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INDUSTRIAL ECOSYSTEMS DIGITAL TRANSFORMATION AND SUSTAINABLE DEVELOPMENT: INTERPLAY IN REINDUSTRIALIZATION CONTEXT

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Abstract

Amid geopolitical turbulence, reindustrialization and import substitution strategic objectives, digital technologies are increasingly positioned as a key instrument for industrial ecosystems' efficiency enhancing. However, its implementation is often fragmented and localized, focusing on individual enterprises short-term operational efficiency, which may adversely affect industrial ecosystems' long-term sustainability and synergistic potential as a whole. The study aims to develop and test a methodology for quantitatively assessing the reciprocal influence between industrial ecosystems digitalization level and sustainable development. Using official data from 2018–2022 for 14 regions of the Volga Federal District and 19 manufacturing industries, an original composite synergy index is calculated, integrating sustainable development and digitalization indicators. The results confirm the hypothesis that the interaction between sustainable development mechanisms and production ecosystems digital transformation can yield both positive and negative synergistic effects. In response to the identified risks, the concept of "strategically managed digitalization" is considered, which mandates assessing the systemic consequences of digital initiatives and prioritizing investments in technologies that strengthen internal linkages within industrial ecosystems. The proposed methodology can serve as an auxiliary tool for evaluating the balance between short-term adaptability and long-term sustainability during digital transformation.

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Introduction

Reindustrialization and import substitution growing relevance, driven by geopolitical turbulence and sanctions pressure, necessitates identifying new drivers for national industrial capacity sustainable development. In this context, digital technologies are increasingly regarded as pivotal instruments for enhancing the adaptability and competitiveness not only for individual enterprises but also for industrial ecosystems as a whole. In practice, however, digital solutions implementation is often fragmented and localized, focusing primarily on achieving short-term operational efficiency within individual organizations. Despite its apparent economic rationale, this approach can undermine an industrial ecosystem's long-term sustainability and synergistic potential, as it overlooks the systemic interconnections among its participants.

This reality presents researchers with digitalization's systemic consequences investigation challenge. Intensive yet uncoordinated digitalization at the enterprise level may correlate with diminished innovation activity and fragmented cooperative ties, suggesting potential dyssynergia. Furthermore, the reciprocal influence between digitalization and sustainable development level in industrial ecosystems remains inadequately studied, particularly within the Russian economy. Given micro-level data limited availability on enterprise digitalization in official statistics, this study adopts a meso-level approach: a highly industrialized constituent territory in Russian Federation or a leading manufacturing sector is considered a holistic industrial ecosystem. This allows to use aggregated Rosstat data in order to quantitatively assess digital transformation systemic effects.

The research hypothesis posits that the interaction between sustainable development mechanisms and production ecosystems digital transformation can yield either positive or negative synergistic effects. Study's aim is to develop and test a methodic for synergistic effect quantitative assessment arising from the reciprocal influence between sustainable development digitalization level in industrial ecosystems. To achieve this aim, the following tasks are addressed: refining the conceptual framework, building an empirical database using Rosstat data from 2018–2022 for Volga Federal District regions and manufacturing industries, interactions ontological model constructing within an industrial ecosystem and calculating an original composite synergy index. The study's scientific novelty lies in developing and testing a synergy index that allows to assess relationship between digitalization levels and industrial ecosystems systemic characteristics, based on aggregated regional and industry data. The proposed approach is applied to identify digital transformation potential dyssynergy effects within the Russian economy. Practical significance of the research is determined by methodic potential applicability for industrial ecosystem coordinators and public authorities as an auxiliary tool. It can be used to assess systemic consequences of digital initiatives and balance short-term adaptability with long-term sustainability and technological sovereignty.

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The article structure is as follows: Section 2 presents existing researches review on industrial ecosystems transformation under digital technologies influence, along with an analysis of their systemic properties - adaptability and sustainability. Section 3 describes the research methodology, including the empirical basis, indicators system, and synergy index calculation methodic based on regional Rosstat data and data, obtained from manufacturing industries in Russia. Section 4 presents and interprets the obtained results, demonstrating mutual influence between sustainable development and digitalization synergy and dyssynergy. Section 5 discusses the anti-synergy causes, formulates "strategically managed digitalization" concept and offers practical recommendations for industrial ecosystem coordinators and public authorities. Section 6 contains the study's conclusion and main findings.

