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Research Article

A Structural-Functional Model for Managing Digital Maturity in a Cluster-Based, Innovation-Active Industrial Ecosystem within Industry 5.0

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Abstract: The rapid advancement of technologies in the context of Industry 5.0 necessitates profound changes and transformations in managing digital maturity within industrial enterprises and clustered industrial ecosystems. This consequently necessitates the creation of adaptive models to ensure sustainable development and improve competitiveness. Effective digital maturity management is a crucial factor in the successful integration of technology into business processes, emphasizing the scientific novelty and relevance of this study. Therefore, this study aimed to develop a structural-functional model for managing digital maturity in clustered innovation-active industrial ecosystem (CIAIE). To achieve this objective, contextual analysis and case study methods were used to analyze the characteristics of Industry 5.0, identify features specific to CIAIEs, and examine the nature of digital maturity in industrial enterprises. Furthermore, system analysis methods served as the foundation for developing a structural-functional model, and modeling methods were used to create an original strategy for evaluating digital maturity. This study identified an expanded terminology in industrial economics and digital economy, based on the interpretations of the concepts "clustered innovation-active industrial ecosystem" and "digital maturity of clustered innovation-active industrial ecosystem", the development of a structural-functional model for managing digital maturity of CIAIE, and a corresponding evaluation method. The results showed that achieving a "very high digital maturity" level in CIAIE required an average investment increase of 25%. This increase significantly improved key parameters such as technical equipment, organizational structure, human resources, product customization, and cybersecurity, based on the principles of Industry 5.0.

Keywords: Cluster innovative and active industrial ecosystem; Digital maturity Digital platform; Digital tools; Industry 5.0

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1. Introduction

In the context of digital transformation across economic sectors and the transition to Industry 5.0, characterized by human-centricity, sustainable development, and the harmonious interaction between humans and modern technologies, several studies have been dedicated to investigating the characteristics of digital transformation (Babkin et al., 2022) and the impact on corporate technological innovation (Carbajal Piña et al., 2024; Fang and Liu, 2024), digital supply chains (Lee et al., 2024), and the integration of digital technologies within the framework of circular economy principles (Narula et al., 2024; Zhen and Yao, 2024; Bolsunovskaya et al., 2023). Previous studies have also explored the specifics of human resources management (Cui and Zhuang, 2024; Zhang and Chen, 2024), risk management (Shang et al., 2023), and the institutional environment in the context of digital economy (Wei and Li, 2024; Shaposhnykov et al., 2023). One of the objectives was to address the challenges arising during digital transformation of business processes in industrial enterprises and clusters (Freitas et al., 2023), as well as the transformative processes occurring in the educational environment, which supplies the production sector with highly qualified personnel possessing essential digital skills (Voronkova et al., 2023). Scientific articles place particular emphasis on the influence of COVID-19 on the assessment of digital maturity in industrial enterprises during the pandemic and post-pandemic periods (Forliano et al., 2023; Ka et al., 2023; de Barros et al., 2021), as well as on understanding the concept of digital maturity (Fang and Liu, 2024; Li and Liu, 2024; Alcácer et al., 2021) and strategies to its assessment (Benazzouz and Auhmani, 2024; Brodny and Tutak, 2023; Cognet et al., 2023; Tubis, 2023) in the new economic realities. Experts have also shown the specific features of Industry 5.0 (Ghobakhloo et al., 2024; Kaswan et al., 2024; Olsson et al., 2024; Rehman and Umar, 2024; Visvizi et al., 2024), an understanding of which enables a more effective assessment of digital maturity in complex, integrated structures, including clustered innovation-active industrial ecosystems (Hetmanczyk, 2024; Babkin et al., 2023; Hein-Pensel et al., 2023).

