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

Abstract. The rapid advancement of technologies in the context of Industry 5.0 necessitates profound changes and transformations in the management of digital maturity within industrial enterprises and complex clustered industrial ecosystems. This, in turn, necessitates the creation of adaptive models that ensure sustainable development and achieve a high level of competitiveness. Effective digital maturity management is also a crucial factor for successful technology integration into company business processes, highlighting the scientific novelty and relevance of the research conducted in this work. The aim of this scientific article is to develop a structural-functional model for managing digital maturity in a clustered innovation-active industrial ecosystem (CIAIE). The following methods were identified: contextual analysis and case study methods, which allowed for the analysis of the characteristics of Industry 5.0 development, the identification of characteristics inherent to CIAIEs, and the examination of the essence of digital maturity in industrial sector enterprises; system analysis methods, based on which a structural-functional model for managing digital maturity was created; and modeling methods, which were used to develop an original approach to its evaluation. The main results obtained during the research are: an expanded terminology of industrial economics and the digital economy regarding the author's interpretation of the concepts "clustered innovation-active industrial ecosystem" and "digital maturity of a clustered innovation-active industrial ecosystem"; a developed structural-functional model for managing the digital maturity of a CIAIE and an approach to its evaluation. The study's findings indicate that achieving a 'very high digital maturity' level in clustered innovation-active industrial ecosystems requires an average investment increase of 25%. This increase significantly improves key parameters such as technical equipment, organizational structure, human resources, product customization, and cybersecurity, ultimately aligning with the principles of Industry 5.0.

Keywords: cluster innovative and active industrial ecosystem; digital platform; digital tools; Industry 5.0; digital maturity

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 of humans and modern technologies, a substantial body of research is dedicated to exploring the characteristics of digital transformation (Babkin et al., 2022) and its impact on corporate technological innovation (Carbajal Piña, Acur and Cetindamar, 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 (Bolsunovskaya et al., 2023; Narula et al., 2024; Zhen and Yao, 2024). Several works delve into 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 the digital economy (Shaposhnykov et al., 2023; Wei and Li, 2024). They also address problematic situations arising during the digital transformation of business processes in industrial enterprises and clusters (Freitas Junior et al., 2023) and the transformative processes taking place in the educational environment, which provides the production sector with highly qualified personnel possessing necessary digital skills (Voronkova, Nikitenko and Vasyl'chuk, 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 (Joaquim F. de Barros et al., 2021; Forliano et al., 2023; Ka, Ying and Tang, 2023), as well as on understanding its essence (Alcácer et al., 2021; Fang and Liu, 2024b; Li and Liu, 2024) and approaches to its assessment (Brodny and Tutak, 2023; Cognet et al., 2023; Tubis, 2023; Benazzouz and Auhmani, 2024) in the new economic realities. Researchers also highlight the specific features of Industry 5.0 (Ghobakhloo et al., 2024; Kaswan et al., 2024; Olsson, Eriksson and Carlsson, 2024; Rehman and Umar, 2024; Visvizi et al., 2024), understanding which enables more effective assessment of digital maturity in complex integrated structures, including clustered innovation-active industrial ecosystems (Babkin et al., 2023; Hein-Pensel et al., 2023; Hetmanczyk, 2024).

To address the identified gaps, this research advances a novel conceptualization of a CIAIE, reinterpreting it as an adaptive, intelligence-driven network characterized by recursive human-machine symbiosis, dynamic resource flows, and embedded sustainability aligned 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 approach not only provides a granular, scalable methodology for assessing digital maturity but also highlights the transformative potential of CIAIEs to foster resilience and value co-creation under complex industrial dynamics. These contributions distinguish the 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 scientific article aims to develop a structural-functional model for managing digital maturity in a clustered innovation-active industrial ecosystem. The objectives are defined as follows: expanding the terminological apparatus of industrial economics and the digital economy, particularly regarding the author's interpretation of a clustered innovation-active industrial ecosystem and digital maturity; developing a structural-functional model for management and an approach to its evaluation. The scientific novelty of this article lies in the development of a structural-functional model for managing digital maturity in a clustered innovation-active industrial ecosystem, oriented towards the integration of Industry 5.0 principles, as well as an original approach to its evaluation.

2. Methods

Figure 1 outlines the sequential methodology adopted for the study, detailing the process from data collection to comparative evaluation. Each step systematically builds upon the previous one to ensure a robust, Industry 5.0-aligned approach to managing digital maturity in clustered innovation-active industrial ecosystems (CIAIEs). The framework emphasizes qualitative and quantitative rigor, integrating advanced techniques like fuzzy logic modeling and comparative benchmarking to validate the proposed model's applicability and effectiveness.

