International Journal of Technology 12(7) 1397-1406 (2021)
Received October 2021 / Revised December 2021 / Accepted December 2021

International Journal of Technology

http://ijtech.eng.ui.ac.id

Methodology for Assessing Industrial Ecosystem Maturity in the Framework of Digital Technology Implementation

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Abstract. The essence of the transformation processes currently taking place in all sectors of the economy, including industry, is increasingly described by the ecosystem approach. Industrial ecosystems have proven to be the models with the highest production efficiency. The effective management of industrial ecosystems is possible only if the mechanisms underlying their dynamics are understood. Achieving a high level of maturity for industrial ecosystems in the framework of digital technology implementation is of particular relevance, and this research aims to develop and test a methodology for assessing the maturity level of such industrial ecosystems by relying on principal component analysis and hierarchical agglomerative clustering. A mature industrial ecosystem gets rapidly integrated into the new technological paradigm and global value chains, is able to compete in global markets in the long term, and has increased potential for industrialization and digital transformation. The proposed methodology is based on the environmental, social, and corporate governance (ESG) methodology for determining the levels of interests in the area of sustainable development of an industrial ecosystem. The proposed approach singles out a fourth assessment projection in addition to ESG, namely the digital maturity. All four maturity assessment projections are proven to be positively and significantly correlated. An industrial ecosystem maturity assessment scale has been developed, including six levels (very high; advanced; basic; elementary; zero; and minus one). The methodology has been tested on the national industrial ecosystem and the metallurgy and mining industrial ecosystem of Russia. The results show that the maturity level of the Russian industrial ecosystem as of mid-2021 is "basic" with the prospect of transition to "advanced." The Russian metallurgy and mining industrial ecosystem maturity level is "advanced." The key directions for increasing the maturity levels of Russian industrial ecosystems based on innovations in various industrial aspects are proposed.

Keywords: Digital maturity; Digital transformation; Ecosystem; Industrial ecosystem; Maturity assessment methodology

1. Introduction

Global transformations affecting all industries and activities are now becoming evident,

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doi: 10.14716/ijtech.v12i7.5390

manifesting themselves in the intensification of complex and volatile processes. This state of external and internal environments is characterized by a whole set of economic, production, social, technological, digital, ecological, and other transformations (Held and McGrew, 2000; Berawi, 2020; Rudskaya et al., 2020; Kusrini et al., 2020). The observed global transformations are largely due to the intensive implementation of digital technologies, fundamentally changing both the quality of life and the system of socioeconomic relations (Fukuda, 2020; Shkarupeta et al., 2020; Shkarupeta et al., 2021). In the near future, Russia is expected to see more active use of the "digital twin" technology and explosive growth in the metallurgy and mining industry (PwC, 2020).

The object of this research is an industrial ecosystem as a complex system of economic agents acting on the basis of autonomy and interconnectedness that are distinguished by their activities and features of functioning, whose goal is the creation of industrial products and/or services that are based on the principle of emergence. The research objectives are as follows: to systematize the existing research on assessing the maturity level of industrial ecosystems; to develop and test a methodology for assessing the maturity level of an industrial ecosystem; to identify the main directions of increasing the maturity level of an industrial ecosystem in the framework of the implementation of digital technologies.

2. Literature Review

Current research on industrial ecosystems includes a toolkit for managing industrial ecosystem regeneration (Diez et al., 2017); building and optimizing a resource-based industrial ecosystem (Fan et al., 2017); studying the impact of industrial symbiosis initiatives on the emergence of regional industrial ecosystems (Susur et al., 2019); finding an approach to lifecycle management based on symbiosis for sustainable resource flows in an industrial ecosystem (Shi and Li, 2019); developing an industrial ecosystem orchestration model in a circular economy (Parida et al., 2019); developing an innovative model of industrial ecosystem transformation based on artificial intelligence (Burström et al., 2021), etc.

A number of terms closely related to industrial ecosystems have been discussed in the literature, emphasizing their interdisciplinary nature, such as innovation-active clusters (Tashenova et al., 2020; Babkin et al., 2020; Rodionov et al., 2020; Babkin et al., 2021; Glukhov et al., 2021).

