Planning methods of modernization of industrial enterprises using graph models

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Abstract. This paper presents the methods of compiling programs aimed at modernizing industrial enterprises of various purposes. These methods help to form the entire sum of all permissible alternative options of modernization programs at initial stages for their subsequent evaluation and comparison. The basis of the method is a ten-graph model that defines a number of options for implementing individual structural components of the modernization program, such as the range of products manufactured, the technological process of manufacturing primary components, the main equipment, the cutting tools and accessories, organization of the manufacturing process, enterprise staff, suppliers of materials and components, financing plans for the modernization program, and the parameters of external macro environment of the enterprise in question. A mathematical model used to form a multitude of alternative options of modernization programs, employing algorithms of searching into the graph depth and width, has been developed. The developed method may be employed to form options for the modernization of industrial enterprises of various purposes. Industrial testing of the developed method has demonstrated its efficiency and flexibility in solving various problems linked to modernization of industrial enterprises.

1. Introduction

The development of industrial production makes it necessary to introduce timely and task-oriented changes into the established mechanism of operation of industrial enterprises. These changes may be implemented via modernizing specific industrial enterprises, which is an integral part of modernization of the country’s economy, including the transition to the 4.0 industry [1-4].

In all likelihood, the refusal to perform modernization will lead to a decrease in profits and bankruptcy of the enterprise in the foreseeable future, primarily due to a bigger technological lag, reduced competitiveness of products and inconsistencies in the level of organization of business processes and the level of technological leaders [5-10].

In practice, the majority of modernization programs, especially in their early stages, are put together in a very short order, and a large number of experts with various professional competencies are involved. Alternatively, they are created to complete more important objectives. These factors
reduce the likelihood of implementing an optimal enterprise modernization program and increase the
risk of making poor management decisions [11-14].

Setting up a modernization program for an industrial enterprise is a complex and multi-faceted
objective which requires analyzing and processing large chunks of information that reflects various
aspects of operation of an enterprise.

A modern trend to reach these objectives is the automation of searching for an ideal or an
acceptable solution using mathematical models and information technology [3, 17-21].

The rapid growth of information technology and market-oriented adaptation of production have led
to the development and implementation of enterprise information systems that combine components of
different purposes and degrees of complexity. However, as the review and analysis of available
sources has demonstrated, the Russian market currently does not have a set of tools needed to create
and select industrial modernization programs, which makes the decision-making process much harder
and, as a result, reduces its quality.

Thus, the task at hand is to develop tools necessary to put together and select an optimal
modernization program for industrial enterprises which would enable to unify all possible solutions
and then select the best one based on a reasonable system of preferences.

The goal of this paper is to develop methods and tools for setting up modernization programs for
industrial enterprises.

2. General provisions of the method
To solve the problem of putting together modernization programs, a cybernetic representation of the
activity of an industrial enterprise was used, which consisted in considering it as a ratio of the sets of
“inputs” W(t) and “outputs” Y(t) of the system. It is believed that, for an operating enterprise, the
dependence Y(W(t)) is of set nature, with the existing multitude of parameters Y = {y_1, y_2, ..., y_n},
explicitly defining the current status S(Y) of the system. Then, a control action over a system is
understood as a set of task-oriented measures leading to a change in the steady-state nature of the
dependence Y(W(t)) and transforming the system into one of the multitudes of its potential states S*(Y*). For an operating industrial enterprise, a modernization program may act as such an impact.
Due to various uncertainties, values of system parameters Y* = {y*_1, y*_2, ..., y*_n}, obtained as a
result of a control action may differ from those planned Y' = {y'_1, y'_2, ..., y'_n}. The measure of the
mismatch between the planned and obtained system parameters is a measure of the quality of the
control action performed.

The term “subject of modeling” refers to the variable components of the resource support for the
economic activities of an industrial enterprise: manufacturing assets (asset portfolio, facilities,
machinery and equipment, vehicles, inventory, etc.), manufacturing process, financial flows,
procurement, supply, marketing, innovation, and more.

An enterprise carries out economic activities in the framework of achieving strategic, tactical, and
operational goals. In the event that a positive decision is made to carry out modernization, an
algorithm used to create and select a modernization program based on deterministic relations between
the elements of the system is implemented.

The solution to this problem by mathematical modeling requires structuring and formalization of
the subject of modeling. In this study, the graph theory has been applied as an appropriate tool. It has
been chosen due to its wide practical application to problems characterized by a branched structure,
complexity of internal relationships, stochasticity and interval nature of the input data, and multi-
factor nature of the results [21].

In order to structure the formation of a set of elements of the industrial enterprise modernization
program, a graph-model in the form of a ten-long hypergraph G=(T, K) (Figure 1) has been developed.
A set of apexes Tp of each segment p of the hypergraph G=(T, K) determines the multitude of options
of implementing separate components of a modernization program. A combination of apexes \{t_{1i}, t_{2j},
\ldots, t_{10n}\} within each edge k∈K of the hypergraph G=(T, K) determines an alternative modernization
program for an industrial enterprise. A multitude of edges of the \( K \) hypergraph forms a multitude of options of alternative enterprise modernization programs.

Here is how segments (edges) of the \( G \) hypergraph are identified.

Apexes of the \( T_1 \) edge describe a range of products (in this case primary components) according to the following features: product name in accordance with relevant documents, material, overall dimensions, weight, quality of surface layer; accuracy of dimensions, layer, and location of surfaces relative to one another; hardness of surface layer, stiffness etc.