This study advanced a novel conceptualization of CIAIE in order to address the identified gaps, reinterpreting it as an adaptive, intelligence-driven network characterized by recursive human-machine symbiosis, dynamic resource flows, and embedded sustainability resonating with Industry 5.0 principles. The proposed structural-functional model transcends traditional linear and stage-based maturity frameworks by incorporating operationalizable mechanisms for human-centricity, cobot integration, and circularity within digital ecosystems. This contextualized method not only offers a granular, scalable methodology for assessing digital maturity but also emphasizes the transformative potential of CIAIEs to foster resilience and value co-creation under complex industrial dynamics. These contributions distinguish model from existing paradigms, such as Deloitte's and Forrester's Digital Maturity Models, and underscore its necessity for addressing contemporary challenges in digital transformation. This study aimed to develop a structural-functional model for managing digital maturity in clustered innovation-active industrial ecosystem. The objectives are defined as follows: expanding the terminological apparatus of industrial economics and digital economy, particularly regarding the author's interpretation of clustered innovation-active industrial ecosystem and digital maturity; developing a structural-functional management model along with a strategy for its evaluation. The scientific novelty of this study lies in the development of a structural-functional model for managing digital maturity in clustered innovation-active industrial ecosystem, oriented toward the integration of Industry 5.0 principles, as well as an original strategy for its evaluation.

2. Methods

Figure 1 presents the sequential methodology adopted for the study, detailing the process from data collection to comparative evaluation. Each step systematically built upon the previous one to ensure a robust, Industry 5.0-alifgned strategy for managing digital maturity in clustered innovation-active industrial ecosystems (CIAIEs). The framework emphasized qualitative and

quantitative rigor, integrating advanced methods like fuzzy logic modeling and comparative benchmarking to validate the proposed model's applicability and effectiveness.

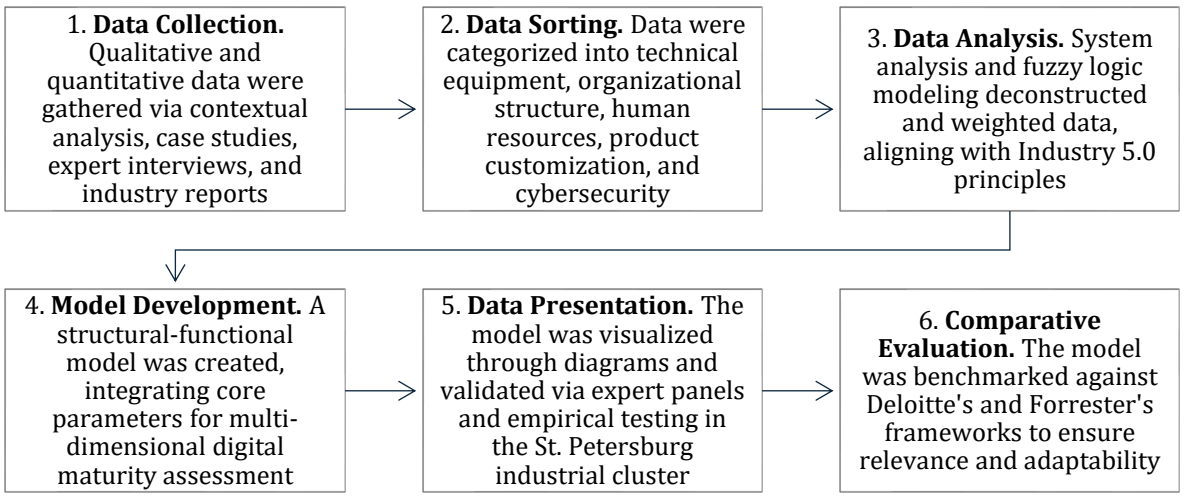

Figure 1 Step-by-Step Methodological Framework for Developing a Structural-Functional Model of Digital Maturity Management

A system-analysis method was used to develop, describe, and graphically represent the proposed structural-functional model for managing digital maturity in CIAIEs. This methodological foundation integrated the core principles of Industry 5.0, emphasizing human-centricity, sustainability, and technological symbiosis. Modeling process produced an original method for assessing digital maturity, incorporating parameters such as technical equipment, organizational structure, staffing, products customization, and cybersecurity. The multidimensional digital-maturity scale refined the traditional 0–1 metric by adding factors like organizational culture, resource allocation, and environmental dynamics, thereby addressing the limitations of oversimplified scales. Validation of a structural-functional model was explained as a multi-phase process. An initial expert-panel review was carried out to provide qualitative insights, followed by empirical testing within the St. Petersburg industrial cluster. This empirical phase used both quantitative and qualitative methods to substantiate model's effectiveness. Comparative analysis with established frameworks, such as Deloitte's Digital Maturity Model, further evaluated model's added value, ensuring its relevance and applicability across diverse industrial contexts. To mitigate potential bias in parameter weighting, fuzzy logic was applied, enabling a more objective and adaptive assessment mechanism. Each parameter was justified by its alignment with Industry 5.0 principles: technical equipment underpinned cyber-physical integration, organizational structure fostered interconnectivity and agility, human resources reflected human-centricity, product customization advanced sustainability goals, and cybersecurity ensured systemic integrity. Moreover, external dynamic factors, including market disruptions and regulatory shifts, were integrated into model, improving its adaptability and real-world applicability for managing digital transformation within CIAIEs.

