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Development of Manufacturing Enterprises in the Context of the New Technological Revolution

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ABSTRACT: The purpose of this article is to provide tools that allow industrial enterprises to make an informed decision on their development. The paper uses the following methods: analysis, synthesis, abstraction, generalization, and graphic method. A selection of 27 factors determining the development level of a manufacturing enterprise has been carried out based on the analysis and generalization of literary sources, taking into account the opinion of the expert community. The selection has been carried out based on eight groups of factors. The paper presents an algorithmic model of the decision-making process for development, taking into account subject-object interaction. The model includes blocks of monitoring the development of an enterprise, including a database to accumulate the necessary information for decision-making. The central block of the model is the assessment of the development level of an enterprise. An original computer application developed on the basis of expert evaluation methods and fuzzy logic in the MathCad software environment has been used to assess the development level of an enterprise. The assessment can be used by an enterprise in the development and adjustment of the development strategy by modeling its development level with various allowable or possible changes in input indicators. A company chooses a strategy based on a comparison of the calculated values of the achieved development levels in different development scenarios. The model was tested and implemented at three Russian machine-building enterprises.

Keywords: Algorithmic model, Industrial enterprise development, Manufacturing industry, New technological revolution.

I. INTRODUCTION

Rapid transformations in all spheres of human activity allow scientists to declare the approach of a new technological revolution, characterized by the penetration of digital technologies into production [18]. Industry 4.0 involves the large-scale introduction of cyber-physical systems, thereby increasing the importance of information as a strategic resource for the development of regions and enterprises [12, 19]. Currently, there are many theories of the development of an industrial enterprise in the trends of the new technological revolution. Implementation of cyclic technologies in production is considered: water recycling, recuperation, purification and recycling of consumables, etc [1]. Particular attention is paid to the practical results of the introduction of elements of the cyclical economy in existing enterprises [14]. In some studies, it is noted that despite the attractiveness of a closed-loop economy under the conditions of limited resources and environmental risks, the current development level of some industries does not allow implementing the principles of this approach widely enough [15]. The "smart enterprise" theory is widely debated in the scientific literature [10]. It is pointed out that the barrier to the use of intelligent products in an industrial enterprise is largely the problems of the digital technologies themselves. For example, the Big Data effect as well as insufficient qualifications of employees [5, 17]. Issues of digital transformation at an enterprise and features of the structure of digital transformation are widely presented [19]. Many of them cite the results of the phased digitalization of existing industrial industries [6]. A large number of scientific articles review the development of industrial enterprises in the trends of the new technological revolution testifying, on the one hand, to the relevance of the topic and, on the other, to the existence of many unresolved problems.

Based on the Industry 4.0 platform, application scenarios are currently being developed, which enable the design and operation of industrial plants that can, if necessary, flexibly transform their production system, i.e., easily adapt to changes in the internal and external environment [2]. Such enterprises will be able to fully meet modern technological requirements and their products will meet the preferences of consumers. At the same time, it is important for active enterprises to implement approaches that allow for stage-by-stage (step-by-step) transformation [13]. Such a requirement is caused both by the need for stable functioning in the process of modernization and the limited resources for modernization. It should be noted that the introduction of any innovation requires the availability of appropriate resources: financial, personnel, temporal, and spatial. At the same time, the costs of an enterprise are borne immediately at the design stage of modernization and the return on investment occurs after some time. All this increases the requirements for the validity of the decision on enterprise development.

The purpose of this article is to provide tools that allow existing industrial enterprises to make an informed decision on their development in conditions of the new technological revolution and limited resources.

