural and economic policies at the company, resolve long-term tasks of digitalization, serve as a tool of strategic development of the company, ensure a single methodical approach to defining the digitalization role in
achieving target indicators specified in the company’s development forecast, free choice of technical & economic solutions and means for building the company’s information and measurement system.

The DTM development programme at the company should be based on the real assessment of production potential for IT introduction the company has, including both internal factors (opportunities of funding digitalization events, business processes, computer literacy level of the company’s staff, technical facilities, management staff readiness, etc.) and external factors (level of digitalization of partner interaction processes, availability of IT companies and IT specialists in the region, etc.).

Introducing some or other means of digital production implementation has different impact on the company performance indicators.

The economic effects from DTM introduction can be divided into direct and indirect. Direct economic efficiency shall be understood as the reasonable use of material & labour resources and increasing the quality of products manufactured obtained due to the optimization of the company production activity. Indirect efficiency is reached by the optimization of extra-production company activity defining the reduction of losses for the company’s management functions. In the framework of this paper the authors consider modeling and simulation of direct economic efficiency.

The use of digital technologies and manufacturings as the means for increasing efficiency of production processes is possible at all stages of the item life cycle, including its development, design, etc.

In terms of the structure, the process of production re-equipment with DTM use is presented in the form of the algorithm for the assessment of DTM introduction efficiency within the already existing or being developed corporate information system consisting of nine stages.

At the first stage the bulk of reference data is formed. The data concern products, organization parameters of the production activity, tools at workplace equipment and external company conditions.

The second stage is the step of forming the system of partial criteria of production activity efficiency assessment as a result of DTM introduction.

A general system for the assessment of production activity efficiency criteria can include partial assessment criteria of two classification groups: characterizing the manufacturing process (temporary, economic, investment) and characterizing the production activity output (such as cost and quality parameters).

The third stage defines the formation of boundary values of the criteria for the system of production activity efficiency assessment and stipulates for the formation of permitted ranges of criteria values at which the efficiency of functioning will be deemed satisfactory. Boundary values are formed in compliance with current external and internal company factors.

At the 4th stage current values of partial assessment criteria are compared with permitted ranges and one should check whether the actual values of assessment criteria fall into the formed admissible value ranges on the basis of the calculations on analytical dependencies.

At the fifth stage a set of critical criteria is formed in compliance with the rule:

\[
\begin{align*}
[F_i]_{\text{min}} & \leq F_i \leq [F_i]_{\text{max}} \Rightarrow \Pi(F_i) = 0 \\
F_i & \leq [F_i]_{\text{min}} \lor F_i \leq [F_i]_{\text{min}} \Rightarrow \Pi(F_i) = 1 \\
\{i = 1, h; \Pi(F_i) \in [0,1]\}
\end{align*}
\]

where \(F_i\) – criterion of production activity efficiency assessment; \([F_i]_{\text{min}}, [F_i]_{\text{max}}\) - minimum and maximum permitted values of the criterion \(F_i\), correspondingly; \(\Pi(F_i)\) – binary variable; \(\Pi(F_i) = 1\) means that the criterion \(F_i\) is included in a set of critical criteria, \(\Pi(F_i) = 0\) – not included; \(h\) – number of criteria used by the system of the production activity efficiency assessment.

At the sixth stage one should search for an optimal combination of parameters of the existing organization of the company production activity (organization parameters) within existing DTM by a segregated set of criteria from the range obtained at the previous stage.

The seventh stage stipulates for assessing the class condition correspondence of the criteria values calculated at the previous stage (1). If due to the change of this group of parameters optimization purposes are not achieved, one should pass to the stage 8.
The stage 8 covers the change of a set of applied new DTM tools for production processes and search for their optimal combination by a total of selected criteria. The solution of the problem includes using the data bases on really and potentially available DTM equipment and technology. Really available equipment should be understood as instrumentation of manufacturing processes applied for the company production activity at the moment. Potentially available equipment should be understood as instrumentation for production processes which can be purchased by the company in a necessary volume and within reasonable terms.

At the final stage one checks the numerical values of criteria in terms of their correspondence to the condition (1) and forming an optimal combination of production system parameters.

