Building the strategy for innovative development of industrial enterprises based on network planning methods

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Abstract. The article substantiates the need to adjust corporate development strategies, business models and production methods, caused by the influence of the fourth industrial revolution (Industry 4.0). Cluster and network structures are capable of ensuring timely digital business transformation. For effective integration into network interaction, it is necessary to form corporate strategies for innovative development based on an effective combination of strategic and operational planning using network methods. The article provides a comparative analysis of the critical path method, the method of evaluation and analysis of programs and projects, the method of graphical assessment and analysis, and the cyclical alternative network model. As a result of the study of network planning methods, it was revealed that the GERT-network modelling allows taking into account the risk factors and uncertainties, and the cyclical alternative network model allows to manage the level of risk and uncertainty. The two-level model of planning and management of industrial production proposed in the article, as well as the developed algorithm for solving the problem of interdepartmental production planning, can be used as the basis for the formation of a strategy for the innovative development of industrial enterprises.

1. Introduction

The fourth industrial revolution, gaining a global reach, is associated with large-scale changes due to digital transformation [1]. Under the influence of this process, international value chains are significantly changing, production systems are undergoing transformation [2]. Following the opinion [3], cluster structures, as a hybrid cooperation format, will not lose their relevance within the framework of the Industry 4.0 concept, but, on the contrary, will be used as an effective mechanism for digital business transformation.

To adapt to these changes, it becomes necessary to adjust national development programs, sectoral and corporate strategies, business models and production methods.

For timely integration into national and global value chains, companies should promptly adjust their corporate strategies for innovative development, taking into account the introduction of significant changes in production processes [4].

The problem of the prospects and feasibility of innovative development strategies is complex, in this regard, it is necessary to present a holistic picture of the implementation of an innovative idea [5]. Therefore, it is advisable to supplement the assessment of innovative strategies (without taking into
account the specific specifics and conditions of enterprise management) with an assessment of its feasibility and determination of the position of the enterprise in the external environment, which is a functional analysis of the need and capabilities of the enterprise to implement this strategy [6].

The results obtained in the course of evaluating innovative strategies make it possible to choose the most promising technology for implementation in production, find ways to reduce investment costs, and also ensure an increase in the economic attractiveness and efficiency of innovation [7-8]. In the process of implementing strategic programs for innovative development, a large number of external and internal risks arise. To reduce them, within the framework of this study, it is proposed to form a two-tier mechanism that allows the most effective combination of strategic planning with operational activities.

2. Methods
To form a strategic program for the industrial enterprises innovative development in the context of digital transformation, the research process used:

1) a systematic approach in the aspect of planning and managing the process of developing a new complex system (project, program) [7,9,10]. Such a process is considered as a single, indissoluble complex of interrelated operations aimed at achieving the ultimate goal, and the departments of specialists participating in it - as links of a single complex system;

2) the format of network models built on the basis of the presentation of the design process and the creation of a new object in the form of directed networks with given characteristics [9-12]. The use of network models makes it possible to obtain a logical and mathematical description of the process of creating a new object and to algorithmize the calculation of the main parameters of this process: its duration, labor intensity, cost.

In the course of the research, a comparative analysis of the Critical Path Method (CPM) [13], the Program Evaluation Review Technique (PERT) [13-14], the Graphical Evaluation and Analysis (GERT) [11], Cyclic Alternative Network Model (CANM). As a result of the comparative analysis, it was revealed that the models for the implementation of processes built using the above methods have different degrees of adequacy. The adequacy of the models to real processes depends on the degree of consideration of random factors. To fully implement the PERT network, like the CPM network, all arcs must be executed. It follows from this condition that such a model cannot include operations with feedback, since they are represented by loops, the existence of which, in turn, means that the final node of the operation must be executed before its initial node. When using the PERT method, as with CPM, there is no possibility of modelling a random sequence of works.