II. METHODS

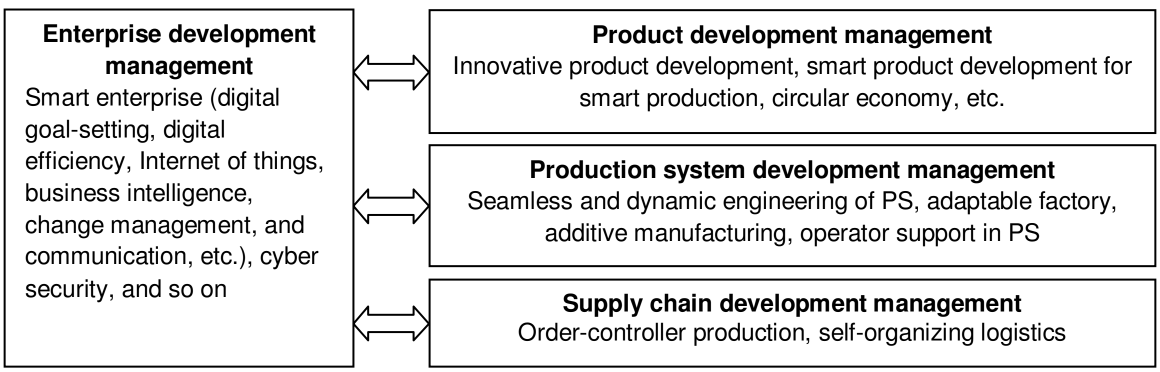
The study was carried out using the following scientific methods: analysis, synthesis, abstraction, generalization, as well as the graphic method. The selection of critical indicators of the development level of an enterprise was carried out using the method of generalization of literary sources and expert assessments [3, 9]. The classical method of fuzzy logic was used Zadeh (1996) [21] to assess the development level of an enterprise, which has proven itself in various management decision-making tasks for economic, environmental, and social processes under the conditions of dynamism and uncertainty of the external environment of an industrial enterprise [16]. Automation of assessing the development level of an industrial enterprise is implemented in the MathCad environment.

III. RESULTS AND DISCUSSION

As the analysis of literary sources shows, the development of an industrial enterprise can occur in various areas of scientific and technological progress. Practically feasible innovations in modern conditions relate mainly to products, production, and management.

The perception of the necessity for enterprise development as a condition for successful existence has led to the creation of development scenarios using Industry 4.0 in a new technological revolution. This takes into account the following main processes: enterprise development management (as an open system), product development management, production system development management, and supply chain development management (Fig. 1).

Appropriate resources are required to implement any of the scenarios. Purposeful transformations are determined mainly by the quality (competence) of management, achievements of an enterprise in the market environment (niche), and available resources (personnel, finance, raw materials, technologies, innovations, etc.). However, the mere possession of resources is not a guarantee that an enterprise will reach the desired level of development. The development level is determined by to what extent, with the available amount of resources, an enterprise is able to carry out certain transformations without compromising its sustainability, i.e. able to adapt and function smoothly.



Compiled based on Böhm *et al.*, (2018) [2]; Kusiak (2019) [10] and Vial (2019) [19].

Fig. 1. Application scenarios of Industry 4.0 in the management of the development of an enterprise, product, production system, and supply chain (PS – Production system).

Table 1: Indicators of the development level of an industrial enterprise.

Environment	Groups of indicators of industrial enterprise development		Indicators of the industrial enterprise development level
External environment (K_1)	Environmental impact of the enterprise (Z_1)		Emissions (X_1), waste (X_2), effluents (X_3)
	Environmental impact on the enterprise (Z_2)	Resource base (Y_1)	Provision of local natural resources (X_4), availability of external raw materials (X_5), availability of financial resources (X_6), labor resources (X_7)
		Political and legal environment (Y_2)	The legislative frame work of the Russian Federation (X_8), political and legal stability (X_9), international law (X_{10})
Internal environment (K_2)	Production subsystem (Z_3)	Production (Y_3)	Market (X_{11}), resource and energy intensity (X_{12}), innovativeness (X_{13}), product safety during the life cycle (X_{14})
		Technology & Engineering (Y_4)	Non-waste level (X_{15}), resource-saving (X_{16}), environmental safety of technologies (X_{17})
	Personnel subsystem (Z_4)		Professional staff (X_{18}), average salary (X_{19}), staff turnover (X_{20})
	Financial Subsystem (Z_5)		Fixed assets (X_{21}), intangible assets (X_{22}), finance (X_{23})
	Organizational subsystem (Z_6)		The share of research and development (X_{24}), the effectiveness of the management system (X_{25}), working conditions (X_{26}), information security (X_{27})

*Compiled based on literary sources (Husgafvel *et al.,* (2017) [8]; Demartini *et al.*, (2019) [4]; Yachmeneva *et al.*, (2019) [20] and the expert survey.