For the implementation of the formed algorithm the authors managed to develop a set of economic and mathematical models:

- forming DTM elements for manufacturing process instrumentation;
- forming a set of partial criteria of the company’s production activity efficiency assessment as a result of DTM introduction;
- searching for the optimal solution of the problem.

The developed mathematical model of forming DTM elements for manufacturing process instrumentation is based upon a multi-layer graph-model of the net structure providing for the generation of options of sets by multiple alternative routes.

The graph-model \( G_t = (V, E, h) \) consists of a set of multiple points - DTM elements used to support manufacturing processes \( V = \{v_1, v_2, \ldots, v_n\} \), a set of multiple ratios – graph arcs \( E = \{e_1, e_2, \ldots, e_m\} \) defining the selection of DTM elements, weighting factors of graph arcs \( h \) showing the efficiency of innovative solutions (see Fig. 1).

For the mathematical statement of the problem it is reasonable to designate separate values of the weighting arc functions through the following: \( c_{ij} = h(e_k) \), where the arc \( e_k \in E \) corresponds to the ordered couple of points \( (v_i, v_j) \). As the values of \( c_{ij} = h(v_i, v_j) \) one can apply some functional or qualitative components from the inclusion of each DTM component in a partial company manufacturing process.

Multiple possible options of innovative solutions are simulated with a set of the graph alternative routes formed at successive transitions between the layers from the edge \( D_s \) containing the reference information to the edge \( C_t \) characterizing the selection of the optimal innovative solution option:

\[
\sum_{j=1}^{n} y_{ij} = 1, \ \forall i \in \{1,2,...,n\} \\
\sum_{i=1}^{m} y_{ij} = 1, \ \forall j \in \{1,2,...,m\} \\
\quad y_{ij} = \{0,1\}, \ (\forall i \in \{1,2,...,n\}, \forall j \in \{1,2,...,m\})
\]

(2)

The formed mathematical model (2) is defined at the set of Boolean variables and can be implemented by using the linear programing methods.

Figure 1. Graph-model of the forming of the DTM elements for manufacturing process instrumentation.
In a general case the programme of DTM development at the company should represent a system of scientifically justified and target reference points, contain the definition of key directions and development parameters:

- systems and means of “digitalization” of processes through all the life cycle stages of the output production (designing, pre-production engineering, planning and management of manufacturing, procurement, servicing, etc.) (edge $v_1=\{v_{11},..., v_{1n}\}$ of the graph $G_i$);
- electronic management of company documents and resources (labour, material and financial) (edge $v_2=\{v_{21},..., v_{2m}\}$ of the graph $G_i$);
- digital management of the company and, in particular, management of item production in the form of “digital factories” (edge $v_3=\{v_{31},..., v_{3k}\}$ of the graph $G_i$);
- integrated information system (IIS) of the company working in the real time mode and integrating all the automation systems available and planned for acquisition (edge $v_4=\{v_{41},..., v_{4d}\}$ of the graph $G_i$);
- systems of management of design and multi-project environment, means (technical, intellectual) necessary to achieve the set goals as well as organization & technical measures providing for a favorable environment of IIS functioning (edge of the graph $G_i$) (edge $v_5=\{v_{51},..., v_{5y}\}$ of the graph $G_i$).

In compliance with the graph-model $G_i$ the number of possible alternative routes corresponds to a set of multiple options of DTM completing taking part in the company production activity:

$$W = D_i \bigcup_{i=1}^{m} v_{ij} \bigcup_{i=1}^{m} C_i$$  \hspace{1cm} (3)

while a set of of multiple DTM options can be defined by a product of graph point sets:

$$V_w = D_i \cdot C_i \prod_{i=1}^{m} v_{ij}$$  \hspace{1cm} (4)

The expressions (3) and (4) are true for DTM introduction at all the identified stages of the company production activity.