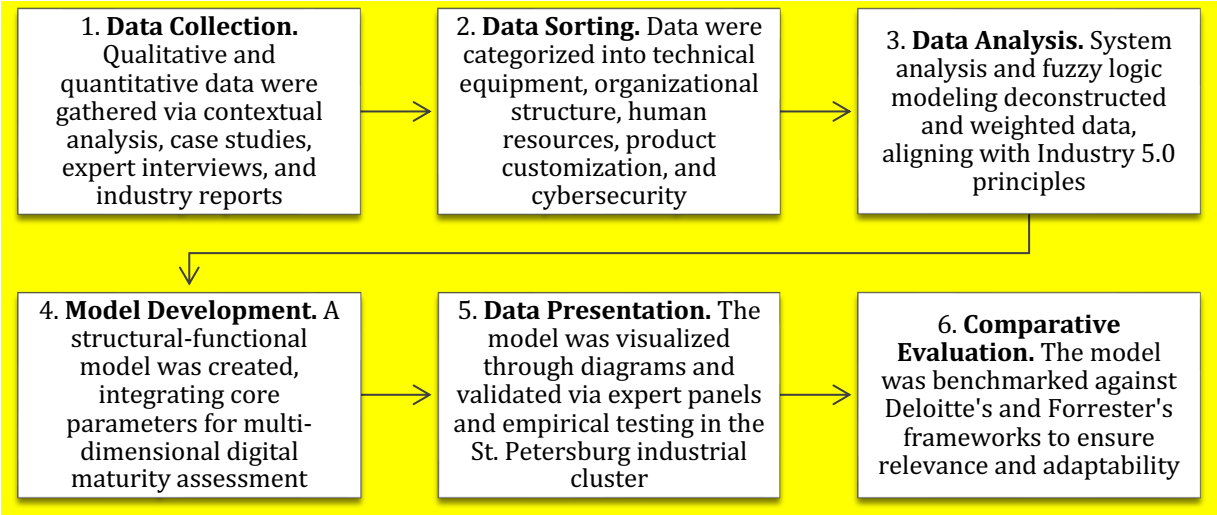

Figure 1. Step-by-Step Methodological Framework for Developing the Structural-Functional Model of Digital Maturity Management

A system analysis approach was utilized to develop, describe, and graphically represent the proposed structural-functional model for managing digital maturity in CIAIEs. This methodological foundation ensures that the model integrates core principles of Industry 5.0, emphasizing human-centricity, sustainability, and technological symbiosis. The modeling process enabled the creation of an original approach to assessing digital maturity. This approach incorporates a set of parameters, including technical equipment, organizational structure, staffing, products and their customization, and cybersecurity. The multi-dimensional digital maturity scale refines the traditional 0–1 metric by incorporating additional factors such as organizational culture, resource allocation, and environmental dynamics, thereby addressing the limitations of oversimplified scales. Validation of the structural-functional model is envisioned through a multi-phase process. Initial expert panel assessments will provide qualitative insights, followed by empirical testing within the St. Petersburg industrial cluster. This empirical phase will employ both quantitative and qualitative methods to substantiate the model's effectiveness. A comparative analysis with established frameworks, such as Deloitte's Digital Maturity Model, will further evaluate the model's added value, ensuring its relevance and applicability across diverse industrial contexts. To mitigate potential bias in parameter weighting, fuzzy logic is applied, enabling a more objective and adaptive assessment mechanism. Each parameter is justified by its alignment with Industry 5.0 principles: technical equipment underpins cyber-physical integration, organizational structure supports interconnectivity and agility, human resources reflect human-centricity, product customization aligns with sustainability goals, and cybersecurity ensures systemic integrity. Moreover, external dynamic factors, such as market disruptions and regulatory shifts, are integrated into the model, enhancing its adaptability and real-world applicability in managing digital transformation within CIAIEs.