3. Results and Discussion

A crucial aspect of digital maturity management is identifying the essence of CIAIE, understood as an association of industrial enterprises that stimulates innovation and improves the competitiveness of each participant. CIAIEs are characterized by networked interactions that facilitate the achievement of common objectives and the effective implementation of modern digital solutions, such as unified digital platforms, to foster communication, the development of new, high-value products, as well as existing offerings. These ecosystems promote joint value creation, with each participant actively contributing to collective growth and innovation. CIAIEs also form

adaptive environments that accelerate business processes and manage both static and dynamic innovative and digital potential for individual enterprises and the ecosystem as a whole. These ecosystems balance competition and cooperation through the development of unified standards, technologies, and infrastructure, ensuring synergy and sustainable development in line with Industry 5.0 principles. Moreover, the ecosystems are characterized as "self-developing structures" due to their inherent dynamism in both functioning and development, including mechanisms for adapting to changing market conditions and supporting the gradual transition of economies toward Industry 5.0. Industry 5.0 is defined by human-centricity, industrial production customization, the pursuit of sustainable development goals, inclusivity, social responsibility, and the creation of cobots, which represent the integration of highly skilled workers and collaborative robots.

Digital maturity of CIAIE refers to the nature and extent of the implementation of modern digital and innovative solutions in company's business processes. It is a comprehensive method that assesses both current capabilities (digital potential) and abilities of complex integrated industrial structures/innovation-active industrial clusters (digital foresight) within the context of Industry 5.0. Figure 2 presents a structural-functional model for managing digital maturity in CIAIE, comprising five levels.

