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Industrial Enterprise Development Management under Digitalization

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Abstract*: The development of an industrial enterprise in order to meet modern requirements should include the components of its digitalization. In Russia, the development of digitalization is supported at the state level. Meantime, limited resources require industrial enterprises to have a sound approach to choosing the direction of their development. This paper presents a methodology for choosing the direction of development of an industrial enterprise, which is based on an assessment of the level of development of that enterprise. An assessment of the level of corporate development is carried out using the method of fuzzy logic and the method of expert assessments. A nonlinear algorithm was used to find an integral indicator of the level of development of an industrial enterprise and choose a direction of development. The assessment process is digitalized and does not require special knowledge and skills of the corporate employees for its implementation. At the same time, it is possible to make adjustments to the indicators that determine the level of development of the industrial enterprise. An assessment of the level of development of an industrial enterprise is implemented in the original InfoLogicTools application in the MathCad simulation environment. Production tests of this application at existing industrial enterprises have allowed making some design changes to the application. The proposed methodology has a practical application. It allowed 3 Russian engineering plants to monitor their development. The monitoring results formed the basis for development activities. Further research is supposed to analyze and develop digitalization of the collection of information on the development of the enterprises.

***Keywords*: development, management, industrial enterprise, digitalization.**

I. INTRODUCTION

Development based on advanced technology and innovation strengthens the competitiveness of an industrial enterprise. Currently, the global trend in the development of industrial enterprises is digitalization [1], [2]. In Russia, the relevance of digitalization is recognized at the state level [3], [4]. The country has launched three national programs that define the vector of long-term scientific, technological and economic development. The Russian industry leaders in implementing the digital transformation strategy are the banking sector and the enterprises developing information technologies. In industrial sectors, digitalization is developing less intensively [5]. Existing industrial enterprises are forced to simultaneously digitize their analog information and digitally transform their businesses [6]. According to experts, the main barriers to the digitalization of the Russian industry are the lack of integration of new and existing technologies and data, the complexity of existing scientific developments for practical use and the low level of competence and knowledge among enterprise employees in this area [7]. The limited resources of industrial enterprises require a sound approach to choosing the direction of development [8]. The development strategy should be based on the real capabilities of an enterprise, which can be identified by assessing the level of corporate development.

The aim of this study is to present a methodology for choosing the direction of development of an industrial enterprise, including an assessment of the development level of an industrial enterprise that does not require special skills of corporate employees for its implementation in the enterprise, since the assessment process is digitalized.

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II. METHODS

In the framework of the digitalization of industrial enterprise development management, it is necessary to formalize as much as possible all the components of the management process. Only in this case, digitalization can be successful. In addition, the high speed of creation and development of technologies leads to rapid, unpredictable changes in the external and internal environments of an industrial enterprise [9], [10]. Consequently, the dynamism and uncertainty of exogenous and endogenous factors, affecting corporate development, are increasing. In such conditions, to identify the level of development of an industrial enterprise, fuzzy logic methods can be applied quite effectively. Fuzzy logic methods have proven themselves in building elements of control systems [11], making managerial decisions [12], and managing economic processes [13]. The use of fuzzy logic methods includes the involvement of experts, as those methods are based on the theory of Fuzzy Sets [14]. Proceeding hereafter, in this paper the authors use an algorithm that formalizes the process of choosing the direction of development of an industrial enterprise, and, in addition, contains some blocks that depend on the results of the work by experts.

A. Algorithm

The choice of the direction of development of an industrial enterprise can be represented in the form of a nonlinear algorithm (Fig. 1). Each block of the algorithm includes a specific set of operations that were performed for engineering enterprises in the South of Russia.