3. Results and Discussion

A crucial aspect of digital maturity management is the identification of the essence of a CIAIE, which is understood as an association of industrial enterprises that stimulates innovation and enhances the competitiveness of each participant. CIAIEs are characterized by networked interaction that facilitates the achievement of common goals and the effective implementation of modern digital solutions, such as unified digital platforms, to enhance communication and foster the development of new, high-value products while

improving existing offerings. These ecosystems promote joint value creation, with each participant actively contributing to collective growth and innovation. They 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. Additionally, CIAIEs 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. Such ecosystems are also characterized as "self-developing structures" due to their inherent dynamism in functioning and development, including mechanisms for adaptation to changing market conditions and the gradual transition of economies to Industry 5.0. Industry 5.0 is defined by human-centricity, industrial production customization, achieving 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 a CIAIE, in turn, refers to the nature and level of implementation of modern digital and innovative solutions in company business processes. It is a comprehensive approach that assesses the 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 a CIAIE, encompassing five levels.

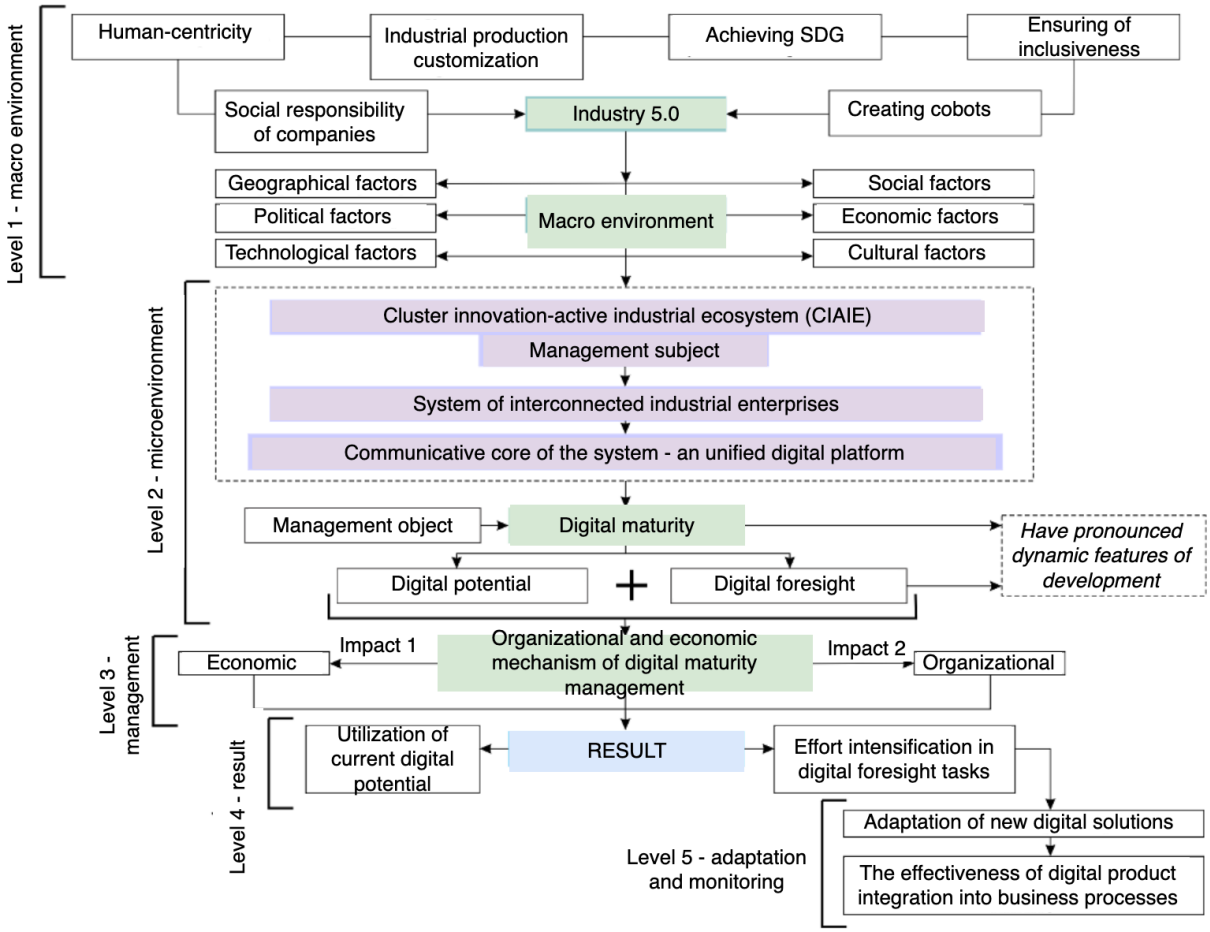

Figure 2. A Structural-Functional Model for Managing Digital Maturity in a Clustered Innovation-Active Industrial Ecosystem

The *macroenvironment* forms the foundational layer, encompassing 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 the CIAIE itself, 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 enhance digital maturity. This mechanism includes modifying structures and processes to cultivate a digital corporate culture and improve inter-organizational coordination through digital platforms, alongside economic strategies that ensure resource allocation, stimulate innovation, and foster 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, aligning with the long-term goals of the CIAIE.