With the adoption of digital technologies, the problem of achieving maturity by Russian industrial ecosystems becomes particularly relevant. Only a mature industrial ecosystem is capable of integrating into the global value chains (World Bank Group, 2020), entering global markets with competitive high-tech products, having prospects for long-term and successful industrialization in the digital age (Industrial Development Report, 2020), and withstanding the challenges and threats posed by increasing planetary pressures (Human Development Report, 2020).

Maturity is a theory of stage evolution, and the stages and pathways of maturation can be defined by a maturity scale (Bertolini et al., 2019); through this, the basis for assessment and comparative analysis of industrial ecosystems can be determined (Hackos, 1997). The maturity of an industrial ecosystem can be considered as a measure of readiness for Industry 4.0 (Nick et al., 2021).

There are not enough studies devoted to assessing the maturity level of industrial ecosystems. Wang et al. (2017) proposed to assess the vulnerability of industrial ecosystems based on an integral vulnerability index. Sun et al. (2018) evaluated the maturity of China's low-carbon energy industry by distinguishing two levels of industrial maturity: product readiness and market maturity. Tolstykh et al. (2020) developed an entropic model to assess the sustainability of industrial ecosystems by assessing the level of cooperation between the industrial ecosystem participants. Another research (PwC, 2020) assessed the digital IQ of Russian companies as a measure of their awareness and readiness to successfully implement digital transformation objectives. Dudareva et al. (2021) developed a model to assess the maturity dynamics of industrial ecosystems.

Currently, the maturity of an industrial ecosystem can be assessed using two approaches: the Industry 4.0 Maturity Index (Rafael et al, 2020; Angreani et al., 2020; Mrugalska and Stasiuk-Piekarska, 2020; Caiado et al., 2021; Zoubek, 2021) and the Organizational Digital Manufacturing Maturity Model—ODM3 (Modrák and Šoltysová, 2020; Berger et al., 2020; Lin et al., 2020; Wagire et al., 2021). The limitation of these methodologies is that they cannot be applied to industrial ecosystems at levels above the corporate level.

Thus, the presented approaches do not allow closing the research gap in the methodology for assessing the maturity level of industrial ecosystems to compare and rank industrial ecosystems based on a unified scale and to develop measures to improve the maturity level of industrial ecosystems. Under these conditions, the hypothesis of the interrelation of the maturity level assessments and the consideration of sustainable development interests and environmental, social, and corporate governance (ESG) ratings of an industrial ecosystem are put forward. The methodology for assessing the maturity level of an industrial ecosystem should be based on the ESG methodology for determining the levels of sustainable development of an industrial ecosystem. The distinction of the proposed approach is to consider the introduction of digital technologies by singling out an additional fourth assessment projection.

3. Materials and Methods

To achieve the goals set in this paper, the authors used general scientific methods as well as economic and statistical methods. The analysis of the market structure and comparison of the dynamics of indicators for sustainable development of industrial ecosystems were done. The methodology of assessing the maturity of an industrial ecosystem was supplemented with principal component analysis (PCA) and hierarchical agglomerative clustering (HAC).

Focus group discussion (FGD) is frequently used as a qualitative approach to gain an in-depth understanding of issues. We reviewed the application of FGD in industrial ecosystem maturity studies. We begin with a brief explanation of the existing methods for novice users. We then discuss in detail the empirical application of the proposed methodology in the area of industrial ecosystem maturity assessment. The number of focus group participants ranged from 3 to 11. There were five (median) focus group meetings. The FGD sessions lasted 30 (median) min. Three main themes emerged from the review: the possibility of applying the ESG methodology for assessment (38%), the need to test the methodology for different industrial ecosystems (33%), and the need to identify the main areas for improving the maturity assessment of an industrial ecosystem (29%).

This research proposes the following methodology for assessing the maturity of an industrial ecosystem in the terms of implementing digital technologies, which includes nine stages (Figure 1). The first stage selects the level of the industrial ecosystem whose maturity is to be assessed: intercountry (global); national; sectoral; regional; and corporate. At the second stage, the initial information is collected on the basis of ESG ratings of companies in the industrial sectors that form the industrial ecosystem. The rank for the three projections is supplemented by the value of the level of digital maturity (the fourth projection), which is obtained from the public sources. At the third stage, all the data are normalized on the basis of the minimax method and reduced to the same scale of measurement in the interval [0, ... 1]. At the fourth stage, the resulting data sample is checked for representativeness. At the fifth stage, the average rank for each of the four projections is determined. Then, at the sixth stage, the obtained values are weighed (in this example, all the projections have the same weight of 0.25). The ESG evaluation methodology for nonfinancial organizations recommends the following ratio of weights: E: 30%, S: 35%, G: 35%). The seventh stage assesses the level of maturity of the industrial ecosystem by calculating the average value of all the projections. At the eighth stage, the resulting maturity level is compared with the assessment scale and a conclusion is made about the final maturity level. The ninth and final stage is devoted to the development of recommendations for improving the maturity level of the industrial ecosystem.

