A fuzzy set model for assessment of a perspectives level for integration of new materials in industrial enterprise processes[a]

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Abstract. The definition of effective improvement vectors is currently one of the most pressing challenges facing the industry representatives. The transition to the sixth technological mode effectively contributes to competition intensification in all markets of industrial products. This is largely due to the fact that existing process systems are at the peak of their effectiveness. Further development requires qualitative changes. However, the principal improvement is a long-term and high-risk process. For this reason the issue of creating effective models for assessment of the strategic lines of processes improvement becomes increasingly important for industrial enterprises. This article considers in details the vector of industrial enterprise processes improvement based on the integration of new materials. As a result, a model allowing to assess a perspectives level for integration of new materials in industrial enterprise processes is created.

1 Introduction

At present, the process of transition to the sixth technological mode has become evident to everyone. The existing process systems achieve an optimization peak that in conditions of a competitive environment generates the need for their qualitative change (principal improvement). This problem is especially actual for industry representatives as investments in this case are more long-term. Therefore, in terms of the qualitative changes in processes at an industrial enterprise, we mean the formation of a new industry, "the Industry 4.0".

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Among the topics of scientific publications on this subject, there are several main trends. Some authors focus their attention at the development of new production technologies, for example, additive technologies, computer engineering, laser material technologies, etc. Gressa & Kalafsky [1] study the influence of additive technologies on the global structure of demand and consumption, that is, the study subject is the long-term economic effect resulted from the introduction of additive technologies in production. Cozmei & Caloian [2] emphasize the capital capacity of additive productions concluding that the additive technologies development will invariably lead to the global improvement of the taxation system. Gebler, Schoot Uiterkamp & Visser [3] agree with them, they see the purpose of additive technologies in increasing the company's profit through the use of consumer surpluses, thanks to the construction of a flexible production system that implies the custom orders production. The consequences of the additive technologies integration into the real economic sector, in particular, the increasing level of different types of risks, were the subject of Mellor, Hao & Zhang' study [4], who stated that one of the significant risks is almost unlimited capabilities in the field of final product use.

Another study line in the area of the sixth technological mode is a wide range of topics related to sustainable development, sustainable production and consumption, that is, the approval of new, sustainable consumer values. Leiserowitz [5] wrote about the relationship between sustainable production and consumption, and achievement of the corresponding long-term economic, social and environmental result. Thogersen [6], Peattie & Collins [7] noted the risks and dissonances of this process, while revealing contradictions between the values and their implementation declared by the companies. Garetti and Taisch [8] studied the factors affecting the industry stability and macroeconomic balance.

Finally, new production technologies and new sustainable values inevitably lead to appearance of new materials, such as metamaterials, aerogels, self-healing materials, foamed metal, bio-ceramics, etc. Although the markets for these materials are only at the stage of implementation according to the life cycle model, they are already the subject of detailed study of scientist-economists. In particular, Menshutina and Lebedev [9] focus their attention to capitalization of enterprises of high-tech industries which deal with developments in the field of new materials. Slyusar [10], Lapshin [11] study the field of the future long-term effect from the implementation of such materials in the production structure, etc.

The whole set of the existing particular solutions of the challenge can be represented as a universal scheme (see Fig. 1).

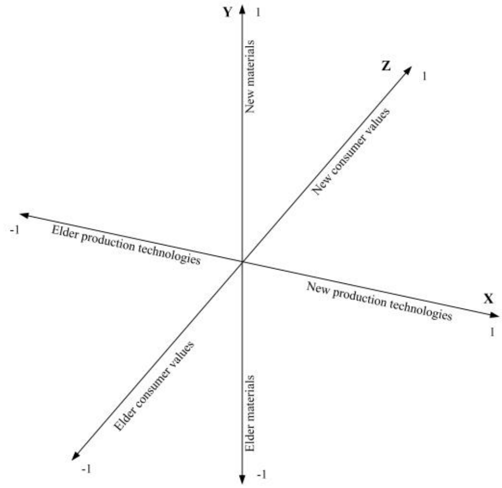

Fig. 1. Process improvement octant.