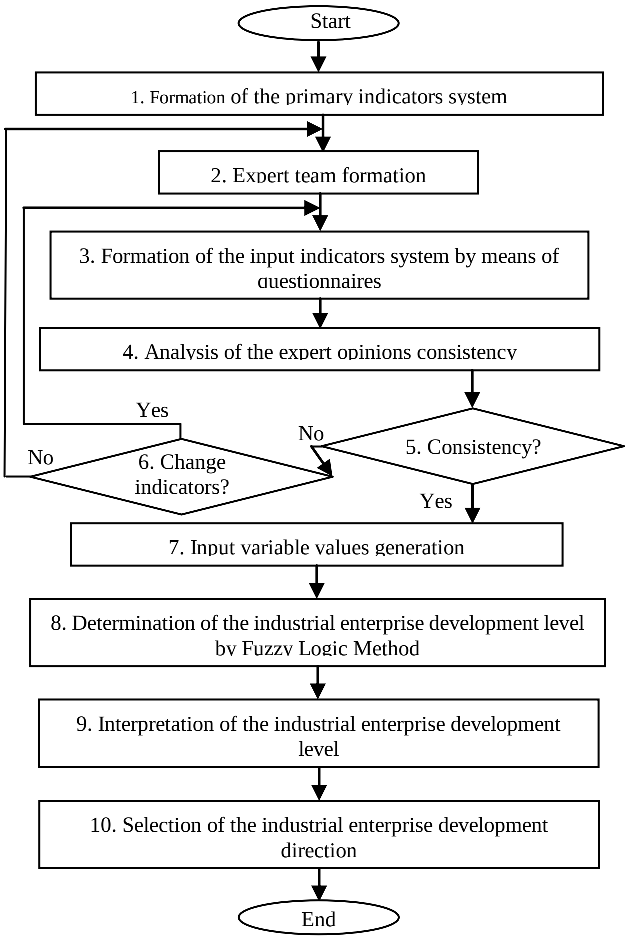

Fig. 1. Algorithm for choosing the direction of industrial enterprise development

Source: compiled by the authors

The choosing process includes a set of actions that are performed in a certain sequence.

As we can see from the algorithm (Fig. 1), first of all it is necessary to form an initial system of indicators (block 1) and an expert team (block 2). Based on expert opinions, the input indicator system is formed (block 3). Block 4 is necessary to analyze the consistency of expert opinions. The indicators are used further if the expert opinions are agreed. (This is the "Yes" arrow from block 5.) Otherwise, it is necessary to implement one of the two options. If the indicators can be changed, it should be done. (This is the "Yes" arrow from block 6.) If not, it is necessary to change the expert team. (This is the "No" arrow from block 6.)

All transitions are shown by the arrows "Yes" and "No" from the logical blocks 5 and 6 of the algorithm. After the transition to the previous block of the algorithm is completed, the corresponding algorithmic blocks are executed again.

As practice shows, the indicators change iterations can be performed up to 3 times. Then the expert team should be changed.

The next step is to determine the input variables values from the enterprise data (block 7) and assess the level of the enterprise development (block 8). The evaluation allows the enterprise to interpret its development capabilities (block 9) and choose the direction of its development (block 10).

B. Performing operations of the algorithm blocks

Assessment of the level of development of an industrial enterprise should be based both on mathematical calculations of economic and environmental indicators and on expert assessments of economic, political, and socio-economic processes that affect business.

Initially, a primary system of indicators was formed, on which the level of development of a modern industrial enterprise depends, and a hierarchical structure of factors of its external (K_1) and internal (K_2) environment was identified. To this end, the necessary data were collected.

An analysis of economic, environmental and social studies by scholars in the field of industrial business [15]-[19] allowed the authors to form 8 groups of indicators that determined the level of adaptive development of an industrial enterprise (R) (Table I).

Table- I: Groups and indicators of industrial enterprise development level

Groups	Indicators for the experts choosing
Enterprise Environmental Impact (Z_1)	dust pollution; waste (X_2); thermal pollution; emission contamination; effluents (X_3); chemical pollution; landscape transformation; gaseous emissions (X_1); electromagnetic pollution; noise pollution; your suggestion
Resources (Y_1)	human resources (X_7); resource providers (X_4); external raw materials availability (X_5); information resources availability; financial resources availability (X_6); local natural resources availability; your suggestion
Policy & Legal Environment (Y_2)	international law; corruption; national legislation (X_8); regional policy (X_{10}); local legislation; political and legal stability (X_9); your suggestion
Products (Y_3)	product safety during the life cycle; specific weight of new products in the total production volume (X_{13}); resource and energy intensity (X_{12}); product competitiveness (X_{14}); sales volume; innovation; market share (X_{11}); diversified assortment; your suggestion
Technologies & Equipment (Y_4)	technology ecological safety; material intensity level (X_{17}); innovation (X_{15}); nonwasteful level; production automation level; resource saving (X_{16}); your suggestion
Staff Subsystem (Z_4)	wage arrears; average salary level (X_{19}); staff professional composition; management gender composition; staff age structure; staff turnover (X_{20}); ratio of managers, specialists and workers; highly qualified employees share (X_{18}); your suggestion
Financial Subsystem (Z_5)	fixed assets depreciation; fixed assets renewal (X_{21}); fixed assets disposal; integral indicator for fixed assets; intangible assets usage (X_{22}); intangible assets security level; integral parameter for intangible assets; return on assets; financial dependence index; environmental costs; profit (structure, quality composition); integral indicator for finance (X_{23}); research and development costs; investments (structure, quality); your suggestion
Organizational Subsystem (Z_6)	share of research and development work as the ratio of the number of own innovation and scientific developments to the total number of innovations implemented during the year (X_{24}); management system efficiency, digitalization of management (X_{25}); environmental management efficiency; investment management efficiency; working conditions (X_{26}); information protection (X_{27}); marketing management efficiency; your suggestion

