Optimizing Cost and Quality of Innovative Solutions at Design Stages of Life Cycle of Engineering High-Tech Items

S Lukina¹, E Korshunova¹, I Dorozhkin¹, M Dobrolyubov², O Zimovets¹

¹Moscow State Technological University Stankin, 1 Vadkovsky line, Moscow 127055, Russian Federation
²Crimean Engineering and Pedagogical University, 8 Training lane, Simferopol 295015, Russian Federation

E-mail: lukina_sv@mail.ru

Abstract. The article develops a method for optimizing the cost and quality of innovative solutions at design stages of a life cycle of engineering high-tech items. The method allows evaluating and comparing a whole set of permissible options of innovative solutions on the basis of all partial and generalized criteria at the stage of production design engineering. The method is based upon a bipartite graph model of component interconnections in engineering high-tech items and the criteria of optimal option selection. To evaluate the options of innovative solutions, the authors form a set of partial criteria united in the categories: production criteria; investment criteria; criteria of evaluating the quality of manufactured products while using a high-tech item; economic criteria; financial criteria; criteria of evaluation on risk types; social criteria; environmental criteria; budget criteria; integral criteria evaluating the quality of an engineering high-tech item on the basis of all indices. To evaluate the cost and quality of innovative solutions, the authors form integrated efficiency functions presented as additive convolutions of partial criteria. The developed method is automated with the use of software tools MS Excel, MS Access, C#. The method industrial approbation demonstrates its operation efficiency and universal nature for solving various problems of the comparative evaluation of innovative solutions at the design stages of a life cycle of engineering high-tech items.

1. Introduction

The company’s innovative activity should result in achieving innovative aims stated in the development strategy by means of a high-quality organization of innovative processes. A key task is the procedure of synthesizing the options of problem solution with a subsequent evaluation of options on the total of selected criteria and taking into account the assumed limitations [1-5].

The innovative component of modern production is acquisition and production of engineering high-tech items with various intended uses, in particular, cutting and auxiliary tools, assemblies and units of process machines, etc. [2]

Any high-tech item is a complex-structured and expensive system the efficient operation of which depends on the accuracy and quality of actuation units and their structural component layout, i.e., the interposition of components in space in relation to each other. Various structural and parameter combinations form multiple structural designs (structures) of such items. The application of unit design principle allows increasing the equipment quality by means of a complete interchangeability of as-
Assembly parts belonging to one group and having the same typical size, decreasing the manufacture cost for such parts by means of the reduction of the production cycle duration [6-8].

On the other hand, under conditions of market economics and harsh competition it is not sufficient to manufacture and supply any new technological machine or tool structure to the market. To enter the market, meet competition and gain the profit, the manufacturer should guarantee that such new products have a range of properties, and the level of their indicators fulfill the demand of a consumer in the best way possible with the consideration of economic, environmental, social and other limitations [7-8].

A design stage of a life cycle of high-tech items in engineering is quite complex and labour-intensive as it requires synthesis and assessment of a larger amount of combinations of structural options and parameter values of acting mechanisms with the purpose of selecting an optimal option defining project innovative solution [9-11].

Most companies select innovative solutions applying investment analysis methods. Innovative solution here is considered as an investment project while the key analysis objects are monetary flows connected to its implementation [5, 6, 12-15]. Taking into account various directions and factors of innovative solution results, it is assumed quite reasonable to include other manifestations (technical, social, budget, etc.) in the scope of analysis.

The process of innovative solutions forming and selection is associated with the necessity of processing large information volumes. Quite frequently such information is not structured and versatile. A contemporary trend of solving such problems is an advanced application of scientific methods and approaches [1, 12, 17-19]. Models and tools applied in economic and company management problems are capable of resolving many tasks. Such tasks partially belong to innovative solution forming and selection, for example, the automation of technical production preparation, stores control, supply chain and risk management, and others [5, 11-15, 20]. However, the method and tools integrating the process of evaluating the cost and quality of innovative solutions at industrial companies should be developed more thoroughly.

The practical significance of the results of such research is formed by means of a growing demand on the part of existing companies.

Basing upon the aforementioned, it seems relevant to develop a method for evaluating the cost and quality of innovative solutions at design stages of a life cycle of engineering high-tech items. Such method development should include generating applied mathematical models and application of tools for their software implementation.