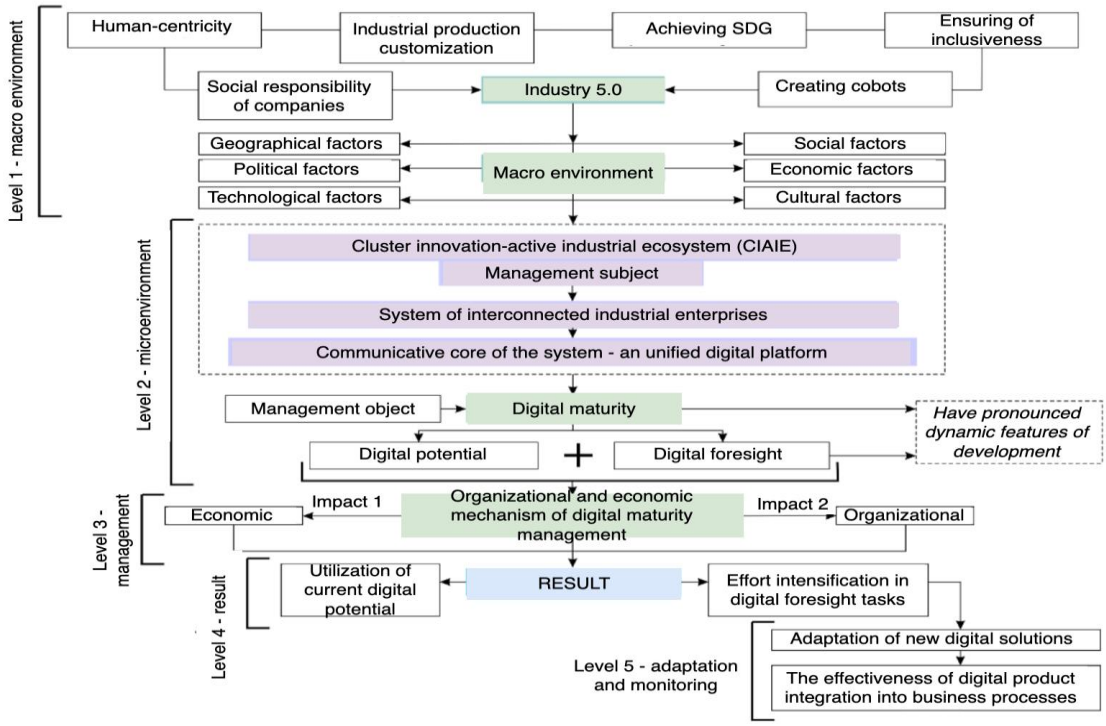

Figure 2 A Structural-Functional Model for Managing Digital Maturity in Clustered Innovation-Active Industrial Ecosystem

The *macroenvironment* forms the foundational layer, comprising geographical, political, technological, social, economic, and cultural factors. Among these, the technological aspect plays a central role in driving digital transformation, enabling industrial ecosystems to adapt business processes and organizational structures to evolving market demands. The *microenvironment* focuses on CIAIE, composed of interconnected enterprises linked through unified digital platforms that facilitate communication and coordination. Digital maturity within this environment is assessed by evaluating current digital potential and anticipating future capabilities through digital foresight, which supports strategic development. The *management* level is defined by an organizational-economic mechanism designed to improve digital maturity. This mechanism includes modifying structures and processes to cultivate digital corporate culture and improve inter-organizational coordination through digital platforms, alongside economic strategies,

ensuring resource allocation, stimulating innovation, and fostering a favorable investment climate. The *result* and the process of *adaptation and monitoring* are interconnected. Initial efforts focus on leveraging current digital potential to build competitive advantages. Concurrently, strategic planning and digital foresight guide the adoption of new digital solutions, while continuous monitoring ensures the effective integration of these solutions into business processes, resonating with the long-term objectives of CIAIE.

This scientific and practical study offered numerous methodologies for assessing digital maturity (Digital Maturity Model - DMM), with the following standing out:

1. Deloitte's Digital Maturity Model: This model comprises key components such as strategy and leadership, organizational culture and innovation, technology and its utilization (primarily AI, Big Data, IoT, etc.), customers experience, and organizational structure—a total of 28 indicators. Its drawbacks include a focus on large organizations, making it less applicable to smaller enterprises. Model also shows a low level of individualization, as it relies on relatively standard assessment criteria, which could neglect the specific needs of firms and the contextual factors influencing the formation of competitive advantages in the market. In addition, model lacks emphasis on cybersecurity, an increasingly crucial criterion in modern digital maturity assessments.

2. Forrester Digital Maturity Model 4.0: This model assesses digital maturity across four groups of criteria: Culture - evaluates a company's willingness to improve employees capabilities through digital technologies; Technology - assesses the the use and adaptation of modern digital products within enterprise operations; Organization - examines the company's readiness to support, manage, and measure the performance of digital solutions; Insights - evaluates how effectively the firm leverages customers data to assess operational efficiency and develop strategies. Some drawbacks of model include the complexity of result interpretation, particularly regarding the collection and analysis of marketing information, and limited flexibility, as model may not fully adapt to evolving market conditions. BCG's digital maturity, Digital Acceleration Index: This model includes 36 indicators for assessing digital strategy, culture, technology, and digital transformation capability. However, it has several limitations, namely a focus on strategic vision, which can lead to neglecting tactical and operational indicators influencing digital maturity; as well as financial and resource constraints businesses face when attempting to attain higher maturity levels.