Source: compiled by the authors based on [15]-[19] and expert opinions

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We used a nested group system such as Resources (Y_1), Policy & Legal Environment (Y_2) for External Effects (Z_2) and Products (Y_3), Technologies & Equipment (Y_4) for Manufacturing System (Z_3). The total number of indicators was 65. In Table I, the indicators are presented in the order in which they were located in the questionnaire.

For further studies, 7 experts were involved. The work of specialists was carried out individually. The expertise was carried out in one round, openly. Experts were asked to assess the significance of pre-selected indicators (i.e., to rank) in each group of indicators, and, if necessary, add their own option. Each expert filled out a questionnaire, which was accompanied by detailed instructions. Then the indicators with the highest scores in each group of indicators were selected.

The arithmetic mean of expert estimates of the indicator was taken as the value of the importance of the indicator. As a result, a total of 27 indicators were selected (X_i, i=1-27, Table I), of these, the estimated indicators amounted to more than 50%. Indicators X_i, i=4-11, 18, 25, 26, 27 are expert ones.

The accuracy or reliability of expert assessments is significantly affected by the consistency of expert opinions. The next step was to establish how much one could trust the received expert estimates. For this purpose, the values of the criteria for the consistency of expert opinions were calculated for each indicator in the group. The calculation results of the variation range, the coefficient of variation [20], and the Kendall coefficient [21] showed the consistency of expert opinions (Table II).

Table- II: Criteria for consistency of expert opinions and their calculated values

Criterion	Values
Variation range	≤ 45%
Coefficient of variation	≤ 0,25
Kendall rank correlation	> 0,75

Source: calculated by the authors based on expert data

The system of selected indicators of the level of development of an industrial enterprise has a four-tier hierarchy (Table III).

Table- III: Hierarchy of the indicators system of industrial enterprise development level

Level	Indicators							
IV	R							
III	K_1			K_2				
II	Z_1	Z_2		Z_3		Z_4	Z_5	Z_6
I	-	Y_1	Y_2	Y_3	Y_4	-	-	-
Input indicators	X_1 X_2 X_3	X_4 X_5 X_6 X_7	X_8 X_9 X_{10}	X_{11} X_{12} X_{13} X_{14}	X_{15} X_{16} X_{17}	X_{18} X_{19} X_{20}	X_{21} X_{22} X_{23}	X_{24} X_{25} X_{26} X_{27}

Source: compiled by the authors

To assess the level of development of an industrial enterprise, the fuzzy logic method was chosen as the most appropriate for the tasks of the work. Therefore, input variables X_i, i=1-27 were used, which corresponded to the indicators chosen by experts (Table I), and the values of which were dimensionless and belonged to the interval [0, 1]. In practice, this is achieved by using the appropriate normalization functions. As an example, see a variable corresponding to the indicator selected by experts, which determines the innovativeness of products. The proportion of new products in the total volume of products is calculated as the ratio of the number of innovative products manufactured using innovative technologies to the total number of products made. Innovative products include: new products for the enterprise itself, new products for the local and/or global market. The share of innovative industrial products (X_{13}) is calculated according to the data of the enterprise:

$$X_{13}=X_{13,NP}/X_{13,P},$$

where $X_{13,NP}$ is the number of innovative products, pieces; $X_{13,P}$ is the total number of manufactured industrial products, pieces; $X_{13} \in [0,1]$. Indicator X_{13} tends to 1.

According to the theory of fuzzy sets [14], let us introduce the linguistic variables associated with indicators of the level of development of an industrial enterprise: R, K_i, i=1, 2; Z_i, i=1-6; Y_i, i=1-4; X_i, i=1-27, and having the names of the relevant indicators (Table I).