1. Selection of indicators for assessing the level of adaptive development of an industrial enterprise. The analysis of the literature on economic and environmental sustainability of an industrial enterprise Husgafvel *et al.*, (2017) [8] and its development in the trends of the new technological revolution Demartini *et al.,* (2019) [4]; Yachmeneva *et al.*, (2019) [20] made it possible to select indicators characterizing the development level of an industrial enterprise, as well as to group and build their hierarchy. At the same time, classes (K_i, i = 1, 2), their constituent subclasses (Z_i, i = 1–6), and subgroups (Y_i, i) (Table 1) were distinguished. For each of eight groups of indicators of the development level of an industrial enterprise (Z_i, i=1, 4–6; Y_i, i = 1–4), a primary set of factors was formed in an amount of 6 to 14 pieces. Sixty-five factors formed the basis of the questionnaire for the final selection of critical indicators. When assessing the factors, the experts had the opportunity to add their version to each group of factors.

Studies have shown that the involvement of experts associated with the object of research, but representing different spheres of activity, allows taking into account multilateral phenomena and obtain a balanced result. In this case, it is advisable to use the views of representatives of the scientific community and industry, as well as public service specialists [3]. Usually, 5-20 experts with diverse experience are involved [9]. In this paper, the selection of indicators was carried out using the method of expert assessment based on the opinions of seven professionals representing the following groups of specialists: manager-practitioners (representatives of machine-building enterprises of the southern region of Russia), teacher-researchers of a regional university, management of the analysis and perspective development of the Ministry of Industrial Policy of the region.

Based on objective data and practical experience, the experts individually assessed the significance of each factor in the group, giving the factor points from the maximum (unit) to the minimum (number of factors in the group) values. At the same time, expert estimates for different factors in the group could coincide. The completed questionnaires were initially processed to determine the degree of consistency of expert opinions on each group of indicators. Different approaches in scientific papers are used to confirm consistency. Given the importance of the concept, it is necessary to simultaneously use several indicators of consistency obtained by different methods in practical studies. In our case, when the assessment is carried out in points, it is advisable to carry out calculations of the variation range, coefficient of variation, and the Kendall rank correlation coefficient [7].

The calculations of the elements of the variation range P were carried out according to the formula:

$P=(p^k_j)$

where

$$p^k_j = \frac{\max\limits_{1\le i \ge 7}\left(\left|C^k_j - A^k_{i,j}\right|\right)}{C^k_j}100\%\ ,\quad C^k_j = \left(\sum_{i=1}^{7} A^k_{i,j}\right)\Big/7$$

$A^k_{i,j}$ is assessment by the i-th expert of the j-indicator of the k-th group of indicators; i=1,…, 7; k=1,…,8; j=1,…,m; m=(10, 6, 6, 8, 6, 8, 14, 7). For k = 1, the following values are obtained: P^1=(30; 0; 12.90; 12.5; 0; 8.7; 9.26; 0; 16.67; 10.26). It is believed that the magnitude of the variation range, i.e. the maximum deviation according to all expert estimates from the average modulus in percent, should not exceed 50%. Calculations of variation range coefficients have shown that this condition is satisfied for all indicators: $p^k_j \le 45\%$, k=1,…,8; j=1,…,m; m=(10, 6, 6, 8, 6, 8, 14, 7).

The coefficient of variation of estimates for the j-th indicator of the k-th group of indicators ((V^k_j) was calculated using the variance (D^k_j) and the standard deviation of the estimates (g^k_j):

$V^k = (V^k_j)$

where

$$V^k_j = \frac{g^k_j}{C^k_j}\ ,\quad g^k_j = \sqrt{D^k_j}\ ,\quad D^k_j = \frac{1}{6}\sum_{i=1}^{7}(A^k_{i,j} - C^k_j)^2$$

k=1,…8; j=1,…, m; m=(10, 6, 6, 8, 6, 8, 14, 7).

The results of calculations of the vector of coefficients of variation of expert estimates (V^k) for k = 1 are presented below:

D^k_j =(0.14; 0; 0.29; 0.28; 0; 0.29; 0.23; 0; 0.29; 0.28),

g^k_j=(0.38; 0; 0.54; 0.53; 0; 0.54; 0.49; 0; 0.54; 0.53),

V^1=(0.13; 0; 0.12; 0.11; 0; 0.08; 0.063; 0; 0.16; 0.10).