Other prominent methodologies include: McKinsey's Digital Quotient (DQ) model, Capgemini and MIT models, Gartner models, CMMI (Capability Maturity Model Integration—primarily used for process assessment but adaptable for evaluating digital maturity of industrial enterprise/cluster), Digital Maturity Benchmark (Google & BCG), PwC (PricewaterhouseCoopers), HBR (Harvard Business Review), the Business Process Maturity Model from Business Process Incubator, and others (Babkin et al., 2024; Novikov and Babkin, 2014). All assessment methodologies can be categorized into three key groups, namely quantitative, qualitative, and mixed, combining elements of the first two. Studies have shown that mixed is the most commonly used, as methodology enables assessment based not only on quantitative parameters but also on expert input. This ensures comprehensiveness, capacity, depth, reliability, and reproducibility, characteristics particularly relevant when adapting effective methodologies to an increasing number of industrial enterprises of varying sizes. Unlike conventional models relying on standardized criteria and primarily targeting large enterprises, the proposed structural-functional model for managing digital maturity in CIAIE offers flexibility. It integrates adaptive parameters and uses fuzzy logic for evaluation, enabling customization to the dynamic nature of CIAIE. In contrast to existing models that often neglect cybersecurity and products customization, model incorporates these aspects as core components, ensuring a comprehensive assessment based on Industry 5.0 principles of human-centricity, sustainability, and technological symbiosis. Although traditional frameworks tend to provide static assessments, this model incorporates dynamic elements of digital potential and foresight, allowing for continuous adaptation to technological advancements and market disruptions. These distinctions position the methodology used as a more context-sensitive and adaptable tool for managing digital transformation within complex industrial

ecosystems.

Previous studies presented a methodology for assessing digital potential of a system-forming innovation-active industrial cluster. Although this methodology comprehensively considered key indicators, it had a relatively static nature. In the current context, understanding the dynamic component of digital maturity is essential (Babkin et al., 2021; Tashenova et al., 2020; Babkin et al., 2019; 2017). Therefore, to assess digital maturity of CIAIE, the following groups of parameters and the corresponding subparameters are proposed:

1. Technical Equipment (TechEq): This group includes indicators regulating the technical readiness of CIAIE to implement and effectively use various digital solutions.
2. Organizational Structure (OrgStr): Comprising indicators that characterize the organizational configuration of CIAIE and its capacity to adapt to digital transformation in business processes.
3. Human Resources (HR): These indicators determine the quantitative and qualitative sufficiency of the workforce, as well as the readiness to respond to digital changes in both current and strategic business activities.
4. Products and Their Customization (PrCust): This group evaluates CIAIE's ability to develop, implement, and commercialize customized products to improve customers satisfaction and meet specific market demands.
5. Cybersecurity (CyberSec): Indicators in this group describe CIAIE's capacity for data protection and information security management.

Digital maturity of CIAIE can be expressed as an integral indicator; $\text{Integral\_DigMaturity}_{\text{CIAIE}}$; incorporating the parameter groups described.

$$\text{Integral\_DigMaturity}_{\text{CIAIE}} = \frac{(\alpha_1 \text{TechEq} + \alpha_2 \text{OrgStr} + \alpha_3 \text{HR} + \alpha_4 \text{PrCust} + \alpha_5 \text{CyberSec})}{n}$$

Where, TechEq: represents the technical equipment indicators; OrgStr: organizational structure indicators; HR: human resources indicators; PrCust: products and customization indicators; CyberSec: cybersecurity indicators; $\alpha_{1\ldots n}$: weighting coefficients for each group of indicators; determined through expert evaluation.

Each indicator group is expressed as an integral value, obtained by aggregating and standardizing the indicators within the group, to facilitate calculation of CIAIE's overall digital-maturity score, ranging from 0 to 1.

Using this scale, three levels of digital maturity can be identified:

- 0-0.3 (low digital maturity): characterized by weak adoption of digital solutions, no strategy for implementing new technologies; limited managerial understanding of the need for digital transformation; no unified digital platform for data management and communication; and a general low level of employees digital skills.
- 0.3-0.5 (medium digital maturity): some business processes are automated or robotized; individual software solutions and products, often with basic functionality, have been implemented; employees have digital skills, but training and retraining are not systematic; and digital-transformation efforts are managed locally within individual companies or divisions, with no unified digitalization program.
- 0.6-0.8 (high digital maturity): digital solutions are integrated into nearly all activities, although the unified digital platform still consists of modules that support specific operations, such as financial, marketing, production, etc.; an integrated digital-transformation program is in place, with clear target indicators resonating with market trends and Industry 5.0 principles and adaptable to macro-environment changes; personnel are highly are highly qualified and digitally skilled; digital corporate culture is established; the organizational structure is flexible enough to support ongoing digital initiatives; and digital infrastructure is optimized for ecosystem tasks, including customized production.