The article purpose is developing a method for evaluating the cost and quality of innovative solutions at design stages of a life cycle of engineering high-tech items on the basis of a set of mathematical models.

To achieve the specified purpose, the following research objectives are stated in the paper:
- forming a graph model of the component interconnections of engineering high-tech items and criteria of selecting an optimal innovative solution option;
- providing a rationale for a total of criteria to select an optimal option of an innovative solution;
- developing a mathematical optimization model to select an optimal innovative solution on a total of partial criteria of cost&quality.

2. Key provisions of the method optimizing innovative solutions cost and quality
The paper suggests selecting an optimal option of an innovative solution by means of the analysis of the vector efficiency function with the following type:

\[ F(x) = F_1(x), F_2(x), \ldots, F_N(x) \rightarrow \max(\min) \]

With

\[ F_i(x) = f(w_i(e)) \rightarrow \max(\min), \quad i = 1, \ldots, N \]
\[ w_i(e) = f'(p_1, p_2, \ldots, p_n) \]
\[ [p_{\min}] \leq p \leq [p_{\max}] \]
where \( F(x) \) – a vector efficiency function for evaluation and selection of the innovative solution from a range of formed options, \( F(x) \) – is a maximized or minimized partial evaluating criterion, \( w_i(e) \) – edge weight, \( p_j \) – management parameter; \( N \) – is a number of partial evaluating criteria taken into account within the problem; \( m \) – is a number of parameters characterizing the innovative solution.

Forming a system of partial evaluating criteria, problem control parameters and limitations for their values is an important task as it largely defines the obtained result [20-24]. A key requirement to the system of criteria is an integral character of the registration of any possible manifestations to minimize potential risks and damage.

Forming a system of evaluating criteria is simulated by a bipartite graph \( G=(V,E) \) given in Figure 1.

The nodes of a left part \( V_1 \) of the graph-model \( G=(V,E) \) form the characteristics of engineering high-tech item components, the nodes of a right part \( V_2 \) represent partial evaluating criteria for innovative solution selecting. The edges of the graph-model \( G=(V,E) \) show the interconnections between the components of engineering high-tech items and partial evaluating criteria. They also define the selection of an optimal option for a specific problem.

![Graph-model of the component interconnections of engineering high–tech items and criteria of selecting an optimal option](image)

Figure 1. Graph-model of the component interconnections of engineering high-tech items and criteria of selecting an optimal option.

In case of the graph model given in Fig. 1, one can show the correspondence of left and right part nodes, demonstrating the interconnections of high-tech items and partial criteria for software selection, in the form of a binary incident matrix developed in compliance with the rule:

\[
X_{v_j,v_{2k}} = 1, \text{ если } v_j \cap v_{2k} \neq \emptyset; \quad X_{v_j,v_{2k}} = 0, \text{ если } v_j \cap v_{2k} = \emptyset
\]  

Incident matrix general view is provided in Table 1.

|       | \( v_{21} \) | \( v_{22} \) | \ldots | \( v_{11} \) |
|-------|-------------|-------------|--------|-------------|
| \( v_{11} \) | \( X_{v_{11},v_{21}} \) | \( X_{v_{11},v_{22}} \) | \ldots | \( X_{v_{11},v_{2l}} \) |
| \( v_{12} \) | \( X_{v_{12},v_{21}} \) | \( X_{v_{12},v_{22}} \) | \ldots | \( X_{v_{12},v_{2l}} \) |
| \ldots | \( \ldots \) | \( \ldots \) | \ldots | \( \ldots \) |
| \( v_{1j} \) | \( X_{v_{1j},v_{21}} \) | \( X_{v_{1j},v_{22}} \) | \ldots | \( X_{v_{1j},v_{2l}} \) |

Each node of the right part \( V_2 \) of the graph-model \( G=(V,E) \) is a set of partial evaluating criteria united by a semantic content.
The system of partial evaluating criteria defining the selection of an optimal innovative solution includes the criteria on ten categories:

- **production criteria**, characterizing the way manufacturing activities are organized by an industrial company planning to operate an engineering high-tech item: volume of commodities production in physical and monetary terms, quality of manufactured products; load factor of fixed assets, duration of a production cycle, piece cost accounting time for item manufacturing, designed capacity, estimated capacity, idle capacity, material consumption factor, waste volume and other criteria.