Stage 1: Selecting the level of the industrial ecosystem for maturity assessment

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Stage 2: Forming an array of raw data by four projections

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Stage 3: Normalizing the data

↓

Stage 4: Checking the sample for representativeness

↓

Stage 5: Determining the average level for each projection

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Stage 6: Determining the weights for each projection

↓

Stage 7: Assessing the level of maturity of the industrial ecosystem by calculating the average of the four projections

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Stage 8: Concluding on the level of maturity by comparison with the assessment scale

↓

Stage 9. Developing recommendations for improving the maturity of the industrial ecosystem

Figure 1 The methodology for assessing the maturity of an industrial ecosystem in terms of implementing digital technologies

The recommended scale for assessing the level of maturity of an industrial ecosystem is based on the selected levels of considering sustainability interests according to the ESG methodology and is presented in Figure 2.

4. Results

The maturity assessment methodology was tested on data of independent European Credit Rating Agency Rating-Agentur Expert RA GmbH (RAEX-Europe) as of July 15, 2021.

A total of 135 companies participated in the calculation of the ESG ratings in Russia, of which 97 companies (72%) were from the industrial sector. The remaining 38 companies were from the telecommunication, finance and financial services, construction, transport, retail, and information technology sectors.

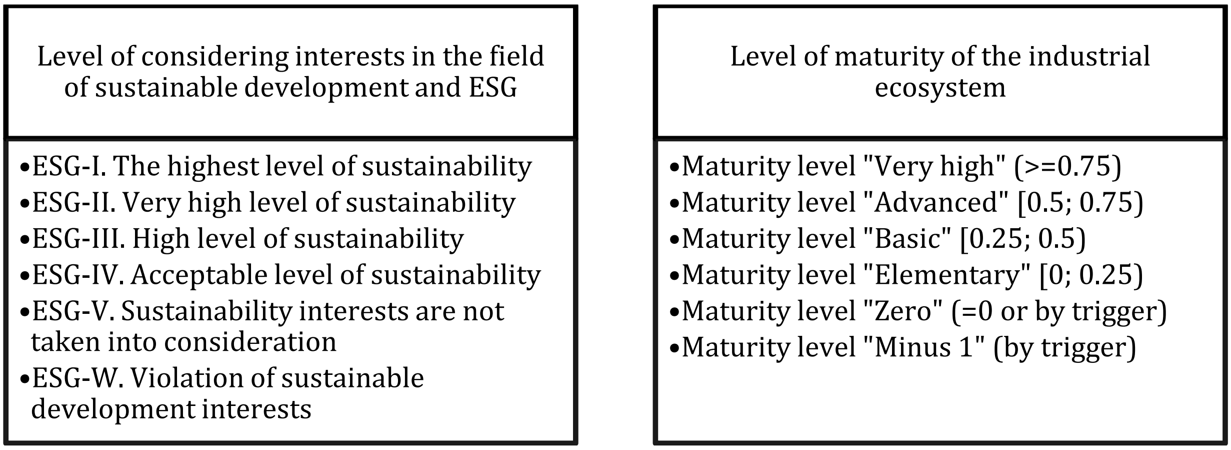

Figure 2 Correlation of sustainability and the maturity levels of an industrial ecosystem
Source: adapted from Rodionov et al. (2018); RAEX (2019)

Data on the environmental (E), social (S), and corporate governance (G) sustainability of industrial companies—actors of the national industrial ecosystem—are presented in Table 1.