Membership functions for all linguistic variables were initially trapezoidal, since practical studies have shown that control objects are characterized by behavior that is close to linear on small intervals of the values of the input and output variables. Given the importance of the stage of constructing membership functions, various methods for its implementation are presented in the scientific literature [22]. In the present work, an approach is applied that has proven itself in practice. The construction of membership functions on universes W=[0.1] was carried out using a survey of experts. For each linguistic variable by each of its fuzzy level, the j-th expert set the value of four numbers (a_j, b_j, c_j, d_j), determining the trapezoidal form of the membership function $\mu(w)$.

The membership function after summarizing the opinions of experts has the structure:

$$\mu(w)=\begin{cases} \dfrac{w-a}{b-a}, & if \quad a \le w \le b \\ 1, & if \quad b \le w \le c \\ \dfrac{d-w}{d-c}, & if \quad c \le w \le d \\ 0, & \text{Otherwise,} \end{cases}$$

where a=min(a_j); b=min{max(a_j), min(b_j)}; c=max{max(a_j), min(b_j)}; d=max(b_j); j is the expert number, j=1,…,7.

All obtained values of a, b, c, d were additionally checked by experts for their appropriateness use. As a result of this analysis, the structures of membership functions were found to be acceptable for all linguistic variables, except for linguistic variables corresponding to the indicators of the External (K_1) and Internal (K_2) enterprise environments.

Experts pointed to the high inertia of the fuzzy inference system for variables K_1 and K_2 in the range of values [0.4; 0.6]. For example, for this interval, a change of 15-18% in the value of K_1 or K_2 caused a change of only 2-3% in the value of R. According to experts, it is very little. The influence of K_1 and K_2

on R is equivalent, and that is correct.

The next step was to carry out the numerical experiments to refine the structure of the membership functions of variables K_1 and K_2 for the interval [0,4; 0,6]. To this end, the sensitivity of the fuzzy inference system (δR) was calculated to systematically change the initial values of the breakpoints for membership functions. In our case, such calculations were performed for δR:

$$\delta R = \min\left(\min_{j} \left(\min_{i} \frac{R_{i+1,j} - R_{i,j}}{K_{1,i+1} - K_{1,i}}\right), \min_{i} \left(\min_{j} \frac{R_{i,j+1} - R_{i,j}}{K_{2,j+1} - K_{2,j}}\right)\right),$$

where $R_{i,j}=R(K_{1,i};\ K_{2,j})$; $K_{1,i}=0{,}4+0{,}02*i$; $K_{2,j}=0{,}4+0{,}02*j$; $i=0,1,\ldots,10$, $j=0,1,\ldots,10$.

The results of the numerical experiments are presented in Table IV. According to experts, the 6th row of Table IV corresponds to sufficient sensitivity for the fuzzy inference system.

Table- IV: Sensitivity of the fuzzy inference system with variations in the breakpoints of membership functions for K_1 and K_2

S. No.	Level	Breakpoints				δR
		a	*b*	*c*	*d*	
1	Low	-	0	0,2	0,4	0,01
	Average	0,2	0,4	0,6	0,8	
	High	0,6	0,8	1,0	-	
2	Low	-	0	0,2	0,42	0,15
	Average	0,2	0,42	0,58	0,8	
	High	0,58	0,8	1,0	-	
3	Low	-	0	0,2	0,44	0,38
	Average	0,2	0,44	0,56	0,8	
	High	0,56	0,8	1,0	-	
4	Low	-	0	0,2	0,46	0,51
	Average	0,2	0,46	0,54	0,8	
	High	0,54	0,8	1,0	-	
5	Low	-	0	0,2	0,48	0,73
	Average	0,2	0,48	0,52	0,8	
	High	0,52	0,8	1,0	-	
6	Low	-	0	0,2	0,499	0,82
	Average	0,2	0,499	0,501	0,8	
	High	0,501	0,8	1,0	-	

Source: compiled by the authors on the basis of InfoLogicTools calculations (based on the MathCad software)

Initially accepted breakpoints for membership functions of linguistic variables K_i, i=1, 2 were changed (Fig. 2). This was done in order to improve the adequacy of the fuzzy inference system. Thus, taking into account the expert opinion, the values of *a*, *b*, *c*, *d* were adjusted (Table V).