- 0.9-1.0 (very high digital maturity) characterized by the digitization and integration of processes within a unified digital platform, customized to meet the specific demands of CIAIE and capable of supporting all types of activities to ensure maximum efficiency; advanced analytics and machine learning tools are used to optimize production processes, including through the operation of digital factories and the active use of digital twins; the implementation of IIoT, blockchain, cloud computing, additive technologies, etc., as an integral part of CIAIE's strategic development; employees have advanced digital competencies, enabling faster and more adaptive implementation of new digital solutions; and a clear pathway toward transitioning to a new form of economic activity – building and developing digital business environment characterized by customized production and a high level of cybersecurity, fully resonating with the principles of Industry 5.0.

The investigation on managing digital maturity within clustered innovation-active industrial ecosystem was conducted using the "Development of Information Technology, Radio Electronics, Instrument Making, Communication Equipment, and Info-Telecommunications in St. Petersburg" cluster as a case study. It is important to note that achieving the minimum threshold of the "Very High Digital Maturity" level (i.e., 0.9 on the interval scale) requires an average increase of 25% in current investments. This increase can increase the overall indicator, thereby improving the values across all criterion groups due to the enhanced level of digital maturity (Table 1).

Increasing the identified parameters in CIAIE led to systemic improvements across subcomponents within each category. In terms of *Technical Equipment (TechEq)*, the integration of advanced technical programs for digital transformation ensures streamlined production and business processes. Technological readiness manifests through the deployment of advanced infrastructure, including unified digital platforms, cloud solutions, additive manufacturing, and the Industrial Internet of Things (IIoT). Robust energy, transportation, and logistics networks, alongside incubators and accelerators, facilitate the seamless adoption and testing of innovative solutions, fostering an environment conducive for continuous technological advancement. For *Organizational Structure (OrgStr)*, greater integration among ecosystem participants amplifies synergistic outcomes. Furthermore, the development of digital corporate culture and leadership, particularly among middle and senior management, strengthens strategic coherence. Information transparency provides accessible data to support managerial decision-making, while unified digital platforms enable the automation and coordination of projects. Process modularity and structural flexibility support scalability and adaptability, allowing multi-level teams to efficiently execute complex, multi-component initiatives. Decentralized digital authority further accelerates responsiveness to innovation, improving communication clarity and operational fluidity. In the domain of *Human Resources (HR)*, digitally competent workforce is essential for the successful implementation of platform solutions. Continuous training and dynamic retraining programs ensure adaptability to evolving market demands. Effective recruitment strategies attract talent with requisite digital skills, while a robust digital communication culture fosters collaboration across CIAIE. The capacity to handle interdisciplinary tasks strengthens cross-functional teams, while incentive systems and career advancement opportunities promote sustained engagement. The integration of remote work capabilities, including digital nomadism, fosters a culture open to digital cooperation and innovation. *Products and Their Customization (PrCust)* benefit from market-driven innovation strategies that emphasize modular product development tailored to customers requirements. Advanced digital solutions enable seamless products configuration through user-friendly interfaces, such as online configurators. Predictive customization, informed by marketing analysis and users data, anticipates client needs, facilitating proactive product offerings. This adaptive customization process improves both customers satisfaction and operational efficiency within CIAIE. Finally, *Cybersecurity (CyberSec)* ensures the integrity of networks, applications, and digital platforms through rigorous security measures implemented across all management levels. Operational security frameworks, disaster recovery protocols, and comprehensive backup strategies are used to mitigate risks. Employees awareness programs further reinforce cybersecurity

resilience, relating CIAIE's digital infrastructure to the highest standards of information security and operational robustness.

Table 1 Increase in Indicators Characterizing Digital Maturity of CIAIE "Development of Information Technology, Radio Electronics, Instrument Making, Communication Equipment, and Info-Telecommunications in St. Petersburg" Upon Reaching the Lower Boundary of the "Very High Digital Potential" Scale

Parameter Name	Value in terms of parameters (current), Integral Value	Increase in Indicator upon Reaching the Upper Boundary of Digital Maturity
Technical Equipment (TechEq)	0.3	+0.75
Organizational Structure (OrgStr)	0.1	+0.25
Human Resources (HR)	0.1	+0.25
Products and Their Customization (PrCust)	0.3	+0.75
Cybersecurity (CyberSec)	0.2	+0.25

Practical recommendations for managing digital maturity of the considered CIAIE emphasize the importance of strategic financial investment, technological enhancement, and organizational development. Achieving the lower boundary of the highest digital maturity level requires increasing financial allocations by an average of 25% over three years. The investment should prioritize the development of technical equipment and the creation of customized products, as these carry the greatest weight in the integral assessment and significantly contribute to the formation of a unified digital ecosystem. Moreover, fostering a robust digital corporate culture is essential for shaping a modern, adaptive organizational structure resonating with Industry 5.0 principles.