Table 1 Initial data for assessing the maturity level of the national industrial ecosystem

	Number of companies	Average rank E	Average rank S	Average rank G
Machinery	1	48.0	39.0	17.0
Energy	10	45.3	52.6	40.7
Food Products	1	65.0	51.0	61.0
Metallurgy & Mining	31	58.2	56.0	70.6
Oil & Gas	17	58.6	69.5	66.8
Paper & Forest Products	8	72.0	74.5	74.2
Chemicals	25	77.0	80.5	88.3
Diversified Corporations	2	117.0	94.5	93.0
Auto Components	1	134.0	131.0	121.0
Containers & Packaging	1	111.0	120.0	131.0
Total	97	65.4	67.8	72.5

Source: calculated from the data provided in the RAEX, 2021

The average E, S, and G ranks of the industrial ecosystems are calculated as the average of the ranks of the companies included in each of the industrial ecosystems. The figures in the "average rank" columns indicate the position of the industry out of the 135 rated companies by the factors E, S, and G.

The data in Table 1 should be supplemented by the fourth projection of the industrial ecosystem maturity assessment, namely the level of digital maturity (D). For this purpose, we will use the data of the calculation of the digital maturity of Russian companies based on the results of the survey of leading Russian companies from key industries conducted by SAP, Deloitte, and iR&D Club (2021). The digital maturity of the companies was assessed in accordance with Deloitte methodology in five areas: client, strategy, technology, operations, and organization. For each area, several key criteria were identified, and the surveyed companies were assessed based on these criteria. A 5-point scale was defined for the evaluation. In terms of industrial ecosystem, the average level of digital maturity in

Russia was 2.6 for the automotive industry, 2.5 for the fuel and energy complex, 2.4 for the metallurgy and mining industry, and 1.6 for the mechanical engineering industry.

Thus, with the data on the four projections, we calculate the maturity level of the national industrial ecosystem and present the results in Table 2.

Table 2 Assessment of the maturity of the national industrial ecosystem in the Russian Federation

Subindustry	E	S	G	D	Maturity level	
Machinery	0.64	0.71	0.87	0.42	0.66	advanced
Energy	0.66	0.61	0.70	0.50	0.62	advanced
Food Products	0.52	0.62	0.55	0.52	0.55	advanced
Metallurgy & Mining	0.57	0.59	0.48	0.48	0.53	advanced
Oil & Gas	0.57	0.48	0.51	0.48	0.51	advanced
Paper & Forest Products	0.47	0.45	0.45	0.46	0.46	basic
Chemicals	0.43	0.40	0.35	0.42	0.40	basic
Diversified Corporations	0.13	0.30	0.31	0.32	0.27	basic
Auto Components	0.01	0.03	0.10	0.52	0.17	elementary
Containers & Packaging	0.18	0.11	0.03	0.52	0.21	elementary
Total	0.52	0.50	0.46	0.46	0.49	basic

Source: calculated from the data provided in the RAEX (2021); SAP, Deloitte and iR&D Club (2021)

Thus, the maturity level in the Russian industrial ecosystem amounted to 0.49 and can be characterized according to the recommended scale as "basic" with a prospect of transition to "advanced." The current state of the development of the national industrial ecosystem is characterized by significant heterogeneity in the development of certain industries and the unequal development of markets and enterprises.

We now apply the proposed maturity assessment methodology to the industrial ecosystem. As an example, let us consider the metallurgy and mining industry (Table 3).

The industrial ecosystem of the metallurgy and mining industry is characterized by an advanced level of maturity.

Let us supplement the assessment with PCA and HAC. The correlation matrix is presented in Table 4. All four maturity projections are positively and significantly correlated.

Eigenvalues F1 = 3.543, F2 = 0.324, F3 = 0.1, and F4 = 0.043. Cumulative variability F1 = 88.339%, F2 = 96.43%, F3 = 98.936%, and F4 = 100%.

It can be assumed that the observations are distributed quite evenly. To confirm this thesis, we use HAC, which confirms the proposed maturity assessment scale. Observations 1–3 (characterized as a very high maturity level), 4–11 (advanced level), 12–13, and 15–17 (basic level), and 14 and 18 (elementary level) are combined into subclusters. In total, the algorithm identified two clusters:

– the first cluster includes eleven objects (observations 1 through 11) with the intraclass variance of 1.21, minimum distance to the centroid of 0.347, mean distance to the centroid of 0.973, and maximum distance to the centroid of 1.751;

– the second cluster includes seven objects (observations 12 through 18) and is characterized by the interclass variance of 1.66, minimum distance to the centroid of 0.474, mean distance to the centroid of 1.123, and maximum distance to the centroid of 1.646.