Within the existing company the selection of an efficient innovative solution justified by DTM introduction should be implemented on the basis of the analysis of a set of performance and financial indicators. Within the group of performance indicators one should define the volume of manufacturing the products $Q$, in physical terms which is the function of the number of the equipment available $a$, equipment technically based performance standard expressed in the final product $H$ and the equipment load factor $K_{ij}$:

$$Q_i = f(a, H, K_{ij}) \rightarrow \text{max}$$ \hspace{1cm} (5)

In case of the equal volume of commercial production existing at the fixed state order the value $Q_i$ is the function of aggregate production capacity $M_{pr}$ and the equipment load factor:

$$Q_i = f(M_{pr}, K_{ij}) \rightarrow \text{max}$$ \hspace{1cm} (6)

The measure of the product output volume of the corresponding quality and range (in physical terms) is the company production capacity:

$$M_{pr} = \sum_{j=1}^{J} a_j \cdot H_j \cdot T_{ej}$$ \hspace{1cm} (7)

where $a$- number of the same-type devices, machines, units; $H$- technically based performance standard of the equipment (for the companies being built – performance standard in compliance with the manufacturer’s data sheet) expressed in the final product; $T_{ej}$- efficient fund of the equipment operation time, hour; $J$- set of the available equipment types;

The volume of the involved equipment in physical terms $A = \sum_{j=1}^{J} a_j$ for each option is defined at the stage of forming innovative alternative variants.

In a general case, providing other things being equal, the criterion of the maximum permitted volume of the manufactured products in physical terms can be characterized by the system:
\{a \to \text{max}, H \to \text{max}, M_{pr} \to \text{max}, K_{pr} \to \text{max} \quad (8) \}

The value of the obtained net output including depreciation \( NO(D) \):

\[ NO(D) = PM - M \to \text{max}, \]

where \( PM \) - volume of the products manufactured due to innovation application in monetary terms on the annual basis, rubles; \( M \) - material costs for manufacturing products on the annual basis, rubles.

The criterion maximization will be defined by the system:

\[ \{PM \to \text{max}, M \to \text{max} \quad (10) \]

The maximum of the manufactured product volume in monetary terms is defined by the maximum volume of the manufactured products in natural terms \( Q \), and the maximum retail price of the product unit \( P \). The condition will be the limitation of the product retail price by the threshold value \([P_m]\) - maximum price at which the market agrees to accept the item in the volume required by the company:

\[ P \leq [P_m] \quad (11) \]

The value of material expenses for a total product volume is defined by the volume of the manufactured items \( Q \) and the value of material expenses for the product unit \( c_v \).

The value of annual income can be defined by the difference of the volume of the net products obtained in monetary terms and the volume of the expenses of the material cost \( M \) and intangible cost \( C_{in} \) for a total volume of products:

\[ AI = PM - M - C_{in} \to \text{max} \quad (12) \]

The group of criteria characterizing the financial results of the innovative solution one can define the value of net income obtained by the company:

\[ NI = (I_v - T_b - P) \to \text{max} \quad (13) \]

where \( I_v \) - income obtained by means of the innovative solution implementation; \( T_b \) - total amount of tax paid to the budget and non-budgetary funds in part relating to the innovative solution implementation; \( P \) - total value of the amounts paid on committed facilities.

The indicator can be calculated on each considered period and for all the period of solution implementation. The indicator maximization is defined by the system of conditions:

\[ \{I_v \to \text{max}, T_b \to \text{min}, P \to \text{min} \quad (14) \]

The criterion characterizing the optimal solution on the net profit Income value \( NI \) can be stated as follows:

\[ NI = E - T_b - P \to \text{max} \quad (15) \]

Here \( E \) is the earnings before interest and taxes \( EBIT \) obtained due to the innovative solution implementation.

The criteria characterizing the value of gross income ratio \( K_e \), operating profit \( K_o \) and net profit \( K_{NO} \), can be written as follows:

\[ K_e = I_v / NO \to \text{max}, K_o = E / NO \to \text{max}, K_{NO} = NI / NO \to \text{max} \quad (16) \]

The optimal solution on the criteria \( (16) \) is characterized by the maximum value of the income, operating profit or net profit obtained by means of solution implementation at the minimum value of the total value of the manufactured products. The criterion characterizing the solution on the value of asset turnover ratio \( K_{at} \) is written as

\[ K_{at} = 2NO /(A_{ib} + A_{ve}) \to \text{max} \quad (17) \]

where \( A_{ib}, A_{ve} \) - correspondingly, the company assets as of the year beginning and end.