The calculated values of V^k, k = 1, ..., 8 do not exceed 0.25, i.e. meet the requirements for consistency of expert opinion.

In the theory of rank correlation, the degree of consistency of expert opinions is determined by the coefficient of concordance, using ranking in descending order of the ratings of each expert for each indicator. In our case, the ranking can be performed for all groups of indicators, because it is known that this procedure gives the most reliable results for the number of indicators m≤10 and the maximum allowable value for it is m=20. An algorithm was used to determine the Kendall coefficient of concordance (W^k), consisting in ranking the matrix of expert estimates for each group of indicators (k=1,..., 8) and sequential calculation of mathematical quantities: rank by the i-th expert of the j-th indicator (R^k_{ij}), sum of rank grades (S^k_j), arithmetic mean of sum of rank grades ($M^k[S^k_j]$), deviation of sum of rank grades (d^k_j), indicators of related (equal) rank grades (T^k_i). Calculation formula:

$$W^k = \frac{12\sum\limits_{j=1}^{m}(d^k_j)^2}{7(7(m^3-m)-\sum\limits_{i=1}^{7}T^k_i)}$$

where

$$S^k_j = \sum_{i=1}^{7} R^k_{i,j}\ ,\quad M^k\left[S^k_j\right] = \frac{1}{m}\sum_{j=1}^{m} S^k_j\ ,\quad d^k_j = S^k_j - M^k\left[S^k_j\right]\ ,$$

$$T^k_i = \sum_{l_r=1}^{L^k_r}(t^3_{l_r} - t_{l_r})$$

l_r=1,…,L^k_r, L^k_r is the number of groups of related ranks; t_{l_r} is the number of related ranks in the l_rth group.

The vector of calculated coefficients of concordance for groups of indicators contains the following coordinates:

$W=(W^k)=(0.96; 0.80; 0.81; 0.79; 0.77; 0.76; 0.78; 0.76)$. The calculated Kendall coefficients for each group of indicators have a value of at least 0.75, i.e. expert estimates can be trusted.

Thus, the results of vector calculations (variational range, variation coefficient, and the Kendall coefficient) showed the consistency of expert opinions and, therefore, the possibility of constructing a consolidated assessment of indicators. In this study, the method of determining the arithmetic mean with rounding to integer values was used for this purpose. Elements of the vector of generalized expert assessments were created according to the rule:

$$C_j^k = \frac{\sum_{i=1}^{7} A_{i,j}^k}{7}$$

where C^k_j is an assessment indicator of the generalized opinion of experts for the j-th indicator of the k-th group of indicators; $A^k_{i,j}$ is an assessment by the i-th expert of the j-th indicator of the k-th group of indicators; $i = 1, ..., 7$; $k = 1, ..., 8$; $j = 1, ..., m$; $m = (10, 6, 6, 8, 6, 8, 14, 7)$.

Based on the vector of generalized expert assessments, critical indicators were determined that have the greatest impact on the development of an industrial enterprise in the southern region of Russia. At least three indicators with the highest generalized scores were selected in each group of indicators. The requirements were taken into account: the total number of indicators – 27, of which the number of calculated – more than 50%. Further, the scheme of developing a consolidated expert opinion, well-proven in practice, was used. The results of the selection were compared with the opinion of each expert, reflected in their questionnaires, and it was supposed, in case of discrepancy, to pass it to the expert for discussion and possible changes. However, the opinion of the experts was highly consolidated and such an adjustment was not needed. Thus, the selection was made of the 27 most significant indicators (X_i, i=1–27), reflecting the influence of the main groups of factors of the internal and external environment of the industrial enterprise on the protection of the enterprise and, at the same time, determining its development (Table 1).

The selected system of indicators is balanced because along with economic indicators (availability of local natural resources, availability of external raw materials, availability of financial resources, labor resources, market, resource, and energy intensity, innovation, fixed assets, intangible assets, finance, share of research and development) contains environmental indicators (emissions, waste, effluents). The system of indicators also includes socially-oriented characteristics. For example, the Working Conditions indicator is introduced for an integral assessment: labor safety, labor protection measures, organization of response in emergencies, statistics on injuries and occupational diseases, level of compliance of working conditions with OHSAS 18001 standards.