The proposed structural-functional model provides practical guidance by deploying unified digital platforms to improve real-time data integration and collaboration within CIAIE. Parameters such as Technical Equipment (TechEq) align with established frameworks like Deloitte's Digital Maturity Model, emphasizing digital infrastructure and AI solutions. However, model used in this study embedded technical readiness within the dynamics of inter-organizational collaboration, cyber-physical integration, and customization reflective of Industry 5.0 principles. Organizational Structure (OrgStr) and Cybersecurity (CyberSec) also resonate with components of Forrester's model but differ by the emphasis on sustainability, human-centricity, and customization. Model incorporates predictive analytics for product customization and zero-trust frameworks to ensure adaptability and resilience. Improved visual elements clarify model's components, bridging theory and practice while supporting tailored digital transformation across diverse industrial ecosystems. A structural-functional model for managing digital maturity in CIAIE is further validated by insights from various industries and regions, confirming its robustness within the framework of Industry 5.0. Studies have emphasized the importance of infrastructure, cybersecurity, and digital platforms for resilience and efficiency, supporting the focus on technical equipment, cybersecurity, and collaboration (Benazzouz and Auhmani, 2024; Narula et al., 2024; Ka et al., 2023). Geographic analyses also showed how infrastructural investments improved digital maturity, supporting the recommendation for increased financial allocations (Brodny and Tutak, 2023). Global perspectives on Industry 5.0 emphasize the significance of human-centricity, sustainability, and technological convergence, principles embedded in the used model (Hein-Pensel et al., 2023; Alcácer et al., 2021). Collectively, the results reinforced model's relevance and adaptability across diverse contexts.

4. Conclusions

In conclusion, the analyzed study supported the following conclusions. As digital transformation accelerated across economic sectors and several countries advanced toward Industry 5.0, managing digital maturity within CIAIE had become increasingly relevant. CIAIE was characterized by networked interaction, joint value creation, the formation of an adaptive

environment for innovation and digital development, as well as the balancing of competition and cooperation. The specifics of managing these integrated structures could be understood through a structural-functional model comprising five levels: the macroenvironment (political, economic, cultural, geographical, technological, and social factors, as well as the specific characteristics of Industry 5.0, significantly impacting functioning of CIAIEs in contemporary conditions); the microenvironment (where unified digital platforms were identified as the communicative core, and the object of management was digital maturity, represented as a combination of digital potential and digital foresight); management (including an organizational-economic mechanism); the result, which could be presented within two areas of intensified efforts, namely developing current digital potential and implementing digital-foresight tasks (possessing pronounced dynamic characteristics); adaptation of new digital products and monitoring their effectiveness. Considering the variety of existing assessment strategies, this study proposed an original method to analyze five parameter groups, namely technical equipment, organizational structure, human resources, products and their customization, and cybersecurity. The sub parameters within each group had dynamic characteristics, enabling a more adaptable and flexible assessment resonating with rapidly evolving market conditions and digital transformations.

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Author Contributions

Aleksandr Babkin and Elena Shkarupeta developed the concept and research design. Aleksandr Babkin, Dinara Mamrayeva, and Larissa Tashenova contributed to the methodology. Dier Karimov and Abduvakhob Umarov performed the formal analysis. Elena Shkarupeta and Larissa Tashenova prepared the original draft. Review and editing were performed by Elena Shkarupeta and Aleksandr Babkin. Visualization was conducted by Larissa Tashenova and Abduvakhob Umarov. Elena Shkarupeta supervised the project administration. Funding for the research was provided by Aleksandr Babkin through the Russian Science Foundation (Project No. 25-18-00978). All authors have read and approved the final manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

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