The optimal solutions are those characterized by the maximum value of the product volume at the minimum assets cost estimate:

\[ \{NO \to \text{max}, A_{ib} \to \text{max}, A_{ve} \to \text{max} \quad (18) \]

The criteria characterizing the optimal solution in terms of product profitability on the income \( R_{is} \), operating profit \( E \) and net profit \( NI \) can be written as:

\[ R_{is} = I_v / VP \to \text{max}, R_{o} = E / VP \to \text{max}, R_{NI} = NI / VP \to \text{max}, \quad (19) \]

where \( VP \) - sales volume for the products manufactured at the innovative solution implementation.

It is reasonable to calculate the values of profitability indicators both separately for each year of the innovative solution implementation (generation, development and operation) and as a total for a whole
period. The optimal solution in terms of product profitability criteria will be characterized by the system of conditions:

\[ \{ I_s \rightarrow \max, \ E \rightarrow \max, \ NI \rightarrow \max, \ VP \rightarrow \max \} \quad (20) \]

The assessment of the innovative solution on its investment component allows evaluating the potential of future investments into its implementation. The criterion characterizing the innovative solution justified by the DTM introduction in terms of the generated amount of the net discounted cash flow from the operating activity \( CFO \) within the certain period is formulated as:

\[ CFO = (CI - CO)/((1+r) \rightarrow \max, \ \quad (21) \]

where \( CI \) - cash inflow due to the operation activity; \( CO \) - cash outflow due to the operating activity; \( r \) - discount rate.

The indicator maximization can be described by the system:

\[ \{ CI \rightarrow \max, \ CO \rightarrow \min, \ r \rightarrow \min, \ \quad (22) \]

The criterion characterizing the value of investment profitability index \( PI \) can be written as follows:

\[ PI = \left[ \sum_{i=1}^{n} \frac{CFO}{(1+r)^i} \right] : [CAPEX] \rightarrow \max, \quad (23) \]

where \( CAPEX \) - Capital Expenditure.

The criterion defining the optimal solution by the internal rate of return \( IRR \) is written as:

\[ \sum_{i=1}^{n} \frac{CFO}{(1+IRR)^i} - \sum_{i=1}^{n} \frac{CAPEX_i}{(1+IRR)^i} = 0, \quad (24) \]

The optimal one will be the solution with a minimum internal rate of return \( IRR \):

\[ IRR \rightarrow \min, \quad (25) \]

For the solutions stipulating for the profit reinvested part in the course of project implementation on the solution implementation it is necessary to use the criterion characterizing the value of a modified internal rate of return \( MIRR \):

\[ \sum_{i=1}^{n} \frac{CAPEX_i}{(1+r)^i} = \sum_{i=1}^{n} \frac{CFO(1+d)^{n-1}}{(1+MIRR)^i}, \quad (26) \]

where \( d \) - reinvestment level.

The optimal solution will be the one characterized by the condition:

\[ MIRR \rightarrow \min. \quad (27) \]

The criterion characterizing the value of investment profitability index \( PP \) can be written as follows:

\[ PP_n = \frac{CAPEX}{\sum_{i=1}^{n} CFI_i} \rightarrow \min, \quad (28) \]

where \( t \) - period of solution implementation.

Taking into account (1), (2), in a general form the mathematical model of the problem of searching for the optimal solution of supporting manufacturing processes at the company with DTM components is the following:
Here $F_{ad}$ - additive convolution of preference criteria $F_i$ (5) - (28) formed by the condition (1); $k_i$ - significance factor of the $i$-the preference criterion; $h$ – general number of preference criteria. $k_i$ can take the values not only from the range $0 \leq 1$. As $k_i$ one could take individual weights of partial criteria, properties or DTM components. For example, $k_i$ can be a conversion factor into a single measurement system or can be used for the transfer of the quality criterion into the quantitative one.

3. Method implementation

When implementing the developed method, models and methods, the authors use the software products MS Excel, MS Access, MS Project, C#.

Selecting Microsoft Excel as one of the tools is explained by the availability of built-in functions and algorithms of the solution search, high accessibility and application visibility. MS Access was used as a main tool for forming data bases of reference and regulatory information on project indicators. MS Project was used as a main tool of the project calendar planning, tracking the as-built schedules and calculations of economic indicators of the innovative projects. The algorithm for assessing the efficiency of DTM introduction is implemented in the form of design software in the algorithmic language C#.