The experts, on the basis of their experience, set dimensionless values of indicators X_i, i= 4-11, 18, 25, 26, 27 in the interval [0,1]. The remaining indicators (X_i, i = 1-3, 12-17, 19-24) are calculated according to the enterprise. Then, the calculated indicators must be normalized so that their values belong to the interval [0, 1]. For this purpose, it is possible to use, for example, the function $U(u)$:

$$U(u) = \begin{cases} \frac{1}{2}\frac{u}{u_0}, & 0 \le u < u_0 \\ 1 - \frac{1}{2}\frac{u_0}{u}, & u \ge u_0 \end{cases}$$

where u_0 is the average value of the normalized indicator (u) for the industry of the region to which the enterprise belongs.

It should be noted that the proposed system of indicators for assessing the development level of an industrial enterprise is quite flexible and allows quickly responding to the transformation of the internal and/or external environment of the enterprise. Corporate governance can make changes to the system of input indicators (X_i, i = 1–27), following new goals, objectives, current problems, emerging threats, and risks. It is possible to adjust various indicators, correlating with the degree of their importance for the enterprise in specific circumstances. The main requirement, in this context, is the balance of indicators in terms of quantity and their resultant impact in the group, to which they belong (Table 1). Moreover, a balanced system should be understood as a combination of them, which, besides the key success factors, provides the company's management with comprehensive information and analytical data for the formation of a development strategy.

2. Algorithmic model of decision-making on development. Making an informed decision on development, which allows developing a feasible realistic development strategy, should be based on a comprehensive analysis of an enterprise's potential. This is necessary for the quality implementation of the proposed development scenario in the context of the new technological revolution. Scenarios are predetermined by the chosen development strategy of an industrial enterprise, objective growth restrictions, subjective reasons, features of the internal and external environment of an enterprise, environmental requirements, etc. At the same time, the passed and planned stages of development and the corresponding position of the industrial enterprise (initial, intermediate, desired), as well as the degree of protection of the enterprise (i.e. it's level of safety), are taken into account.

Thus, decision-making on development is an important process that must be provided with the necessary information, systematization, and accumulation. Modern conditions are characterized by high dynamics; therefore, enterprises must constantly monitor their development level and make adjustments, both in current activities and in development plans. Formalization of decision-making at an enterprise allows simplifying this process, making it as streamlined as possible. The algorithmic model of decision-making on development represents the necessary actions and their sequence thus allows using the digital technologies in the development management system. Besides, the algorithmic approach to recording is quite clear and, therefore, does not require special knowledge to adjust and adapt the development management model. Fig. 2 presents an algorithmic model of decision-making, built on the basis of the subject-object interaction. The model contains a database for the accumulation of information on development, as well as monitoring units 2, 3, and 4 for carrying out the enterprise self-assessment development.

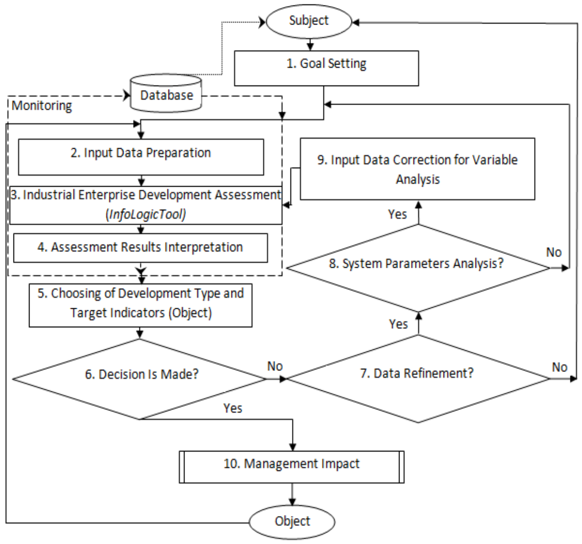


Fig. 2. Algorithmic model of the decision-making process on development taking into account subject-object interaction.