2. Related works

Contemporary industrial ecosystems are undergoing a fundamental transformation driven by digital technologies, evolving from centralized, linear models towards distributed, platform-based structures founded on co-creation of value (Benitez, Ayala, Frank, 2020; Bakhtadze, Suleykin, 2020; Wolfert et al., 2023; Babkin et al., 2024). As documented in the literature, this transformation ked drivers include technologies such as the Industrial Internet of Things (IIoT), artificial intelligence (AI), cloud computing, digital twins, and 5G networks (Alcácer, Cruz-Machado, 2019; Babkin et al., 2021). These tools enable real-time data exchange, predictive analytics, and process automation, forming the foundation for concepts like smart manufacturing and adaptive supply chains. Digital platforms are considered as industrial ecosystems infrastructural core, integrating diverse participants (suppliers, customers, partners) and facilitating cross-sectoral innovation, resource sharing, new business models development (Ahokangas et al., 2021; Gamidullaeva et al., 2021; Zhou et al., 2024; Das, Dey, 2021). A significant research focus is the transition towards human-centric and sustainable development models (Industry 5.0, circular economy), where digital twins and platforms enhance personnel well-being, resource efficiency, and adaptive management (Villani et al., 2025; Romanova, Igishev, 2025; Dou et al., 2023). Such ecosystems benefits include enhanced collaboration and innovation (Popov, Simonova, Zyrianov 2025; Das, Dey, 2021), alongside cost and resource optimization (Mayorova, 2021; Bakhtadze, 2020). However, their implementation faces challenges, including complex regulatory requirements, data security risks, and open standards need.

Within this context, analyzing the systemic properties that determine ecosystem viability is crucial. In systems theory and organizational studies, adaptability and resilience are recognized as complex systems fundamental yet distinct properties (Mayar et al., 2022; Mavlyanova et al., 2024). A clear distinction between these concepts is necessary for industrial ecosystems.

Adaptability refers to a system's capacity for local, short-term adjustments in response to environmental changes. It involves operational learning, experimentation, and flexibility, considering individual enterprises or ecosystem subsystems, facilitated by intensive information flows and social capital (Lv et al., 2018; Ivanov, 2023). Resilience (stability),

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conversely, characterizes entire industrial ecosystem ability to maintain or return to a target state following disturbances, ensuring long-term predictability and operational continuity through standardization and robust structures (Lv et al., 2018; Ivanov, 2023; Pujiyanti et al., 2024). Although traditionally viewed as paradoxical, the contemporary perspective emphasizes their complementarity: resilience provides a foundation for effective adaptability, which in turn prevents system stagnation (Hellriegel, Slocum, 1972; Horn, Urias, Zweekhorst, 2022). Consequently, an imbalance where excessive focus on the short-term adaptability of individual actors weakens systemic linkages presents a significant risk.

The subsequent consideration is how digital technologies influence this balance. Theoretically, digital technologies are intended to enhance industrial ecosystems key systemic properties by increasing transparency, for instance through blockchain and IoT (Tiwari, 2024; Hsu, Schletz, 2023; Ebinger, Omondi, 2020), strengthening cooperation via platforms (Cepa, 2021; Moshood et al., 2024; Agrawal et al., 2022; Kamolova et al., 2025), and improving forecasting through AI and digital twins (Vössing et al., 2022; Annan, Bajwa, 2024; Ladynin, 2024; Assanova et al., 2025). However, empirical studies indicate that implementation often yields different outcomes. Instead of synergy, ecosystem fragmentation is observed due to technologies isolated adoption. Technologies are deployed for internal processes local optimization, considering individual enterprises, often at system-wide objectives expense. Furthermore, new dependencies on imported platforms create cybersecurity risks and threaten technological sovereignty (Ancillai et al., 2023; Sharma et al., 2020; Liu et al., 2022; Reim, Andersson, Eckerwall, 2022; Hsu, Schletz, 2023; Matheus, Janssen, Janowski, 2020).