Table 3 Assessment of the maturity level of the metallurgy and mining industrial ecosystem in the Russian Federation

Company (observation)	E	S	G	D	Maturity level	
1. NLMK	0.95	0.97	0.78	0.48	0.79	very high
2. SUEK	0.89	0.92	0.80	0.48	0.77	very high
3. Severstal	0.84	0.96	0.85	0.48	0.78	very high
4. RUSAL	0.86	0.81	0.66	0.47	0.70	advanced
5. EVRAZ	0.81	0.80	0.67	0.47	0.69	advanced
6. MMK	0.79	0.67	0.84	0.47	0.69	advanced
7. Nornickel	0.61	0.88	0.67	0.47	0.66	advanced
8. Metalloinvest	0.72	0.79	0.45	0.47	0.61	advanced
9. TMK	0.74	0.61	0.58	0.47	0.60	advanced
10. OMK	0.64	0.90	0.40	0.47	0.60	advanced
11. UK Kuzbassrazrezugol	0.78	0.53	0.24	0.47	0.51	advanced
12. Chelpipe Group	0.47	0.54	0.44	0.46	0.48	basic
13. Raspadskaya	0.36	0.38	0.53	0.46	0.43	basic
14. Mechel	0.03	0.04	0.36	0.45	0.22	elementary
15. Sibanthracite Group	0.34	0.43	0.13	0.46	0.34	basic
16. Russian Coal	0.27	0.35	0.13	0.46	0.30	basic
17. UMMC	0.39	0.39	0.01	0.46	0.31	basic
18. IMH	0.04	0.16	0.01	0.45	0.16	elementary
Total	0.58	0.62	0.47	0.47	0.54	advanced

Source: calculated from the data provided in the RAEX (2021); SAP, Deloitte and iR&D Club (2021)

Table 4 The correlation matrix of the four maturity projections of the metallurgy and mining industrial ecosystem in the Russian Federation (Correlation matrix (Pearson (n))

Maturity projections	E	S	G	D
E	1	0.901	0.756	0.950
S	0.901	1	0.746	0.935
G	0.756	0.746	1	0.766
D	0.950	0.935	0.766	1

All values are different from 0 with a significance level alpha = 0.05

5. Discussion

The results of the maturity assessment of the industrial ecosystem do not contradict similar studies (Angreani et al., 2020; Berger et al., 2020; Lin et al., 2020; Dudareva et al., 2021) but supplement them, enabling an expanded understanding of the ultimate goal of the industrial ecosystem, which should be pursued after determining the maturity level in the terms of digital technology implementation. Thus, the research's conclusion of significant heterogeneity in the development of the sectors of the national industrial ecosystem corresponds to the conclusion that "the dynamics of the industrial ecosystem maturity indicators across groups is quite substantial" (Dudareva et al., 2021). The calculated value of the integrated maturity in the Russian industrial ecosystem of 0.49 as of 2021 corresponds to the described development dynamics (Berger et al., 2020; Lin et al., 2020; Dudareva et al., 2021).

Most industrial ecosystems are actively evolving thanks to widespread digitalization. The Russian industrial ecosystems must implement five key industrial ecosystem projects by 2030 to achieve maturity and digital transformation in the following enlarged areas: innovations in the organization of production; technological innovations; product innovations; innovations in human resources; and innovations in public administration. In addition, industrial enterprises should create cross-industry ecosystem cooperation on the basis of efficient technologically advanced productions by using the project principle of management.

6. Conclusions

Upon identifying the problem of achieving maturity by Russian industrial ecosystems, a methodology for assessing their maturity has been developed as a continuation of the existing research in this area. The proposed methodology is distinguished by considering the implementation of digital technologies. The methodology has been tested on the Russian industrial ecosystem as well as on the Russian metallurgy and mining industrial ecosystem. The results showed that the national industrial ecosystem is at a basic level, whereas the metallurgy and mining industrial ecosystem is at an advanced level of maturity. The main directions for increasing the maturity level of industrial ecosystems have been systematized. Further research should focus on updating the maturity assessment of the industrial ecosystem for other subindustries and on developing an optimization model, including the one based on machine learning algorithms.

Acknowledgements

The research was carried out within the framework of the project No. 20-010-00942A of the Russian Foundation for Basic Research.

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