When modelling the processes of planning and production management, the most effective are network models with a stochastic structure. The GERT network can be classified as a control graph, which is a graph-analytical model with a sufficiently large number of input specifications. A stochastic network can be executed by executing a certain subset of arcs; in this case, the execution time of each arc is chosen in accordance with a certain probability distribution. In stochastic networks, for the execution of a node, it is not necessary to execute all the arcs included in it. Therefore, such models allow for the existence of cycles and loops.

The Cyclic Alternative Network Model is a development of the GERT model. In addition to the GERT method, CANM allows you to manage renewable resources and thereby vary the time of work execution. CACM is a finite, directed, cyclic graph, consisting of many events and arcs, which can be deterministic and probabilistic - alternative. The graph is built in accordance with the given technological constraints and conditions of the nodal logic. In the process of choosing a strategy for the innovative development of an industrial enterprise, it is proposed to use the method of matrix diagnostic analysis.

3. Results
The matrix model for choosing a development strategy in accordance with the assessment of the innovative potential of the enterprise and the prospects for implementing the strategy is shown in figure 1.
Strategy implementation prospects

High
High innovation potential / Good prospects. Leader's strategy (mastering innovation)

Low
Innovation potential / Good prospects

Doubtful
High innovation potential / Doubtful prospects

Deficit or absence of sources of cost formation / Doubtful prospects

The innovative potential of the enterprise

Figure 1. Matrix model for choosing a development strategy.

Industrial enterprises that fall into the 1st quadrant (a combination of high innovative potential and good prospects for implementing the strategy for mastering innovations) move on to drawing up operational plans, however, in the process of their implementation, external and internal risks arise, which necessitate reconfiguring the processes of manufacturing innovative products. Identification and classification of risk factors and uncertainties in operational planning and management of the production process allow for their accounting and formalization.

The transition to the procedure for drawing up operational plans involves a certain sequence of stages.

At the first stage, the interdepartmental control system (ISCS) solves the problem of determining, at the time of the receipt of an order for the manufacture of a product, the minimum permissible completion date for this order with restrictions on production resources. Resources represent specific equipment and personnel with previously planned work and time off. At this stage, for each work, an early start date and a late finish date – “time gates” are determined. The duration of work and operations at this stage includes the time of equipment changeover, the time of transportation of parts and assemblies between operations, etc.

The manufacturing process of manufacturing a product is represented in the form of a cyclic alternative network model - a cyclic alternative oriented graph, which allows simulating both random events in the process of manufacturing a product and random durations of production works and operations.

The second stage of daily shift planning and supervisory control takes place in the shop control system (SCS). The production tasks launched from the first level into the shop for a group of interchangeable equipment are a certain set of production operations that have relations of precedence and incompatibility with each other, indicating the “time gate”. For each pair of operations, the time of transportation of parts between operations, the time of changeover of equipment during sequential processing of these parts, is determined. The purpose of this stage is to draw up a shift (daily, weekly) production schedule within the workshop according to groups of interchangeable equipment that would satisfy the restrictions imposed from the first level - all operations must be performed within their own "time gates". In this case, it is possible that any operation will be performed on a machine that is different from that planned at the first stage.

It is possible to use different criteria when scheduling - uniform load of equipment, minimum number of changeovers, minimum number of machines used, etc. During the shift, this process can be run several times to adjust the schedules.

The input and output information for each level is presented in accordance with table 1.
Table 1. Input and output information of intershop and workshop control systems.