The scientific and practical literature offers numerous methodologies for assessing digital maturity (Digital Maturity Model - DMM), among which the following stand 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.), customer experience, and organizational structure—a total of 28 indicators. Its drawbacks include a focus on large organizations, making it less applicable to smaller enterprises. It also exhibits a low level of individualization, as the model is built on relatively standard assessment criteria, which could lead to neglecting the specific needs of firms and the context that characterizes them, which influences the formation of competitive advantages in the market. The model also lacks a focus on cybersecurity, which is a crucial criterion in modern conditions for assessing digital maturity.

2. Forrester Digital Maturity Model 4.0: This model's assessment takes place within four groups of criteria: Culture - determines a company's willingness to expand employee capabilities with digital technologies; Technology - assesses the nature of the use and adaptation of modern digital products in the enterprise's activities; Organization - within this section, the company's readiness to actively support digital solutions, manage them, and achieve target performance indicators is identified; Insights - determines how well a firm leverages customer data to assess operational efficiency and develop strategies. Among its drawbacks are the complexity of interpreting results, particularly regarding the collection of marketing information, and its limited flexibility, as it is not entirely capable of adapting to modern market conditions. BCG’s digital maturity, the Digital Acceleration Index the model presents 36 indicators for assessing digital strategy, culture, technology, and digital transformation capability. However, it has several limitations: a focus on strategic vision, which can lead to neglecting tactical and operational indicators that influence digital maturity; and financial and resource constraints that businesses might encounter when striving to achieve higher levels of digital maturity according to this assessment methodology.

Other prominent methodologies include: McKinsey's Digital Quotient (DQ) model, Capgemini and MIT models, Gartner models, CMMI (Capability Maturity Model

Integration—primarily used to assess processes but adaptable to evaluate the digital maturity of an industrial enterprise/cluster), the Digital Maturity Benchmark (Google & BCG), PwC (PricewaterhouseCoopers), HBR (Harvard Business Review), the Business Process Maturity Model from Business Process Incubator, and others (Novikov and Babkin, 2014; Babkin A.V. et al., 2024). Overall, all assessment methodologies can be categorized into three key groups: quantitative, qualitative, and mixed, combining characteristics of the previous two types. Studies have shown that mixed methodologies are most commonly encountered, as they allow for an assessment based not only on quantitative parameters but also include expert input, ensuring principles of comprehensiveness, capacity, depth, reliability, and reproducibility. This is particularly relevant for adapting the most effective methodologies in the activities of an increasing number of industrial enterprises of varying sizes. Unlike these models, which rely on standardized criteria and primarily target large enterprises, our proposed structural-functional model for managing digital maturity in CIAIEs offers flexibility by integrating adaptive parameters and employing fuzzy logic for evaluation. This enables customization to the dynamic nature of CIAIEs. In contrast to existing models that often neglect cybersecurity and product customization, our model includes these aspects as core components, ensuring a comprehensive assessment aligned with Industry 5.0 principles of human-centricity, sustainability, and technological symbiosis. Moreover, while traditional frameworks tend to provide static assessments, our model incorporates dynamic elements of digital potential and foresight, allowing for continuous adaptation to technological advancements and market disruptions. These distinctions position our methodology as a more context-sensitive and adaptable tool for managing digital transformation within complex industrial ecosystems.

In previous research, the authors presented a methodology for assessing the digital potential of a system-forming innovation-active industrial cluster. This methodology comprehensively considered key indicators but had a more static nature. Currently, understanding the dynamic component of digital maturity is crucial (Babkin, Tashenova and Chuprov, 2017; Babkin et al., 2019; 2021; Tashenova et al., 2020). Therefore, to assess the digital maturity of a CIAIE, we propose considering the following groups of parameters and their constituent subparameters:

1. Technical Equipment (TechEq): This group includes indicators that regulate the technical readiness of a clustered innovation-active industrial ecosystem for implementing and effectively utilizing various digital solutions.
2. Organizational Structure (OrgStr): This group comprises indicators that characterize the specific features of the organizational structure of a CIAIE and its ability to adapt to the digital transformation of business processes.
3. Human Resources (HR): These parameters determine the sufficiency (both quantitatively and qualitatively) and suitability of the workforce to digital process changes within the current and strategic business activities of a CIAIE.
4. Products and Their Customization (PrCust): This group of indicators reflects the capabilities and abilities of a CIAIE to develop, implement, and commercialize customized products to maximize customer satisfaction and meet their needs and requests.
5. Cybersecurity (CyberSec): These indicators characterize the features of data protection within a CIAIE.