The developed models and software tools were applied for evaluating the efficiency of the company production activity in the real sector of economy. The authors considered the process of pre-production engineering (edge $v_i$ of the graph $G_i$) for the project of introduction of the robotic system of laser cutting.

The pre-production engineering process was divided into several stages: forming a 3D geometrical image of the product, selecting cutting way and technology, technical re-equipment and assessment of the production activity efficiency due to the DTM introduction at the manufacturing site.

The scheduled plan of the innovative project of DTM introduction and technological re-equipment means for a manufacturing site is equal to 2.8 years.

To optimize the parameters of the innovative solution rationalized by DTM introduction, the authors used simulation modeling of the company production activity under the mathematical model (29) stipulating for the representation of measurements in time of the outlined assessment criteria both in visual form as diagrams and in table form.

The result of simulation modeling is the selection of technical and organization parameters of the innovative project on DTM introduction providing for the following efficiency indicators of the company production activity: investment payback period of 1.5 years at the project general duration of 2.8 years; average rate of return $ARR=110.49\%$; internal rate of return $ARR=96.19\%$; modified internal rate of return $MIRR=49.86\%$; profit index $PI = 2.03$; net present value $NPV = 1,680,857$ USD.

4. Conclusions

As a result of the conducted research the authors developed a method for assessing the efficiency of industrial company production activity in connection with digital technology and manufacturing use.

The method is based on a set of mathematical models used to form the tools for equipping manufacturing processes with DTM components; forming a whole of partial criteria to assess the efficiency...
of the company’s production activity as a result of DTM introduction; searching for an optimal problem solution.

The industrial approbation of the method showed its efficiency at the solution of production tasks related to DTM introduction at various stages of product and manufacturing life cycles.

Further method development stipulates for the efficiency assessment of industrial company production activity in connection with DTM introduction within the national economy sector.

References
[1] Kapitanov A 2016 Special characteristics of the multi-product manufacturing Proc. Eng. 150 832–836
[2] Feofanov A, Milkina Y 2011 Planning of multi-product machine-building enterprise Econ. Manag. Mech Eng 1 5-7
[3] Negri E, Fumagalli L, Macchi M 2017 A Review of the Roles of Digital Twin in CPS-based Production Systems Proc. Manufacturing 11 939-948 https://doi.org/10.1016/j.promfg.2017.07.198.
[4] Kumari P, Shalini P, Prasad M, Yarlagadda K 2017 Digital Manufacturing- Applications Past, Current, and Future Trends Proc. Engineering 174 982–991 https://doi.org/10.1016/j.proeng.2017.01.250
[5] Choi S, Jun C, Zhao W B, Noh S D 2015 Digital Manufacturing in Smart Manufacturing Systems: Contribution, Barriers, and Future Directions In Advances in Production Management Systems Innovative Production Management Towards Sustainable Growth 460 21-29
[6] Delaporte P, Alloncle A P 2016 INVITED Laser-induced forward transfer: A high resolution additive manufacturing technology Optics and Laser Technology 78 33-41 https://doi.org/10.1016/j.optlastec.2015.09.022
[7] Kutin A, Dolgov V, Podkidyshev A, Kabanov A 2018 Simulation modeling of assembly processes in digital manufacturing Proc. CIRP 67 470 – 475
[8] Malaka R, Auricha J 2013 Software tool for planning and analyzing changes in manufacturing systems Proc. CIRP 12 348-353
[9] Härting R Ch, Reichstein Ch, Schad M 2018 Potentials of Digital Business Models – Empirical investigation of data driven impact in industry Proc. Computer Science 126 1495–1506
[10] Karpov A, Kharin A, Kharina O 2016 Educational environment forming on the basis of the human capital development SHS Web of Conferences 9 02019 https://doi.org/10.1051/shsconf/20162902019
[11] Kharin A, Kharina O, Rodyukov A, Petrova E A 2018 perspective model of innovative integrated structure comprising university, research facility and enterprise Mordovia university bulletin 28(3) 333-343 https://doi.org/10.15507/0236-2910.028.201803.333-343
[12] Yeleneva Ju, Kharin A, Yelenev K, Andreev V, Kharina O, Kruchkova E 2018 Corporate knowledge management in Ramp-up conditions: The stakeholder interests account, the responsibility centers allocation CIRP Journal of Manufacturing Science and Technology 23 207-216 https://doi.org/10.1016/j.cirpj.2017.12.002
[13] Korshunova E, Novoseltseva J 2016 The development of the technologic base of innovation-oriental industrial enterprise on the basis of agglomeration Innovation 8(214) 13-16
[14] Grigor’ev S, Dolgov V, Krasnov A, Kabanov A, Andreev N 2015 A method of technological audit of technical re-equipment projects in aircraft production enterprises Russian Aeronautics 2 244-250 https://doi.org/10.3103/S106879981502018X
[15] Kutin A, Dolgov V, Milkin V 2014 The Method for the Production Potential Evaluation of Multinomenclature Engineering Production. Avtomatizatsiya Sovremennyx Tekhnologij 6 27–33
[16] Rogalewicz M, Sika R 2016 Methodologies of knowledge discovery from data and data mining methods in mechanical engineering Manage. Prod. Eng. Rev. 7(4) 97–108
[17] Kujawinska A, Rogalewicz M, Kijewska J 2016 Application of expectation maximization method for purchase decision-making support in welding branch Manage. Prod. Eng. Rev. 7(2)
[18] Negahban A, Smith J 2014 Simulation for manufacturing system design and operation: Literature review and analysis J.Manuf. Syst. 33 241-261