- **investment criteria**, characterizing the results of innovative solution implementation with the account of money time value: net present value (NPV), internal rate of return (IRR), modified internal rate of return (MIRR), pay-back period (PB), discounted pay-back period (DPP), discounted cash flow (DCF), free cash flow to the firm (FCFF), free cash flows to the equity (FCFE), debt-service cover ratio (DSCR) and other criteria;

- **criteria for the evaluation of the manufactured production quality when using** engineering high-tech item: requirements on accuracy and quality, yield percentage and other indices.

- **economic criteria**: expenses for purchasing raw and other materials and their decrease comparing with similar products; expenses for staff remuneration and their decrease comparing with a precedent; expenses for maintenance and operation of floor spaces and their decrease comparing with similar ones; expenses for the services of contracting organizations and their decrease comparing with the similar ones; expenses for all types of regular preventive repairs and overhauls and their decrease comparing with similar expenses, and other criteria.

- **financial criteria**: earnings due to the implementation of a management decision on innovative solution implementation; net value of products manufacture, gross profit due to the management decision implementation, commercial expenses caused by the management decision implementation, control expenses connected with the implementation of a management decision, interests to be received because of the management decision implementation, interests to be paid because of the management decision implementation, other income due to the management decision implementation, other expenses because of the management decision implementation, income due to the management decision implementation net of taxes; net profit connected to the management decision implementation, profitability of the activity estimated by the net profit value; profitability of products estimated by the income, the amount of tax benefits which can be obtained due to the decision implementation, the amount of subsidies which could be obtained by means of the product manufacture assimilation; the value of excise payments connected to the decision implementation, customs payment connected with the implementation of the management decision, the value of environmental payments because of the implementation of the management decision, the value of environmental payments because of the management decision implementation, other criteria.

- **evaluation criteria on risk types**: technical unfeasibility, lack of investment financial resources, change in currency rates, mismatch of scheduled deadlines for program implementation with actual ones, mismatch of actual and estimated expenses, legislative risks, risks of change in the market situation; risks caused by partner dishonesty; lack of high-quality staff and other criteria;

- **social criteria**: number of created jobs, growth in the health level of employees, growth in staff qualification, level of staff satisfaction with employment terms and other criteria;

- **environmental criteria**: volume of polluting emissions, amount of nature-oriented payments, costs for waste treatment and other criteria.

- **budget criteria**: budget integral income, budget income on profit tax, budget income on added value tax, budget income on property tax, budget income on personal income, budget income on insurance payments and other criteria.

- **integral criteria** evaluating the quality of an engineering high-tech item on a total of indicators: intended use, reliability, producibility, unification, patent, safety, environmental, economic, ergonomic, aesthetic.
The intended use indicators characterize the key properties of such high-tech item defining its main functions and the area of efficient use and combine the systems of classifying, functional and construction indicators and composition&structural indicators.

Classifying indicators define a certain classification group (type, kind) to which an engineering high-tech item belongs.

Functional and technical efficiency indicators of such item characterize the structure efficiency in the period of operation as well as the progressiveness of technical solutions. Structural indicators reflect the level of design&engineering solutions; building-block design, blocking effect, interchangeability of structural components. The indicators of the composition and structure characterize the composition and structure of materials.

Reliability indicators define the stability of the quality of an engineering high-tech item due to the preservation of high indicators of the intended use during a set time interval. The tool reliability indicators should include the factors of reliability, service durability, maintainability and structure storage properties.

Ergonomic indicators characterize the properties of a man-machine system and take into account physiological, gynecological and psychological human traits at the interaction with an engineering high-tech item.

Aesthetic indicators reflect the level at which a human being perceives such item. These are also indicators of information expression, layout integrity and form rationality.

Productibility indicators characterize the properties of an engineering high-tech item which provide for an optimal distribution of material and labour resources during the life cycle. In the productibility indicators’ group one should distinguish the indicators of labour intensity, material intensity and net cost which could be presented in the form of consolidated, structural, specific, comparable and relative indicators.

Environmental indicators characterize the level of harmful impact on the environment arising at the operation of the machine engineering high-tech item.