The model includes setting goals for the development of an industrial enterprise (block 1), preparing the necessary information for decision-making X_i, i=1–27 (block 2). To determine the indicator "enterprise development level" (R) (block 3), we used the method of fuzzy logic and expert estimates, while fuzzy sets were constructed using the classical approach Zadeh, 1996) [21] and trapezoidal membership functions [16]. The study applied a four-level hierarchy of input data. All variables that are at the tops of the Fuzzy inference tree by levels from fourth to first are linguistic: R, $K=\{(K_i)_1^2\}$, $Z=\{(Z_i)_1^6\}$, $Y=\{(Y_i)_1^4\}$, $X=\{(X_i)_1^{27}\}$. The following measurement scales were used to adequately reflect the correspondence of qualitative indicators to the characteristics of real objects: five-level (for linguistic variable R: low, below average, medium, above average, high) and three-level (for all others: low, average, high). All membership functions were set on the universe A= [0,1]. Calculations at each vertex of the Fuzzy inference tree were carried out using the classical Mamdani algorithm Manan *et al.*, (2019) [11] including the operations Fuzzification, Aggregation, Activation, Accumulation, and Defuzzification. When implementing the calculations, the output variable of the lower level becomes the input for the highest level of the hierarchy. The Mamdani algorithm was applied 13 times in the system of the logical conclusion of the assessment of the industrial enterprise development level. The InfoLogicTools computer program was developed in the computer modeling environment MathCad, which was composed of modules and automates the process of assessing the level of enterprise development. No additional personnel training is required for the evaluation and the computer user's knowledge is sufficient since it is only necessary to set the values of the input variables (X_i,i=1–27). At the same time, program modules can be easily replaced, if necessary, for example, to change the appearance of the membership function.

The evaluation results allow the company to assess its capabilities to achieve development goals, choose the direction and target factors-objects for development (blocks 4, 5). If it is not possible to make a development decision (block 6), then the enterprise either changes the development goals (go to block 1), or carries out an additional analysis of the system parameters (block 9), or additional information stored in the enterprise database is entered into the analysis. If a development decision is made, then the corresponding managerial impact is carried out (block 10). The response of the control object to the impact is evaluated, recorded in the database, and transmitted to the control subject for decision making.

An algorithmic model of Fig. 2 should be used to develop an enterprise development strategy and adapt existing development scenarios in the conditions of a new technological revolution. For this, it is necessary to carry out calculations for various transformations of critical parameters that are possible for the enterprise. The results obtained should be compared and the most acceptable one for the company should be chosen.

IV. CONCLUSIONS

The analysis of scientific literature on the development of industrial enterprises in the new technological revolution, problems in the development of Russian enterprises, as well as the use of the method of expert assessments, allowed choosing the factors in the process of research that determine the development level of an industrial enterprise. A total of 27 indicators were selected. Of these, estimated indicators accounted for more than 50%. The values of the remaining indicators are determined by experts who may be employees of the enterprise itself. Grouping of the selected factors allowed building their four-level hierarchy, which formed the basis for assessing the development level of the enterprise. Our original computer program was used to assess the level of development of an industrial enterprise, built in the MathCad environment based on the classical method of fuzzy logic. The assessment can be applied in forecasting for the selection of strategy of development of the enterprise and adaptation of existing approaches and scenarios of development of the industrial enterprise in the conditions of the new technological revolution. For this purpose, it is necessary to carry out calculations at various possible transformations of critical parameters. The results obtained should be compared and the best scenario should be chosen for implementation.

The proposed algorithm of managerial decision-making takes into account subject-object interactions. The object is selected based on development goals and resource, spatial, temporal, and other capabilities of an enterprise. The object can be adjusted as a result of, for example, monitoring. The subject is the management system, which can include employees at the first stages of the transformation of the enterprise in the trends of the new technological revolution. The management system must be fully automated when implementing a "smart enterprise".

The suggested algorithmic model of the decision-making process on development is tested on data of the industrial enterprises of the machine-building complex of the southern region of Russia. The implementation of the algorithm and the InfoLogic Tools program at three existing enterprises in the region showed the effectiveness of the proposed tools and contributed to the implementation of a phased innovation and technological transformation by the enterprises in conditions of limited resources.

In further studies, it is planned to develop principles and models for the integrated development of the existing production enterprise in the trends of the new technological revolution.

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