This octant consists of 8 sectors due to its geometry. Each axis features one of 3 highlighted improvement lines, and has 2 opposite states. Thus, each of the sectors is featured by the state of three main lines of process improvement. The description of these fields is given in Table 1.

Table 1. Description of process improvement octant fields.

Item No.	Field	Field description
1	"A fundamentally new process"	X=1; Y=1; Z=1.
2	"Integration of new materials to meet the new needs"	X=-1; Y=1; Z=1.
3	"Integration of new materials to better meet the existing needs"	X=-1; Y=1; Z=-1.
4	"A new way to meet the existing needs"	X=1; Y=1; Z=-1.
5	"New technologies to meet new needs"	X=1; Y=-1; Z=1.
6	"Meeting the new needs by using old ways"	X=-1; Y=-1; Z=1.
7	"New technologies to meet old needs"	X=1; Y=-1; Z=-1.
8	"Insignificant improvement"	X=-1; Y=-1; Z=-1.

Based on the content analysis results, it was established that one of three listed lines or their combination was laid down in the basis of the solutions proposed by the scientists-researchers. The effectiveness of each of the described improvement lines can be significantly different depending on many factors. However, an industrial enterprise can use each of them at the strategic planning level. These lines can be compared based on three criteria: capital capacity; risk level; long-term economic effect. The expert comparison of the described lines based on the above criteria is shown in Fig. 2. This comparison is made based on a ten-point scale, where 10 is the maximum value of the criterion, and 1 is the minimum one. The expert group consisted of 10 leading scientists-researchers in this field representing the profile academic departments of SPbPU and SPbGEU. An expert review was made based on the Delphi method.

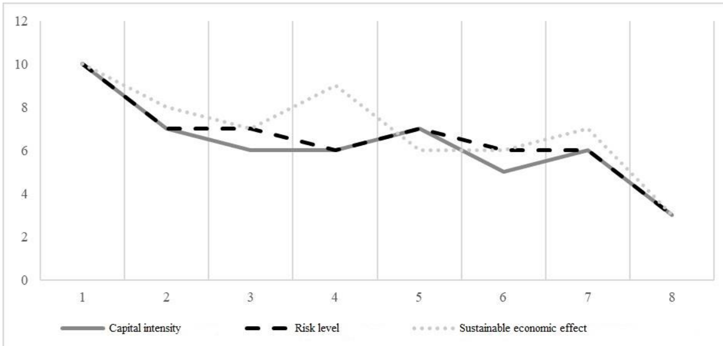

Fig. 2. Expert comparative study of the process improvement.

According to the presented data, we can conclude that the long-term economic effect is provided to a greater extent in case of new materials integration. This is due to the fact that only the use of new materials will form fundamentally new properties of the final product, which, in turn, will create a new consumer value, while maintaining the already formed material and technical base of the industrial enterprise. In this case, the risk level shows insignificant deviations for most states (boundary (1 and 8) states can be neglected, as they imply either, in fact, the formation of a new activity line, or a minor improvement that more is of additional). Capital capacity shows the lowest results in the case of lines which do not involve the new materials integration. First of all, this is due to the fact that the markets for new materials are unsaturated, and the manufacturers of new materials are not able to create a scale effect. However, the most potentially effective line is 4 – "A new way to meet the existing needs", and 2 – "Integration of new materials to meet the new needs". This statement is based on the fact that with a relatively low risk level these lines are featured by a relatively higher long-term economic effect exceeding their capital capacity. Therefore, the advanced field for industrial enterprises as part of transition to the new technological mode is the processes improvement through the new materials integration.

According to the study – Transparency Market Research, the capacity of the world market for new materials will grow by an average of 10.4% per year, and will reach 102.48 billion dollars by 2024, against only 42.76 billion dollars in 2015 [12]. Based on the analysis of the statistics presented in the company's reports -Transparency Market Research, Markets and Markets and Grand View Research, the following new materials most relevant and prospective for industry development were identified: metamaterials; aerogels; bioceramics; graphene; foamed metal; self-healing materials. The market for each of the presented materials is rapidly growing, and a lack of experimental experience of their application in the industry indicates an increased risk level of their integration into the processes. However, these are the industrial enterprises that will be able to successfully integrate these materials, be competitive in the long term. Therefore, the model building to assess the prospects for integrating these materials into the processes of industrial enterprises is an extremely critical task.