The digital maturity of a CIAIE can be represented as an integral indicator — $\text{Integral\_DigMaturity}_{\text{CIAIE}}$ — which incorporates the parameter groups described above.

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

where TechEq – represents the technical equipment indicators, OrgStr – represents the organizational structure indicators, HR represents the human resources indicators, PrCust – represents the indicators related to product production and customization, CyberSec – represents the cybersecurity indicators, $\alpha_{1...n}$ – are the weighting coefficients for the groups of indicators, determined through expert evaluation.

Therefore, each group of indicators also represents an integral value, determined by the aggregation of indicators within the group, standardized to facilitate subsequent calculation of the final digital maturity value of the CIAIE, which ranges from 0 to 1.

Next, using an interval scale, we can identify levels of digital maturity:

- 0-0.3 – low digital maturity of a CIAIE is characterized by: weak adaptation of digital solutions, lack of a strategy for implementing new technologies; absence of managerial understanding within companies regarding the necessity of digital transformation; the absence of a unified digital platform for data management and ensuring effective communication; and a low level of digital skills among employees.;
- 0.3-0.5 – medium digital maturity of a CIAIE is characterized by: some business processes being automated and robotized; individual software solutions and products, often with simple functionality and content, being implemented; employees having digital skills, but employee training and retraining not being systematic; management of the digital transformation process within the CIAIE being carried out locally (within individual companies or divisions), with a unified digitalization program still absent.;
- 0.6-0.8 – high digital maturity of a CIAIE is characterized by: digital solutions being integrated into nearly all activities, although a unified digital platform at this stage of digital maturity is represented by modules that facilitate only specific operations, such as financial, marketing, production, etc.; an integrated program of digital transformation for the CIAIE being in place, clearly defining target development indicators, aligning with key market trends and principles of Industry 5.0, and being adaptable based on changes arising from the impact of macro-environment factors; personnel having a high level of qualification, including necessary digital skills; a digital corporate culture being established; the organizational structure of the CIAIE being flexible and capable of implementing new forms of digital transformations; and the digital infrastructure being optimized for the tasks of the industrial ecosystem, including customized production.
- 0.9-1.0 – very high digital maturity of a CIAIE is characterized by: processes being digitized and integrated into the activities of a unified digital platform, individualized to meet the demands of the CIAIE and facilitating all types of activities, ensuring maximum efficiency; advanced analytics and machine learning tools being utilized to optimize production processes, including within the framework of operating digital factories and actively using digital twins; the implementation of IIoT, blockchain, cloud computing, additive technologies, etc., being an integral part of the CIAIE's strategic development; employees possessing advanced digital competencies, making the adaptation of new digital solutions faster and more adaptable; and a clear possibility of transitioning to a new form of economic activity – building and developing a digital business with customized production and a high degree of cybersecurity, fully aligning with the principles of Industry 5.0.

The research on managing digital maturity within a 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 an example. It is important to note that to reach the minimum threshold of the integral indicator on the interval scale for "Very High Level of Digital Maturity" (in this case, 0.9), an average increase of 25% in current

investments is required to adjust the value upwards. This, in turn, will lead to an increase in indicators across the criterion groups due to increased digital maturity (Table 1).

Table 1 Increase in Indicators Characterizing the Digital Maturity of the 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