Safety indicators characterize the properties of the item structure necessary to provide human safety at its operation.

Patent indicators characterize patent protection and the item structure patent purity.

The unification indicators characterizing the content of unified and original components in the structure, one should distinguish the capacity to the unification of body and fastening components with various options of abutting surfaces. The unification indicator can be limiting at the evaluation of the options of modular structures of machine engineering high-tech items.

In the general case the conclusion on a technical&economic level of an engineering high-tech item can be stated on the basis of the analysis of generalized efficiency criteria - net cost and metalwork performance.

To provide a broader estimate of the level of a designed structure quality when making a machine engineering high-tech item, it would be sufficient to calculate a generalized quality indicator $\Phi_K$ being an additive convolution of partial criteria:

$$
\Phi_K = \sum_{j=1}^{\Phi} \sum_{i=1}^{10} \Phi_j m_i \rightarrow \min ,
$$

where $\Phi_j$ — value of a partial efficiency function of the $i$-th quality indicator of an engineering high-tech item; $m_i$ is a weight parameter of the $i$-th quality indicator of the engineering high-tech item; $\Phi$ — general number of efficiency functions subject to accounting.

The provided list of partial criteria is not comprehensive, and it is possible to form additional criteria in the framework of practical problem solving. Due to a complex nature of the manifestation of innovative solution implementation results, in practice the system of evaluation criteria is seldom limited by one criterion which leads to a necessity of applying multi-criteria optimization methods.

In practice multi-criteria optimization problems are resolved with the help of specially developed methods of multi-criteria optimization [1]. The paper uses the method of additive convolution of criteria to solve a multi-criteria optimization problem:
where $k_i$ - significance factor of the $i$-th preference criterion; $h$ - general number of partial criteria from ten categories.

To obtain an optimal solution, the paper applies the following iteration algorithm:

- the first step is to form an efficiency function of the kind ($\psi_i(\phi_i(x), \phi_2(x), ..., \phi_m(x)) \rightarrow \max(\min)$), a set of preference criteria $\phi_i(x)$, $i=\{1,2,\ldots,m\}$ and limitations for their values;
- the convolution of criteria on (4) is formed;
- automatic defining of the point $x^k$ providing a maximum (minimum) value of the efficiency function $\psi_i$ and the value of a criterion vector $\phi_i(x)$ in this point;
- a decision-taking person (DTP) evaluates the obtained values of the criterion vector $\phi_i(x)$, and in case the result is admissible, it is accepted. In the opposite case the weight values and/or limit values can be changed.

A lexicographic mechanism of iterations can be added by preference criteria ranking. In this case the following steps are performed:

- the DTP ranks partial criteria in the descending order of priority, the criteria are numbered in compliance with the rank in descending order;
- further, one should define the optimal value of the first rank criterion $\max(\min)\phi_i(x)$ and a corresponding value of the parameter $x_1$;
- the optimal value of the second rank criterion at simultaneous fulfillment of the optimality by the first rank criterion $\max(\min)\phi_i(x)$;
- the procedure should be continued until the values of all the identified preference criteria are optimized;
- the obtained result is assessed by the DTP, after that the result is either accepted or the changes are made to the criteria composition of ranks.

A lexicographical iteration mechanism may be completed by a concession method which allows accounting the ranges of the criteria permissible values in addition to their absolute optimal values. In this case the following steps are performed:

- the DTP ranks partial preference criteria $\phi_i(x)$ in the descending order of priority;
- one defines the optimal value of the first rank criterion $\phi_i(x)$ and the corresponding parameter value $x_1$;
- further, the permitted range of the first rank criterion deviation from the optimal value (concession) $\Delta_1$;
- one solves the problem of obtaining an optimal value of the second criterion $\phi_i(x)$, the obtained solution $x_2$ maximizes the second preference criterion providing for a simultaneous obtaining of the first criterion within the range $\Delta_1$;
- the concession on the second criterion is set $\Delta_2$;
- the algorithm is implemented until all the criteria are analyzed.

3. Method implementation

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

The selection of Microsoft Excel as one of the tools is pre-conditioned by the presence of in-built functions and algorithms of solution searching, high availability and software visibility; this software package is installed on the user’s computer immediately after installing a Microsoft operation system.