In response to this gap between potential and actual effects, strategically managed digitalization concept is emerging (Parviainen et al., 2022; Zaman et al., 2024; Tagscherer, Carbon, 2023). Its essence lies in implementing technologies as unified industrial ecosystem development strategy integral part. This approach entails a systematic process involving stages of goal positioning, current state analysis, roadmap development and implementation, where managerial practices and strategic vision play a central role (Parviainen et al., 2022; Björkdahl, 2020). Particular attention is given to overcoming challenges such as resistance to change and the necessity of developing new competencies (Eller et al., 2020; Kallmuenzer et al., 2024; Rachinger et al., 2019; Calderón-Monge, Ribeiro-Soriano, 2023; Teshayev et al., 2025).

The conducted review identifies a significant research gap. Despite extensive investigation, a deficiency exists in quantitative methodologies for digitalization systemic impact assessment. While specific technologies and general management principles benefits are well-documented, the direct relationship between individual enterprises micro-level digitalization and its integral macro-characteristics of industrial ecosystems remains insufficiently explored. Tools to evaluate whether a digital initiative enhances synergy or, conversely, leads to dyssynergy (anti-synergy) are underdeveloped. This study attempts to partially address this gap by adapting existing approaches to the Russian context.

3. Studies methodology

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This study develops a methodology for calculating a synergy index to quantitatively assess digital technologies influence on industrial ecosystem systemic properties. The methodological foundation employs a regional approach, whereby a highly industrialized Russian Federation constituent territory can be considered a holistic industrial ecosystem (Mityakov, 2024; Makhmudova et al., 2025). Furthermore, the ecosystem approach is extended to individual manufacturing sectors, allowing them to be treated not as isolated elements but as dynamic networks of interconnected entities focused on goods and services joint production. This facilitates aggregated statistical data usage at regional and sectoral levels to evaluate systemic effects.

3.1. Empirical Base and Sample

The research empirical foundation comprises official Russian Federal State Statistics Service (Rosstat) data for the period of 2018–2022 from 14 Volga Federal District regions. This sample allows to make industrial ecosystems comparative analysis with varying sectoral specializations, technological and industrial development levels. An additional sample contains data for 19 of the most developed manufacturing industries.

3.2. Synergy Index Calculation Indicators System (S)

The synergy index is calculated as a function of two composite indices reflecting industrial ecosystem systemic properties:

$$S = f(Sustainability, Digitalization). \quad (1)$$

In order to operationalize each parameter, indicators system is formed based on adapted and verified metrics from Mityakov & Mityakov (2024) and Korovin (2023) works. The system comprises the following indicators:

1. Sustainability Level (K):

- Industrial production growth rate – calculated as the percentage ratio of industrial production volume in the current year to the previous year, minus one hundred (for sectors, data corresponds to the specific manufacturing activity; for regions, it represents manufacturing as a whole).
- Investments in fixed capital growth rate – calculated as the percentage ratio of investment volume in fixed capital in the current year to the previous year, minus one hundred (for sectors, data corresponds to the specific manufacturing activity; for regions, it represents investment in manufacturing as a whole).
- Return on sales (profit ratio to cost) – economic sustainability indicator measured as a percentage, calculated analogously to the previous indicators.
- Innovative goods in total goods shipment share – measured as a percentage, calculable both for sectors (activity types) and for regions regarding manufacturing.
- Current environmental protection expenditures as a percentage of sold industrial products – environmental sustainability indicator, calculated for both sectors and regions.

2. Digitalisation Level (D):

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- Organizations share using personal computers, for sectors and regions, measured in %.
- Organizations share using servers, for sectors and regions, measured in %.
- Organizations share, using local area networks (LAN), for sectors and regions, measured in %.;
- Organizations share, using websites, for sectors and regions, measured in %.

3.3. Synergy index calculation methodic (S)

For each indicator x, three parameters are calculated, characterizing its influence specific aspects on ecosystem sustainability or its digitalization level. The first parameter, x_1(mean value over the observation period), captures the scale effect. The second parameter, x_2 (linear trend slope), reflects indicators' growth/decline dynamics. The third parameter, x_3 (standard deviation), determines risk degree (volatility) associated with the indicator. Subsequently, for sustainability, these parameters are denoted by the letter k, and for digitalisation, by the letter d.