2 Assessment model and results

The research subject specificity does not allow using one of the most common assessment methods as is, since a sufficiently accurate and adaptive prospects assessment model can not be based on statistical or exclusively expert methods only. The solution for the problem of increasing the results accuracy of assessing such phenomena lies in the methods application based on the fuzzy sets theory. Methods based on the fuzzy sets theory are based on an expert assessments system; however, as against the statistical and expert estimation methods, they provide the possibility to take into account the uncertainty level by using the membership functions (μ (x) ∈ [0; 1]) of a subset to a given set [13].

The prospects are assessed based on a system of indicators built as per the hierarchical principle, and defined in different units of measurement. At the first system level there are extended criteria, the aggregate interaction of which synergistically affects the level of integration prospects. The second system level is represented by specific indicators affecting one or another criterion. These indicators describe the state of both the external and internal environment of an industrial enterprise. The system of these indicators is given in Table 2.

Table 2. The indicators featuring the prospects level for integration of new materials into industrial enterprise processes.

Item No.	First level indicators	Second level indicators	The line of influence on the final result
1	Capital capacity	Average integration cost	↑=>↓
2		Possibility for integration with the existing processing technologies	↑=>↑
3		Human resources cost	↑=>↓
4		Cost of additional research	↑=>↓
5	Risk level	Level of process imperfection of the material	↑=>↓
6		Degree of differentiation of the world distribution of manufacturers	↑=>↑
7		Degree of differentiation of application areas	↑=>↑
8		Level of application areas adjacency	↑=>↑
9	Long-term economic effect	Current market capacity	↑=>↑
10		Growth rate of market capacity	↑=>↑
11		Current capacity of main consumer markets	↑=>↑
12		Level of process development of application areas	↑=>↑

The formed model has 2 linguistic variables: the prospects level for integration of new materials and the level of each specific indicator under consideration (12 indicators in total). The term-set of each linguistic variable consists of 5 subsets:

– Linguistic variable X is the prospects level for integration of new materials;
– The linguistic variable Y is the values of the specific indicators.

Its own level of significance r_i is assigned to each indicator. In accordance with the system hierarchy, it was found that the first level indicators are of equal importance. The second level indicators, in turn, are equally important for the first level ones.

The standard five-level 01-classifier developed by A. O. Nedosekin and most commonly used, where the membership functions are trapezoidal triangular numbers [14] is applied as a classifier for the prospects level for integration of new materials. This classifier has 5 node points, where a membership function value is equal to one (0.1, 0.3, 0.5, 0.7, 0.9).

Based on the results of calculation of each of the specific indicators, their values are recognized by the criterion $\lambda ij \in [0;1]$. This indicator correlates the specific indicators with the values of the 01-carrier:

$$\lambda_{iJ} = 1 - \frac{X_i - \alpha_3^*}{\alpha_4^* - \alpha_3^*}, \quad (1)$$

where α_3^* and α_4^* are the T-numbers of the i-th subset of the term-set.

Based on the results of recognition of the specific indicator values, the integral indicator of the prospects level for new materials integration (X) is calculated:

$$X = \sum_{j=1}^{5} p_j \sum_{i=1}^{n=12} r_i \times \lambda_{iJ}, \quad (2)$$

where p_j is node points of the 01-carrier

The obtained integral indicator of the prospects level for new materials integration is linguistically interpreted in the same manner as the specific indicators.

The fuzzy set model for assessment of the prospects level for new materials integration into the industrial enterprise processes is proposed. This model compensates for the disadvantages of other models by integrating both statistical and expert indicators which have a synergistic effect on the final result. Further research will be devoted to approbation and improvement of the generated model.

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