The developed models and software tools were applied for evaluating the cost and quality of innovative solutions for the companies in the real sector of economy.

For example, when introducing a stand-alone subdivision at the existing machine builder, the authors set the problem of defining key parameters of a generated production system, including the se-
lection of process equipment, the company’s operation mode, procurement procedures under the condition of minimizing the amount of additional funding and forming a sufficient capacity to realize the production program. This problem was solved with the application of developed models, methods and software means.

The reference data in this problem are the following: scheduled labour intensity of the production program implementation, composition of the required manufacturing operations, necessary professions of employees and other parameters formed in the reference information system.

To solve the problem, the authors developed a graph-model $G_1 = (V, E)$ given in Fig. 2. The nodes of graph model parts representative to model parameters are: $V_{ij}$ - company’s operation mode; $V_k$ - are the characteristics of component suppliers. The parameters of manufactured products, process technology, production organization, staff composition, funding procedure forming the other nodes of the graph-model $G_1 = (V, E)$ are set in this problem. In addition, the set external variable is a mechanism of obtaining process equipment - equipment lease at the main plant.

![Graph-model of a problem of creating a stand-alone subdivision at the existing enterprise.](image)

In compliance with the task set by the DTP, the efficiency function for this research was formed in the form (5):

$$EF = \left[ PE_{\text{wp}} + CAP + \sum_{i=1}^{l} PC_i \right] \rightarrow \text{min} \quad (5)$$

where $PE_{\text{wp}}$ are the expenses for purchasing components and goods and materials; $CAP$ are the expenses for the displacement of the leased equipment; $PC_i$ is the volume of monthly expenses for the subdivision funding; $I$ is the duration of production program implementation in months.

In practice, the efficiency function defines a minimum volume of additional funding necessary for the implementation of a production program described by the parameters of the node $V_{ij}$.

Making up the procedures of component procurement to provide the necessary volume of goods and materials required forming a procurement plan for component purchase according to the estimates for machines and collection of commercial offers from suppliers at the research preliminary stage. A full list of components necessary for procurement was preliminary formed on the basis of the design documentation on each position of the output program. One should mention that a part of components was bought by the organized stand-alone subdivision directly from the existing company. The following characteristics were assigned to each unit of goods and materials for procurement: $PE_{\text{wp}}$ - component price; $DE_{\text{wp}}$ - price of delivery from the supplier’s storage to the storage of goods and materials of the organized subdivision, $\tau_{\text{wp}}$ - the period of component supply. The components with the same naming can be bought from various suppliers. The model limitations are supplier commodities stocks. With the purpose of automation of processing, price advantages with the characteristics of goods and materials are formed into the data base in the environment Microsoft Access.
The minimization of a partial evaluation criterion of the efficiency function (5) describing the amount of expenses for the procurement of components and goods and materials and corresponding limitations are defined by the expressions (6) and (7):

\[
PE_{ij} = \sum_{i=1}^{l} \sum_{j=1}^{J} \left( AM_{ij} \cdot PR_{ij} + TC_{AMij} \right) \rightarrow \min
\]  

(6)

\[
PR_{ij} \rightarrow \min, \ TC_{AMij} \rightarrow \min, \ \tau_{del} \rightarrow \min, \ \left[ AM_{ij} \right] \geq AM_{ij}, \ \sum_{j=1}^{f} {AM_{ij}} = [AM]
\]  

(7)

where \( i \) – naming of components (goods and materials); \( j \) – total amount of the component naming in compliance with the procurement plan; \( j \) – supplier from which one can purchase the components of the naming \( i \); \( AM_{ij} \) – scope of procurement of components (goods and materials) of the naming \( i \) from the supplier \( j \); \( PR_{ij} \) – price of the component (goods and materials) unit of the naming \( i \) from the supplier \( j \); \( TC_{AMij} \) – cost of delivery of components (goods and materials) of the naming \( i \) in the scope of \( AM_{ij} \) from the supplier \( j \) to the storage of the organized subdivision; \( \tau_{del} \) – period of delivery of components from the supplier \( j \) to the storage of the organized stand-alone subdivision; \( [AM_{ij}] \) – surplus stocks of components (goods and materials) of the naming \( i \) from the supplier \( j \); \( [AM] \) – necessary amount of the components (goods and materials) of the naming \( i \) according to the procurement plan.