All parameters are normalized within range from -0.5 to +0.5 using min-max normalization. For the first two parameters, which increase positively affects sustainability and digitalization levels, the formula is:

$$x_{norm} = \frac{(x - x_{min})}{(x_{max} - x_{min})} - 0{,}5. \quad (2)$$

For the third parameter, which increase negatively affects sustainability and digitalization levels, inverse normalization is applied:

$$x_{norm} = \frac{(x_{max} - x)}{(x_{max} - x_{min})} - 0{,}5. \quad (3)$$

Composite indices for each indicator are calculated as normalized values arithmetic mean of three parameters (scale, dynamics, risk):

$$k_{norm} = \frac{k_{norm1} + k_{norm1} + k_{norm1}}{3}, \quad (4)$$

$$d_{norm} = \frac{d_{norm1} + d_{norm1} + d_{norm1}}{3}. \quad (5)$$

Industrial ecosystem sustainable development (K) and digitalization (D) integral indices for each region and industry are calculated as arithmetic mean of the composite indices across indicators set:

$$K = \frac{\sum_{i=1}^{n} k_{normi}}{n}, D = \frac{\sum_{i=1}^{m} d_{normi}}{m}, \quad (6)$$

The integral synergy index (*S*) for each regional or sectoral industrial ecosystem is calculated as the sum of the two composite indices:

$$S = K + D. \quad (7)$$

Result Interpretation:

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- S > 0: Positive synergy is observed. Digitalization increase coincides with systemic linkages strengthening.
- S≈0: No synergistic effect is present. Digitalization dynamics doesn't influence industrial ecosystem systemic properties.
- S<0: Anti-synergy (dyssynergy) is observed. An increase in digitalization coincides with sustainability weakening.

Within this study, "synergy" and "dyssynergy" terms describe coordination between industrial ecosystems' key subsystems development trajectories. Positive synergy (S > 0) is interpreted as a situation where intensive digital transformation occurs alongside systemic resilience parallel strengthening. Negative synergy, or dyssynergy (S < 0), indicates these processes misalignment: digitalization increase happens against cooperative potential declining backdrop and overall ecosystem sustainability. Thus, the S index does not directly measure the synergistic effect from cooperation but serves as systemic balance indicator – specifically, balanced development – between technological modernization and industrial ecosystem fundamental properties. The proposed methodology allows to approximate assess digitalization joint dynamics and industrial ecosystem systemic characteristics based on available aggregated data. It should also be noted that the synergy index is sensitive both to indicators selection, weighting and normalization method. Its values should be interpreted as conditional benchmarks rather than precise measurements.

4. Results

Figures 1 and 2 present the calculated integral synergy indices for Volga Federal District regions and key manufacturing sectors, respectively, which are analyzed as industrial ecosystems.

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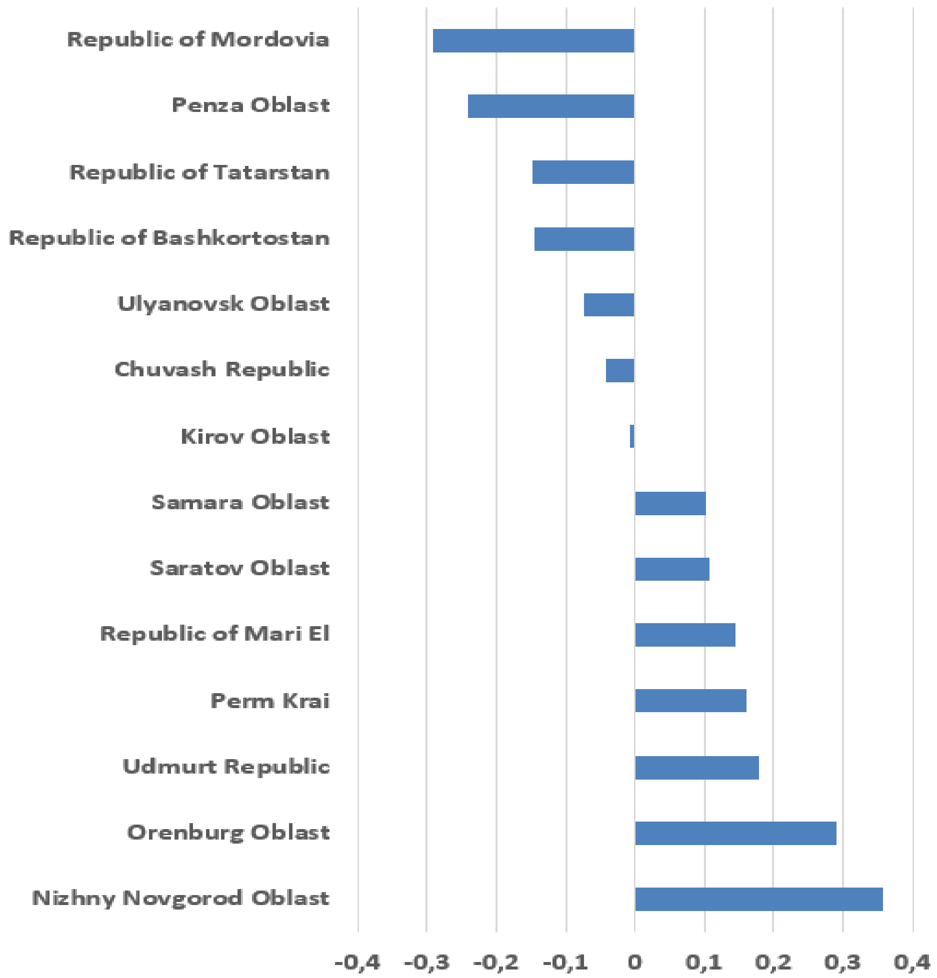