[19] Mello C, Turrioni J, Xavier A, Campos D 2012 Action research in industrial engineering: design organization proposal for its application Production Journal 1 1-13 https://doi.org/10.1590/s0103-65132011005000056

[20] Trojanowska J, Kolinski A, Galusik D, Varela M, Machado J A 2018 Methodology of Improving Manufacturing Productivity Through Increasing Operational Efficiency of the Production Process, Advances in Manufacturing 22-32 https://doi.org/10.1007/978-3-319-68619-6_3

[21] Starzyńska B, Hamrol A 2013 Excellence toolbox: Decision support system for quality tools and techniques selection and application Total Quality Management & Business Excellence 24(5) 577–595 https://doi.org/10.1080/14783363.2012.669557

[22] Aqlan F, Al-Fandi L 2018 Prioritizing process improvement initiatives in manufacturing environment Int. J. Prod. Econ. 196 261-268

[23] Sanz-Calcedo J, Gonzalez A, Lonez O, Salgado D, Herrera J 2015 Analysis on integrated management of the quality, environment and safety on the industrial projects Procedia Eng. 132 140-145

[24] Kapitanov A, Mitrofanov V 2019 General Principles and Design Strategy of Optimal Reconfigurable Manufacturing Systems Lecture Notes in Mechanical Engineering 1347

[25] Bensmaine A, Dahane M, Benyoucef L 2013 A non-dominated sorting genetic algorithm based approach for optimal machines selection in reconfigurable manufacturing environment Comput. Ind. Eng. 66(3) 519–524

[26] Bensmaine A, Dahane M, Benyoucef L 2014 A new heuristic for integrated process planning and scheduling in reconfigurable manufacturing system Int J Prod Res 52(2) 3583-3594

[27] Lukina S V 2011 Automating procedures for formation and choice of structural component layout of modular cutting tools in step of technical preparation production Vestnik Saratov State Technical University 1 241-247

[28] Lukina S, Kosov M, Tolkacheva I 2019 Predictive modeling of design innovative solutions on tooling configurations at high-tech manufacturing companies Lecture Notes in Mechanical Engineering 1885-1893 https://doi.org/10.1007/978-3-319-95630-5_202

[29] Lukina S, Korshunova E, Dorozhkin I 2018 Methods of automated control over composition and structure of metalworking equipment MATEC Web of Conferences 224 01095 https://doi.org/10.1051/matecconf/201822401095

[30] Lukina S 2015 Formation of the system of the local indicators to assess the quality of the cutting tool at the stage of technical training of production Metal Working and Material Science 4 43-50 https://doi.org/10.17212/1994-6309-2015-4-43-50

[31] Lukina S 2015 The technique of optimizing of the production activity of industrial plant on the basis of a complex of predictive models of formation and selection of design innovative solutions in the field of high-tech industries Vestnik MSTU «STANKIN» 1(32) 125-129