The automation of the process of selecting the values from data bases on suppliers and components (see Fig. 2) under the conditions (6), (7) allows forming the component procurement procedure at suppliers.

The provision of process equipment to work places of the mentioned stand-alone subdivision required conducting technological production preparation at the research preliminary stage. The initial condition in the framework of this problem is the decision on selecting the method of equipment arrangement in a workshop by the types of process equipment (by sections). The selection of equipment for a production system was conducted with the application of the developed by the authors automated system for selecting work place equipment at industrial enterprises. At the preliminary research stage the equipment data base is formed. Each equipment unit was assigned a set of characteristics. For each type of machines both general and unique characteristics were identified. For example, to select gear hoppers, the authors form the following partial evaluating criteria (8):

\[
GM_{max} \rightarrow \max, \ D_{SG_{max}} \rightarrow \max, \ D_{HG1_{max}} \rightarrow \max, \ D_{HG2_{max}} \rightarrow \max, \ L_{SCR_{max}} \rightarrow \max, \ NUM_{MIN} \rightarrow \min, \ L_{ax} \rightarrow \max,
\]  

(8)

\[
D_{T} \rightarrow \max, \ D_{MVR} \rightarrow \max, \ SPD_{T} \rightarrow \max, \ S_{r} \rightarrow \min, \ S_{y} \rightarrow \min, \ PWE_{EE} \geq [PWE_{EE}], \ M_{r} \rightarrow \min, \ EE_{ax} \rightarrow \min,
\]

\[
L_{exp} \rightarrow \min, \ Cap \rightarrow \min, \ OP_{exp} \rightarrow \min,
\]

and their values limitations:

\[
GM_{max} \geq [GM], \ D_{SG_{max}} \geq [D_{SG}], \ D_{HG1_{max}} \geq [D_{HG1}], \ D_{HG2_{max}} \geq [D_{HG2}],
\]  

\[
D_{HG3_{max}} \geq [D_{HG3}], \ D_{WG_{max}} \geq [D_{WG}], \ L_{SCR_{max}} \geq [L_{SCR}], \ L_{SCR_{max}} \geq [L_{SCR}],
\]

\[
L_{SCR{max}} \geq [L_{SCR}], \ L_{SCR{max}} \geq [L_{SCR}],
\]

(9)

where \( GM_{max} \) – the largest module of a cut wheel on steel, mm; \([GM]\) – module of a cut thread required by the statement of work; \( D_{SG_{max}} \) – the largest diameter of cut spur gears; \([D_{SG}]\) – diameter of cut spur gears required by the statement of work; \( D_{HG1_{max}} \) – the largest diameter of cut spiral gears (30°); \([D_{HG1}]\) – diameter of cut spiral gears required by the statement of work (30°); \( D_{HG2_{max}} \) is the largest diameter of spiral gears (45°); \([D_{HG2}]\) – diameter of cut helical gears required by the statement of work (45°); \( D_{HG3_{max}} \) – the largest diameter of cut helical gears (60°); \([D_{HG3}]\) – diameter of cut helical gears, required by the statement of work, mm (60°); \( D_{WG_{max}} \) – the largest diameter of cut worm gears, mm; \([D_{WG}]\) is the diameter of cut worm gears required by the statement of work, mm; \( L_{SCR_{max}} \) is the maximum length of the spur gears rim; \( L_{SCR{max}} \), \( L_{SCR{max}} \), \( L_{SCR{max}} \) is the maximum length of the rim of cut helical gears, mm (correspondingly, 30°, 45°, 60°); \( NUM_{MIN} \) is the least number of cu teeth; \( L_{ax} \) is the
distance between the table and mill axes, mm; \( L_{fix} \) is the distance from the table plane to the mill axis, mm; \( L_s \) is the distance from the spindle rod axis to the support guideways, mm; \( D_T \) is the table diameter, mm; \( MVM_T \) – maximum table displacement, mm; \( SPD_T \) – accelerated table displacement, mm; \( S_{sx}, S_y \) are the overall dimensions of the table on its length and width, mm; \( M_{MT} \) – machine weight, kg; \( EE_{cas} \) is power consumption; \( L_{exp} \) – amount of monthly lease payments, rubles. (in compliance with the requirements of internal regulatory documents, it is defined at the preliminary research stage by means of obtaining independent market evaluation with the attraction of a specialized company); \( Cap \) – amount of expenses for the dislocation of an equipment unit; \( OP_{exp} \) is a statistical value of expenses for operation and machine servicing, rubles.