Fig. 1. Volga Federal District Integral Synergy Indices Regions

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Fig. 2. Integral Synergy Indices for Manufacturing Sectors

The results presented in Figures 1 and 2 demonstrate digitalization ambiguous impact of on the systemic properties of industrial ecosystems. The integral synergy index varies significantly across both Volga Federal District regions and manufacturing sectors, indicating substantial differentiation in digital transformation nature and consequences. Among regions, Nizhny Novgorod Oblast (0.356) exhibits the highest synergy level, followed by Orenburg Oblast (0.292) and Udmurt Republic (0.178). These territories likely benefit from a more coordinated approach to implementing digital solutions, which strengthens cooperative ties and innovation activity. Conversely, several regions, including Tatarstan (–0.149), Bashkortostan (–0.144), and Mordovia Republics (–0.291), show negative index values. This suggests dyssynergies presence: despite digitalization high level at individual enterprises,

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industrial ecosystems systemic resilience and cooperative potential as a whole show no improvement or are declining.

A similar pattern is observed at the sectoral level. The highest synergy indices are recorded in high-technology sectors such as Computer and Electronic & Optical Product Manufacturing (0.346), Metallurgy (0.334) and Machinery and Equipment Manufacturing (0.305). In these sectors, digital technologies appear to be integrated into system-wide value creation processes. Meanwhile, sectors such as Motor Vehicle Manufacturing (–0.113), Pharmaceutical Manufacturing (–0.043), and especially Wood and Cork Manufacturing (–0.257) demonstrate negative index values. This may be linked to digital solutions fragmented implementation, local optimization focus and persistent dependence on imported technological platforms.

Collectively, these findings confirm research hypothesis: mutual influence between sustainable development mechanisms and digital transformation production ecosystems can yield both positive and negative synergistic effects.

5. Discussion

The empirical results confirm research hypothesis: digital technologies intensive adoption by industrial ecosystem individual participants, without strategic coordination, does not automatically enhance its systemic resilience. Conversely, in Volga Federal District several regions and manufacturing sectors, an anti-synergy effect is observed: a situation where an increase in digitalization level of coincides with rising systemic vulnerability. This outcome is not a consequence of digital technology adoption per se, but rather stems from its implementation manner in holistic ecosystem strategy absence.

Dyssynergy emergence can be explained by three interrelated factors. Firstly, pressure to achieve short-term economic results amid geopolitical uncertainty and sanctions drives enterprises towards internal processes local optimization at the expense of inter-organizational linkages development. In this context, digitalization becomes a tool for isolation rather than integration, undermining industrial ecosystem's cooperative dynamics foundations. Secondly, coordination lack among ecosystem participants leads digital infrastructure fragmentation: solutions disparate implementation without harmonized standards, data architectures and business objectives preclude economies of scale, collaborative learning, and cross-sectoral innovation. Thirdly, persistent reliance on imported software platforms and cloud services creates risks to technological sovereignty, limits adaptability to national priorities and increases vulnerability to external constraints, directly contradicting import substitution and reindustrialization strategic goals.