| ISCS Input                                                                 | ISCS Output                                                                 | SCS Input                                                                 | SCS Output                                                                 |
|---------------------------------------------------------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| 1. Specifications of all products. Based on the specifics:                 | 1. The “starting point” of the optimization in-shop search:                  | 1. “Time gates” - early start dates and late end dates for each operation of all products of one shift (half shift, weeks, etc.) | 1. Detailed dynamic in-shop schedule                                      |
| 1.1. For new technological operations, normalized (duration / labor intensity of production operations) operational technological processes of production of all products | 1.1. “Time gates” - early start dates and late end dates for each operation of a new product, including the end date for work on a new product |                                                                           |                                                                           |
| 1.2. For the rest of the operations - sampling of the execution times of these operations with the volume necessary to ensure the given level of significance (the last N values are taken for each operation) | 1.2. For each operation, the resource assigned to it is indicated           |                                                                           |                                                                           |
| 2. The volume of work in progress at the time of receipt of a new order - orders “in production” | 2. Calculated material requirements. Requests for the purchase of materials for a new product | 2. The list of the resources of the work centre (workshop, site, etc.), resource groups available for this shift | 2. For all operations - sampling the execution time of these operations |
| 3. Composition of the new order                                            |                                                                            |                                                                           |                                                                           |
| 4. The list of resources according to work centres (workshops, sections, etc.), resource groups, resource work schedules with indication of working and free time periods | 3. Unfinished production volume data                                        |                                                                           |                                                                           |
| 5. Warehouse stock status. Information on the availability of materials in warehouses, expected receipts of materials from suppliers, sampling according to the delivery times of materials from suppliers |                                                                            |                                                                           |                                                                           |

Orders from customers are processed at the ISCS level. It is assumed that the ISCS as a whole has information about the total capacity of a particular workshop or equipment groups. ISCS solves the following tasks: 1) ensuring supply chains of materials and components to the shops; 2) ensuring interdepartmental cooperation; 3) determination of the timing of orders.

The lead times are set based on priorities. Priorities are assigned to the ISCS, as its operators are more aware of the degree of importance and the need for accurate execution of a particular order.

Further, the SCS toolkit is used. Knowing in detail the real and predicted state of equipment and human resources in the workshop, taking into account the planned preventive maintenance of equipment, instrumentation, vacation schedules and other operational and tactical workshop information, detailed planning of production processes is carried out. This is necessary to achieve the following goals: to fulfil the tasks set from above (from the ISCS) as accurately as possible in this shop;
optimize production processes according to one of the in-shop criteria (maximum equipment load, minimum number of equipment used, uniform equipment load, minimum energy consumption, minimum changeovers, minimum movement of parts in the workshop, etc.).

After agreeing on the plans, the shop systems begin to work at the operational level (shop dispatchers, foremen, section managers). In the event of disturbing influences (equipment breakdown, work performed earlier or later than the specified date, marriage, etc.), in order to maintain the optimal production and minimize costs, the production process is repeatedly rescheduled at the workshop level. The shop floor system must fulfill the order readiness plan agreed with the inter shop system, re-planning the production processes at the expense of the shop's internal resources. And only if the internal resources of the workshop are insufficient to complete the production task on time, the SCS requests an adjustment of the production schedule for this workshop in the ISCS.

Thus, the schedule becomes dynamic and can change many times during the shift (planning and scheduling based on the real state of equipment and orders). At the stage of operational execution, the SCS in real time can provide information to the ISCS on the actual implementation of the current plan in various sections: for a specific order, for machines (downtime, work, repairs), for the volume of work in progress, for accounting for the in-house warehouse and the movement of materials from the machine to the machine, etc.

The use of the proposed two-tier mechanism allows for the most effective operational planning and management. The proposed model was tested at one of the Russian machine-building enterprises (on the territory of the Krasnoyarsk Territory). An example of a directed CANM graph obtained as a result of model approbation is shown in accordance with figure 2.

Figure 2. An example of a directed CANM graph obtained as a result of model testing.

A formal presentation of the methodology for drawing up an intershop production schedule will look like this.

1. The production model of the enterprise.
   1.1. Two finite sets O and R are set, the elements of which are, respectively, operations and resources (personnel and equipment). A set O contains all the operations that all resources from the set R can perform.
   1.2. The set O is divided into groups of operations \( \hat{O}_h \) \( (h = 1, g) \) and sets R into groups of possible executors \( \hat{R}_h(\hat{O}_h) \). The resource group itself can contain subgroups nested within each other.
   1.3. For each resource at any time interval, its own work schedule is determined.
2. Model of material and technical support of production.
2.1. A list of warehouses is set.