Selection was conducted with the following conditions fulfilled:

\[
\begin{align*}
\text{NUM}_T \cdot TF_{ef} & \geq [LI_T] \\
\text{NUM}_T & \rightarrow \min \\
TF_{ef} & = (N_k - N_{wk})D_{as} \cdot k_{abs}
\end{align*}
\]

(10)

where \( \text{NUM}_T \) is a number of machines of the type \( \tau \); \( TF_{ef} \) – effective fund of the company’s operation time; \([LI_T]\) – planned labour intensity of operations under a production programme. \( T_k \) – number of calendar days in a year; \( N_{wk} \) – number of day offs in a year (weekend, vacations, diseases, study leaves, failures to appear); \( D_{as} \) – duration of a work shift, h; \( k_{abs} \) – coefficient of working hours losses (reduced and pre-holiday working days).

The solution of a mathematical optimization model (8) – (10) is transformed into an algorithm in the software C#. Simulating the process of comparing innovative solution options was conducted by means of information computer processing tools.

In compliance with the results of a series of numerical experiments the authors select technical, process and organization parameters of the innovative project on the basis of which the existing machine builder organizes a stand-alone production unit with 248 equipment pieces serviced by operational staff totaling to 521 people. A required volume of additional funding is equal to 269.9 million rubles. The estimated project pay-back period is 1.5 years at its general duration of 5 years.

4. Conclusions

As a result of the conducted research, the authors form a method for optimizing the cost and quality of innovative solutions at design stages of a life cycle of engineering high-tech items.

The method is based on a set of mathematical models used for forming and selecting an optimum option on a total of partial and integrated preference criteria.

The method industrial approbation demonstrates its operation efficiency and universal nature for solving various production tasks.

The authors provide an example of applying research results while developing the project on generating a standalone subdivision of an existing machine-tool building company. The authors form a problem graph model, various options for achieving the project aims, efficiency functions of an optimal option, recommendations on the key parameters of a generated system. On the basis of application of the developed software products the research selects the means of equipping workplaces and calculating financial-economic indices of the subdivision functioning.

The subsequent development of the method suggests applying an integrated analysis and accounting for person-specific partial criteria and limits of special processing equipment and fittings as well as the adaptation of the obtained results in the problems of industrial park upgrade at the enterprises with a high level of internal cooperation (in particular, in the framework of uniting into corporate companies).

5. References

[1] Kapitanov A 2016 Special characteristics of the multi-product manufacturing Procedia 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] 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

[4] 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

[5] 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

[6] Korshunova E, Novoseltseva J 2016 The development of the technologic base of innovation-oriental industrial enterprise on the basic of agglomeration *Innovation* 8(214) 13-16

[7] Grigor’ev S, Dolgov V, Krasnov A, Kabanov A, Andreev N 2015 A method of technologic audit of technical re-equipment projects in aircraft production enterprises Russian *Aeronautics* 2 244-250 https://doi.org/10.3103/S106879981502018X

[8] Kutin A A, Dolgov V A and Milkin V A 2014 The Method for the Production Potential Evaluation of Multinomenclature Engineering Production, Avtomatizatsiya *Sovremennye Tekhnologii* 6 27–33

[9] 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

[10] 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) 29–33

[11] Negahban A, Smith J 2014 Simulation for manufacturing system design and operation: Literature review and analysis *J. Manuf. Syst.* 33 241-261

[12] 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

[13] Trojanowska J, Kolinski A, Galusik D, Varela M, Machado J A 2018 Methodology of Improvement of 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

[14] 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

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

[16] 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

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

[18] 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

[19] 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

[20] 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 I 241-247

[21] 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 https://link.springer.com/chapter/10.1007%2F978-3-319-95630-5_202

[22] 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

[23] 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

[24] 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 hightech industries Vestnik MSTU «STANKIN» 1(32) 125-129