Apexes of the \( T_2 \) edge describe the process of manufacturing primary components: manufacturing operations, manufacturing steps and their order, component positioning method, cutting speed, feeding speed, and cutting depth for each operation; spindle RPM at transition, the number of operating strokes, cutting power, the parameters of coolants applied, and other manufacturing parameters according to a component type.

Apexes of the \( T_3 \) edge describe the main equipment: machine model, precision class, the number of controlled coordinate axes, threshold spindle RPM values, the number of steps of rotation rate, main drive’s engine power, the biggest weight of a component to be machined, tool storage magazine capacity, time of tool replacement, the biggest feed thrust by coordinates, the rate of quick displacement of working elements; overall dimensions, price, delivery date etc.

Apexes of the \( T_4 \) edge the cutting tools and accessories used in the manufacturing process: name, design parameters, geometric parameters, accuracy class; material of the working and the tail part; features of operation, regulated resistance etc.

Apexes of the \( T_5 \) edge describe the organization of the manufacturing process: type of enterprise’s manufacturing structure (domain-specific, technological, mixed); the degree of consistency of the product stock list; the degree of specialization of jobs; the principle of job distribution on sites; the degree of discontinuity of the manufacturing process; the principle of the distribution of labor during the operation; the method of introducing components into the manufacturing process etc.

Apexes of the \( T_6 \) edge describe the mode of operation of the enterprise: the duration of a work shift; the number of shifts per day; the number of working days per year; wage scheme; tariff rates; salaries; the size of the additional payments established by employment contracts etc.

Apexes of the \( T_7 \) edge describe the personnel structure of the enterprise: categories of workers; specialization, qualifications, working experience, competencies, level of education, results of employee certification etc.
Apexes of the T₈ edge describe the suppliers of materials and components: prices for each item of the stock list; product quality; the duration of after-sales service; supplier location; minimum number of items in an order; goodwill; history of relationship with the supplier etc.

Apexes of the T₉ edge describe the financing of a modernization program: source of financing (own funds, loaned funds, federal target programs, complex financing); amount of financing; interest rate; method of interest charge; due date for interest payment; due date for loan repayment; the value of economic benefit lost due to potential tidying up etc.

Apexes of the T₁₀ edge describe the parameters of the external macroenvironment of an enterprise: the values of taxes and fees applicable in the region; inflation rate in the region; current foreign exchange rates; possible tax preferences; requirements of regional legislative acts in terms of environmental protection; customs requirements; demographic situation; population trends in the region; climate features in the region etc.

Therefore, each alternative modernization program is characterized by associating various segments {t₁₁, t₂₂, ..., t₁₀₀} within the k ∈ K edge of the hypergraph G = (T, K), and the set of possible alternative modernization programs is described by a set-theoretic representation in the form of association:

\[ \{T\} = T_1 \cup T_2 \cup T_3 \cup T_4 \cup T_5 \cup T_6 \cup T_7 \cup T_8 \cup T_9 \cup T_10 \]

In each specific case, according to (1), a set of non-repeating parameters of alternative modernization programs can be formed as a set of workarounds for the graph G = (T, K).

The mathematical model of a set of workarounds of the graph G = (T, K) has been put together using the width and depth search algorithms in the form of the following expression:

\[
\begin{align*}
    k_j &\geq t_{ij} \quad \forall k_j \in K, \quad i = 1, T_{11} \\
    k_i &\geq t_{0j} \quad \forall k_i \in K, \quad t = 1, T_{10} \\
    k_a &\geq 10; \quad \forall k_a \in E \\
    k_{ip} \cup k_{ip} &\geq \emptyset, \quad l = 1, 10 \\
    k &\in K, \quad t \in T
\end{align*}
\]

The definition of apexes of the hypergraph G = (T, K) explicitly requires the accumulation and processing of large amounts of data. At the same time, the incompleteness of the analyzed data is likely to lead to an underestimation of the possible risks or the impossibility of solving the problem. Accordingly, a necessary element of model analysis for various scenarios is the creation and storage of an input data system, which makes it possible to clearly determine the parameters of the arising relationships of elements.

The need for storing, accessing, and processing large amounts of data can be implemented by any of the currently used database access systems, both client-server (Oracle Database, MS SQL, etc.) and the file-server ones (Access, Paradox, etc.).

3. Implementation of the method

MS Visual Studio, MS Access, C #, and MS SQL were used to implement methods and the developed models (1) and (2).

The developed models and tools were used to create programs for the modernization of enterprises in the real sector of the economy; to prepare projects aimed at creating a separate division of the existing machine-tool enterprise; to expand the machining production operating under the contractual basis; to expand the production capacity of an enterprise specializing in the production of equipment for processing section and sheet material; and to build a portfolio of business areas of an engineering company.
4. Conclusion
The factors that determine the structural composition of an industrial enterprise’s modernization program have been identified and described analytically. A graph-model used to create a set of elements of the modernization program has been developed.

An algorithm has been developed to put together alternative versions of the modernization program, taking into account the complexity of the structure of the simulation object.

The developed method helps initially to form all the many acceptable options for modernization programs for their subsequent evaluation and comparison.

Forming a set of preference criteria for evaluating options for modernization programs represents a development of the method.

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