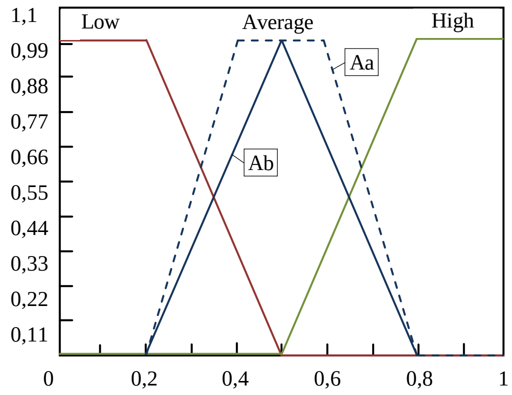

Fig. 2. Membership function for K_i, i=1, 2, (Aa, initial design; Ab, final design)

Source: compiled by the authors based on expert opinions

Table- V: The breakpoints of membership functions

Linguistic Variables	Level	Breakpoints			
		a	*b*	*c*	*d*
Z_i, i=1–6;	Low (L)	-	0	0,2	0,4
Y_i, i=1–4;	Average (Av)	0,2	0,4	0,6	0,8
X_i, i=1–27	High (H)	0,6	0,8	1,0	-
K_i, i = 1, 2	Low (L)	-	0	0,2	0,499
	Average (Av)	0,2	0,499	0,501	0,8
	High (H)	0,501	0,8	1,0	-
R	Low (L)	-	0	0,15	0,25
	Below average (BAv)	0,15	0,25	0,35	0,45
	Average (Av)	0,35	0,45	0,55	0,65
	Above average (AAv)	0,55	0,65	0,75	0,85
	High (H)	0,75	0,85	1,0	-

Source: compiled by the authors on the basis of expert assessments and InfoLogicTools calculations (based on the MathCad software)

To construct a fuzzy conclusion, a hierarchy of variables was used, which corresponded to a hierarchy of indicators of the level of development of an industrial enterprise (Table III). This allowed identifying a system of nested knowledge bases, each of which contained from 9 to 81 fuzzy control rules.

The relevance of presenting expert knowledge by levels is determined not only by the natural hierarchy of identification objects, but also by the need to take into account new variables as knowledge about the object accumulates. In addition, the limited dimensionality of knowledge bases corresponds to the limited ability of a person core memory to simultaneously hold and compare concepts (signs). In the constructed fuzzy inference system, the output variable of the lowest hierarchy level was the input variable for the highest hierarchy level.

In the work, knowledge bases are built on the basis of the principle of completeness, and they reflect all possible combinations of membership functions. The fuzzy control rules were set for each output variable; their number depends on the number of input variables.

The fuzzy control rules for the highest level of hierarchy (IV) are presented in Table VI.

Table- VI: The fuzzy control rules

Rule	Input 1 (K_1)	Input 2 (K_2)	Output (R)
1	L	L	L
2	L	Av	BAv
3	Av	L	BAv
4	Av	Av	Av
5	H	Av	AAv
6	Av	H	AAv
7	H	H	H
8	L	H	Av
9	H	L	Av

Source: compiled by the authors based on expert opinions

In the work, a fuzzy inference system was used to find the numerical value of each variable of the hierarchy level I-IV (Fig. 3), built on the basis of the Mamdani system.

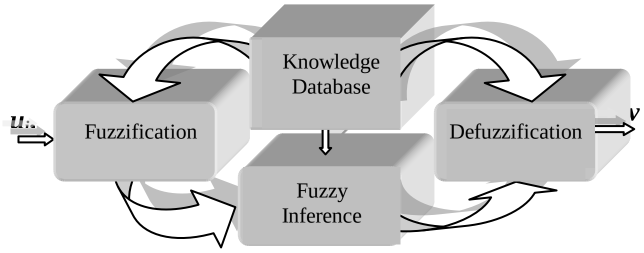

Fig. 3. Fuzzy Inference system scheme (u_i, i=1,…, n, input digit variables; v, output digit variable)

Source: [12], [23].

In this case, the Mamdani system contains standard procedures [23]: Fuzzification, Aggregation, Activation, Accumulation, and Defuzzification. Defuzzification was carried out by the method of the center of gravity, i.e. the digit value of each output variable (V) was calculated as the abscissa of the center of gravity of the area bounded by the graph of the membership function curve of the corresponding output variable:

$$v = \frac{\int_0^1 x\mu(x)dx}{\int_0^1 \mu(x)dx},$$

where v was the result of Defuzzification, being the digit value; x was the variable corresponding to the output linguistic variable V; $\mu(x)$ was the membership function of a fuzzy set that corresponded to the output variable V after Accumulation.

To find R, Mamdani inference was applied 13 times.