In response to these identified risks, the study examines "strategically managed digitalization" concept. While existing research emphasizes strategic vision need and coordination in technology adoption, this study proposes adapting this approach through digital initiatives' systemic consequences quantitative assessment. The core proposal is that any digital initiative should undergo preliminary or retrospective evaluation of its impact on industrial ecosystem integral properties – specifically, using developed synergy index. This

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approach can form diagnostic tools basis to identify dyssynergies. For instance, IIoT implementation project should consider not only internal efficiency gains but also integration potential with value chain partners, considering national standards and domestic platforms.

Strategically managed digitalization principle could be in prioritizing systemic solutions over local ones. State support and investment should be directed primarily towards technologies that strengthen internal linkages within the industrial ecosystem: open-source platforms for collaborative development, national industrial clouds with open interfaces, and standardized data exchange formats among enterprises, research institutions, and universities. Such solutions form ecosystem "digital fabric", enhancing its adaptability without compromising resilience and sovereignty. Furthermore, "strategically managed digitalization" concept can be directly applied in practice by industrial ecosystem coordinators (e.g., industrial clusters management companies, techno parks, industry associations) and public authorities. Specifically, it enables procedures preliminary assessment implementation for digital projects systemic consequences before their funding or scaling, state support reorientation from local to systemic solutions and both regional or industry synergy dynamics monitoring.

It must be acknowledged that proposed methodic has certain limitations. It relies on aggregated regional and sectoral data, which precludes individual enterprise behavior direct analysis or intra-sectoral variations identification. Furthermore, the synergy index calculation assumes a conditional benchmark for digitalization level close to unity, requiring additional verification in other contexts. Nevertheless, it is potentially extrapolatable to economy micro-level: within detailed data on individual organizations digitalization and cooperative linkages, a similar index could be used to assess its contribution to industrial ecosystems' resilience. This opens prospects for developing personalized recommendations for individual ecosystem participants digital transformation trajectory. It is also important to emphasize that obtained results depend on indicators composition and normalization. Altering these parameters can change index's sign, indicating conclusions conditional nature and careful interpretation need.

Thus, the transition from reactive to strategically managed digitalization represents not only a technical but also an institutional challenge, requiring industrial ecosystem coordinators and public authorities roles reconsidering in digital infrastructure balanced development ensuring.

6. Conclusion

The study confirms the hypothesis that industrial ecosystem participants' digital advancement does not, by itself, guarantee enhanced systemic resilience or synergistic potential. Volga Federal District regions and manufacturing sectors data analysis over the period of 2018–2022 revealed significant differentiation in digital transformation systemic effects. Alongside positive synergy instances (e.g., Nizhny Novgorod Oblast among regions, Computer and Electronic & Optical Products manufacturing among sectors), dyssynergy cases were recorded (e.g., Republic of Mordovia among regions, Wood and Cork products and Motor Vehicles manufacturing among sectors). These findings indicate that, without strategic coordination, digitalization can lead to fragmented cooperative ties, local optimization at the expense of system-wide goals and increased technological dependence on imported solutions.

Consequently, digital technologies can exert either a positive or negative influence on industrial ecosystems sustainability, contingent upon implementation context. In turn, industrial ecosystem governance mechanisms can similarly have either a positive or negative impact on digital transformation efficacy. In response to the identified risks, the paper explores "strategically managed digitalization" concept potential application. This approach mandates digital initiative systemic consequences assessment through its impact on industrial ecosystem integral properties, specifically, cooperative potential, innovation activity, and resilience.

The synergy index developed in this study can serve as an assessment practical tool, enabling industrial ecosystem coordinators and public authorities to promptly identify dyssynergies and reallocate resources towards systemic solutions. These include domestic open-source platforms, standardized data exchange formats, and national industrial clouds. The obtained results underscore systemic context critical importance when planning digital transformation within reindustrialization and import substitution framework.

It is important to note that digitalization mechanisms are evolving rapidly. Industrial enterprises are now beginning to adopt tools such as machine learning, Big Data analysis, and IIoT. Once sufficient statistical material has been accumulated and analyzed, it will be possible to compare 'early-stage' and 'advanced' digitalization effects in terms of its reciprocal influence on industrial ecosystems' sustainable development indicators.

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