2.2. The level of stocks by warehouses and storage locations is analysed: a set of purchased components, semi-finished products and materials, as well as the number of “free” (not reserved for the production of other products) components or materials in the company's warehouses at a time \( t \) is set.

2.3. A sample is made according to the delivery times of purchased components and materials from suppliers \( t^{\text{supp}}_{\text{beta}} \).

3. Model of unfinished production.

3.1. A product specification is being developed - an assembly tree for each product, the need for purchased components, semi-finished products or materials for the product \( k \) is determined.

3.2. A cyclic digraph of the operational technological process of production and assembly of a product \( k \) is built.

3.3. The belonging of the arcs-jobs to one of the groups of operations is determined, a resource is assigned from the group of possible executors \( R_h(\partial_h) \) to perform this operation.

3.4. The norms of labor intensity, duration of operations are set (if the duration of this operation does not depend on the volume of the production resource assigned to it).

3.5. The “time gate” within which an operation can be performed is determined, taking into account the previously calculated “current” start and end dates of operations, as well as the early start dates and late end dates of operations tied to resources.

3.6. The coefficients of tension of all operations of the product \( k \) are determined. Since each product is represented by a separate CANM digraph, the operation intensity coefficients are calculated only from the account of this digraph.

4. Based on the data of clause 1 and clause 3, the equipment load factors are determined at specified time intervals.

5. Parameters of arcs are set in the CANM column.

5.1. In the CANM graph for a product \( k \) the probabilities \( p_{ij}^k \) of transitions from vertex \( i \) to vertex \( j \) are given, taking into account statistical production data on the percentage of successful production \( \rho_{cz} \), on the percentage of production defects \( \delta_{cz} \) (leading to a complete rework of this unit), on the percentage of production defects \( \vartheta_{cz} \) (leading to the completion of this unit).

5.2. On the basis of statistical data, the duration of operations is set in the CANM column.

6. The order for a new product is analysed. Similarly to paragraph 3, a product specification is developed, a cyclic digraph of the operational technological process of production and assembly of a product is built, labor intensity and duration of operations are set, preliminary dates for product shipment are determined, taking into account the wishes of customers.

7. The task of drawing up an operational production plan for the interdepartmental level is formulated: for a given level of reliability \( p \) (for example, \( p = 0.95 \) or \( p = 0.97 \)) it is necessary to determine the minimum possible completion date for a new incoming order, taking into account restrictions on equipment loading and supply of purchased components and materials.

8. The solution to the problem of drawing up interdepartmental production schedules for discrete production of custom-made type is carried out according to the following algorithm.

Step 1. We exclude alternative paths in the CANM column, calculate the approximate future duration and labor intensity of production operations.

Step 2. We calculate the requirements for materials. Determine the starting early start dates, late end dates of operations, their reserves, the critical path in the graph, the intensity factors of operations (at this step, the employment of resources is not taken into account).

Step 3. Determine the early start dates and late end dates of operations, including the dates of purchases of materials (this step takes into account the availability of resources and the possibility of their reallocation).
4. Conclusion

Thus, in the context of the digital transformation caused by the fourth industrial revolution (Industry 4.0), there is a need for a serious adjustment of industry innovation strategies, corporate development strategies, business models and production methods.

Cluster and network structures have high potential capable of stimulating technological progress and ensuring timely digital transformation of business [3]. At the same time, all network participants (industrial enterprises) need to reformat business processes and production methods, taking into account external and internal risk factors. These adjustments should be taken into account when forming corporate strategies for innovative development based on an effective combination of strategic planning with operational activities.

The study of network planning methods showed that GERT-network modelling allows to take into account the risk factors and uncertainties, and the cyclical alternative network model allows to manage the level of risk and uncertainty. The proposed two-level model of planning and management of industrial production makes it possible to link the tasks of strategic and operational planning. The developed algorithm for solving the problem of interdepartmental production planning allows reducing the level of risks and uncertainty by redistributing pools of renewable resources. According to the authors, a two-level development model and an algorithm for solving the problem of interdepartmental production planning can form the basis for the formation of a strategy for the innovative development of industrial enterprises.

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