The application of the presented methodology allows an industrial enterprise to identify the level of its development and development indicators (Table I). Knowing the level of its development and the significance of all development indicators, an enterprise can make an informed decision on its development. The unsatisfactory value of a particular indicator can serve as the basis for directing the maximum efforts of the company toward development, which is aimed at the growth of this particular indicator.

III. RESULTS AND DISCUSSION

The proposed methodology was applied at 3 engineering plants in southern Russia as part of the digitalization of management. To assess the level of development of an industrial enterprise, InfoLogicTools application was built in the MathCad simulation environment. At the same time, the authors were faced with the task of developing a software product that would be as simple as possible in practical use and easily transformed. That is why InfoLogicTools is built on a modular basis. This makes it easy to upgrade and customize depending on the business tasks. For example, expansion is allowed, as well as the replacement of one or more indicators of the industrial enterprise development system (Table I).

To use InfoLogicTools, the user just needs to enter the values of the input variables. Further, all calculations are carried out automatically, and a person does not need to take an active part in the calculations. At the same time, if necessary, the user has the opportunity to monitor the calculated value of each indicator, make any changes to it to find out what results they will lead to, thus simulating the impact of the proposed changes. These data are important for an industrial enterprise, as they allow companies not only to analyze their current activities, but also to predict the consequences of particular activities introduced by the company. Therefore, when formulating a development strategy, as well as medium and short-term planning, management needs to know the level of development of the enterprise and the impact of individual indicators on this development. Thus, the assessment and its analysis contribute to the adoption by the enterprise of an informed decision on its development.

Production tests of the application showed that the use of InfoLogicTools did not require special knowledge and advanced computer skills. The test results demonstrated the need for changes to increase the protection of the application from unauthorized access to the computing process. In particular, access to the computation area was hidden in the interface.

The proposed methodology was used to develop a strategy and adjust existing plans for the development of 3 machine-building plants. The calculations were performed according to the data of plants for 2018 (Table VII).

Table- VII Levels and critical indicators of development for machine-building plants

Plant	*R*		Degree of Truth	Critical indicators
	Value	*Level*		
Fiolent	0,75	AAv	1	Z_4, X_{18}
Pneumatic	0,51	Av	1	Z_3, Y_3, X_{13}
Selmache	0,41	BAv	0,87	Z_3, Y_4, X_{15}

Source: calculated by the authors based on the data of machine-building plantsMonitoring of the development of enterprises, which used the proposed methodology, allowed those plants to select critical indicators (Table VII). Enterprises have worked out some measures aimed at improving their development indicators. For the development of the personnel subsystem, the Fiolent plant created a joint department with a regional university and concluded an agreement on the training of information technology specialists for the plant. Pneumatic plant decided to develop the production subsystem of the enterprise, paying more attention to products. To this end, it developed 5 new types of products and began to introduce them into commercial production. For the Selmache plant, a critical indicator was the innovativeness of equipment and technology, which was a component of the production subsystem of the enterprise. To date, the plant has prepared a production site for innovative equipment, purchased the first batch of new equipment and began its installation. In addition, all enterprises in their development plans outlined gradual digitalization. Despite the fact that the digitalization of management (X_{25}) is not among the critical indicators of the studied enterprises, such a choice of the direction of development of enterprises once again proves the importance of digitalization for them.

IV. CONCLUSION

Digitalization is a sign of modernity. The digitalization of management enhances the competitiveness of enterprises in the context of rapid growth in the quantity and quality of technology.

The algorithm for choosing the direction of industrial enterprise development was built in this paper. It includes an assessment of the level of development of the industrial enterprise. This assessment allows enterprises to make a reasonable choice of direction for their development. Fuzzy sets are used to make the assessment. The fuzzy logic method has proved itself well in the conditions of uncertainty of the external environment of the enterprise.

The proposed methodology has theoretical significance, since it is the result of a generalization of the theoretical principles of the fuzzy logic method for managing the development of an industrial enterprise in the context of digitalization.

The results of the study are of practical importance. In Russia, the introduction of digital technologies in production has difficulties, such as the complexity of existing scientific developments for practical use. Therefore, the toolkit is very useful if it does not require special knowledge for application.

The developed InfoLogicTools application in the MathCad modeling environment has demonstrated the possibility of its use. Using the proposed methodology, 3 machine-building enterprises identified critical indicators of their development. This allowed them to work out some measures to improve their level of development.

Further research will be aimed at digitalizing the collection of information on the development of an industrial enterprise.

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