Enhancing the identified parameters in CIAIEs leads to systemic improvements across subcomponents within each category. In terms of *Technical Equipment (TechEq)*, the integration of progressive 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 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 primed for continuous technological advancement. For *Organizational Structure (OrgStr)*, greater integration among ecosystem participants amplifies synergistic outcomes. The cultivation of digital corporate culture and leadership, particularly within middle and senior management, enhances strategic coherence. Information transparency ensures accessible data for managerial decision-making, while unified digital platforms enable the automation and coordination of projects. Process modularity and flexibility support scalability and structural adaptability, allowing multi-level teams to efficiently execute complex, multi-component initiatives. Decentralized digital authority further accelerates responsiveness to innovation, enhancing communication clarity and operational fluidity. In the domain of *Human Resources (HR)*, a digitally competent workforce underpins the successful implementation of platform solutions. Continuous training and dynamic retraining programs ensure workforce adaptability to evolving market demands. Effective recruitment strategies secure talent with requisite digital skills, while a robust digital communication culture enhances collaboration within the CIAIE. The capacity for 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 customer requirements. Advanced digital solutions enable seamless product configuration through user-friendly interfaces, such as online configurators. Predictive customization, informed by marketing analysis and user data, anticipates client needs, facilitating proactive product offerings. This adaptive customization process enhances customer satisfaction and operational efficiency within the CIAIE. Finally, *Cybersecurity (CyberSec)* ensures the integrity of networks, applications, and digital platforms through rigorous security measures at all management levels. Operational security frameworks,

disaster recovery protocols, and comprehensive backup strategies mitigate risks. Employee awareness programs reinforce cybersecurity resilience, aligning the CIAIE's digital infrastructure with the highest standards of information security and operational robustness.

Practical recommendations for managing the digital maturity of the considered CIAIE emphasize the need for strategic financial investments, technological enhancements, and organizational development. Achieving the lower boundary of the highest digital maturity level requires increasing financial allocations by an average of 25% over a three-year period. This investment should prioritize the development of technical equipment and the creation of customized products, which hold the greatest weight in the integral assessment and contribute to the formation of a unified digital ecosystem. Additionally, fostering a robust digital corporate culture is essential for shaping a modern, adaptive organizational structure aligned with Industry 5.0 principles.

The proposed structural-functional model provides practical guidance by deploying unified digital platforms to enhance real-time data integration and collaboration within CIAIEs. Parameters like Technical Equipment (TechEq) align with established frameworks, such as Deloitte's Digital Maturity Model, emphasizing digital infrastructure and AI solutions. However, our model embeds 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) align with Forrester's model but differentiate through sustainability, human-centricity, and customization. The model incorporates predictive analytics for product customization and zero-trust frameworks for cybersecurity, ensuring adaptability and resilience. Enhanced visual elements clarify the model's components, bridging theory with practice and supporting tailored digital transformation in diverse industrial ecosystems. The structural-functional model for managing digital maturity in CIAIEs is validated by insights from various industries and regions, demonstrating its robustness within Industry 5.0. Studies highlight the importance of infrastructure, cybersecurity, and digital platforms for resilience and efficiency, aligning with our focus on technical equipment, cybersecurity, and collaboration (Benazzouz and Auhmani, 2024; Ka, Ying, and Tang, 2023; Narula et al., 2024). Geographic analyses underscore how infrastructural investments enhance digital maturity, supporting our recommendation for increased financial allocations (Brodny and Tutak, 2023). Global perspectives on Industry 5.0 emphasize human-centricity, sustainability, and technological convergence, principles embedded in our model (Alcácer et al., 2021; Hein-Pensel et al., 2023). These findings collectively reinforce the model's relevance and adaptability across diverse contexts.

4. Conclusions

The research conducted within this article yielded the following conclusions: in the context of digital transformation across economic sectors and the transition of several countries to Industry 5.0, the management of digital maturity within CIAIEs becomes increasingly relevant. CIAIEs are characterized by networked interaction, joint value creation, the formation of an adaptive environment for innovation and digital development, and the balancing of competition and cooperation. It is crucial to understand the specifics of managing such integrated structures, which can be traced through the prism of a structural-functional model presented through five levels: the macroenvironment (political, economic, cultural, geographical, technological, and social factors, as well as the specific characteristics of Industry 5.0, significantly impacting the functioning of CIAIEs in contemporary conditions); the microenvironment (where unified digital platforms are

identified as the communicative core, and the object of management is digital maturity, represented as a combination of digital potential and digital foresight); management (including an organizational-economic mechanism); the result, which can be presented within two areas of intensified efforts: developing the current digital potential of the CIAIE and implementing tasks related to digital foresight (possessing pronounced dynamic characteristics); adaptation of new digital products and monitoring their effectiveness. Considering the variety of approaches to assessing the digital maturity of the CIAIE object under consideration, an original approach has been proposed, which includes an analysis of the following parameter groups: technical equipment, organizational structure, human resources, products and their customization, and cybersecurity. The sub parameters included in each group possess dynamic characteristics, allowing for a more adaptable and flexible assessment in the context of ever-changing market conditions and digital transformations.

Conflict of Interest

The authors declare no conflicts of interest.

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