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FRACTAL DYNAMICS OF THE INNOVATION ECOSYSTEM: THE CASE OF THE REPUBLIC OF SERBIA

Summary

The paper explores the theoretical framework of fractal innovation ecosystems as a contemporary approach to understanding the structure and dynamics of innovation processes, focusing on three key dimensions of fractality: self-similarity, scalability, and emergence in the context of the Republic of Serbia. The concept of fractality enables a deeper insight into complex, self-similar, and multilayered patterns that shape innovation networks and their adaptive dynamics. It refers to a model that integrates the key concepts of national innovation systems, helix innovation models, and the open innovation paradigm, while explaining the mechanisms through which local patterns shape global structures and enable the diffusion of innovations without loss of identity.

Empirical examples from Serbia confirm the relevance and applicability of the fractal approach. Local technology parks, startup communities in smaller cities, informal mentorships, and digital collaboration platforms demonstrate the model's capacity to shape policies that reflect local specificities while enhancing global competitiveness. Fractal logic allows the transfer of successful patterns from urban centers to less developed regions without the need for institutional reconstruction, ensuring scalability while preserving functionality.

It is concluded that the fractal innovation ecosystem represents a relevant theoretical and practical framework for understanding and advancing innovation in contemporary economic conditions.

Key words: fractal innovation ecosystem, self-similarity, scalability, emergence, innovation, Republic of Serbia.

INTRODUCTION

In an age defined by rapid technological advancement and pervasive digital transformation, innovation no longer emerges from isolated research laboratories but unfolds within complex, multilayered ecosystems that bring together a wide spectrum of actors, ranging from startups and

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universities to corporations and public institutions. Traditional models of innovation analysis often fall short in capturing the complexity, nonlinearity, and interdependence inherent in these systems, thereby creating a need for new theoretical frameworks.

One of the contemporary perspectives on understanding innovation is the concept of *innovation ecosystems*, within which the *fractal innovation ecosystem* stands out as a distinctive model grounded in the principles of complexity theory and fractal geometry (Carayannis & Campbell, 2012). Fractality, defined as a system's ability to display self-similar patterns across different scales, provides a deeper insight into the structure and dynamics of innovation processes (Arthur, 2009).

The structure of a fractal innovation ecosystem rests on three fundamental dimensions: self-similarity, scalability, and emergence. These dimensions determine how innovations are created, disseminated, and transformed within interconnected systems (Carayannis & Campbell, 2009). For the ecosystem to function effectively, it is also essential to recognize several *auxiliary dimensions,* elements that, while not forming the system's core logic, enable the operationalization of its key principles. Although secondary in structure, these dimensions are vital for translating fractal principles into practical innovation environments. Their identification and management form the foundation for designing resilient, adaptive, and creative innovation ecosystems, especially in light of contemporary challenges and the growing demand for sustainable development.

As first articulated by Mandelbrot (1982), *fractality* refers to geometric forms that exhibit self-similarity, where patterns repeat at multiple levels of scale. In nature, fractal structures can be observed in clouds, coastlines, mountain ranges, and vascular systems; in social systems, fractality manifests through recurring patterns of behavior, organization, and communication. Mandelbrot's theory of fractal geometry made it possible to model structures that elude traditional Euclidean analysis, opening the door to interdisciplinary applications in economics, biology, art, and increasingly, innovation studies (Mandelbrot, 1997).

Within innovation ecosystems, fractality is reflected in the recurring patterns of collaboration, organization, and value creation, regardless of the system's size or level. This perspective reframes innovation not as a linear progression but as a dynamic, evolving network shaped by iterative and nonlinear interactions.

The purpose of this paper is to theoretically elaborate the key foundational dimensions of the fractal innovation ecosystem and to develop an analytical framework that facilitates their systematic understanding. Beginning with a critical examination of existing theoretical approaches in innovation studies, the paper aims to contribute to the further conceptualization of contemporary innovation paradigms, emphasizing the complexity and multilayered nature of challenges that define modern sociotechnological contexts.

Methodologically, the research relies on qualitative analysis of secondary sources, including relevant academic literature on innovation ecosystems, strategic documents issued by the Government of the Republic of Serbia concerning innovation and digital transformation, and reports from science and technology parks operating within the national innovation landscape. In doing so, the paper seeks to provide a theoretically grounded foundation for designing innovation strategies suited to the dynamic and uncertain conditions of contemporary development.

THE INNOVATION ECOSYSTEM AS A RESULT OF SYNTHESIZING PREVIOUS THEORETICAL EXPLANATIONS OF INNOVATION PROCESSES: LITERATURE REVIEW

The concept of the *innovation ecosystem* represents an integration of several earlier theoretical perspectives on innovation. Among the most significant are the *national innovation system*, *helix models of innovation*, and the *open innovation* paradigm. Adner (2006) defines an innovation ecosystem as a network of interdependent actors whose collective efforts generate value through collaboration.

The *national innovation system* offers a framework for analyzing innovation within the specific institutional, cultural, and political context of a given country. Innovation is understood not as an isolated event but as the outcome of interactions among enterprises, universities, research institutes, government agencies, and financial intermediaries. The term "national" underscores the role of the state in shaping the regulatory and policy environment, while "system" highlights the interconnected institutions that collectively determine a nation's innovative capacity.

The *helix models of innovation* extend this understanding by emphasizing the interactions among universities, industry, government, civil society, and the natural environment. These models are based on the premise that innovation arises not solely from market dynamics but from the synergy of knowledge creation, economic activity, and institutional support—promoting the generation and dissemination of socially valuable and sustainable innovations (Cvetanović et al., 2025).

The *open innovation* model, introduced by Chesbrough (2003), marked a paradigm shift in innovation management by transcending the boundaries of closed R&D systems. In this model, companies leverage external knowledge by forming partnerships with startups, universities, suppliers, and even competitors. Open innovation involves a two-way flow of knowledge, outward (through licensing, spin-offs) and inward (through crowdsourcing, strategic alliances). Subsequent works (Chesbrough & Bogers, 2014) further emphasize that open innovation is a distributed process that requires managing knowledge across organizational boundaries, utilizing mechanisms such as joint development, corporate venturing, and digital platforms (see Table 1).

Table 1
Relevant Theoretical Explanations of Innovation Processes

Model	Explanation of the Innovation Process
Structure	Innovation develops through institutional coordination, involving the roles of the state, universities, and industry (Freeman, 1987; Lundvall, 1992).
National innovation system	Connects systemic interactions with iterative development (Etzkowitz & Leydesdorff, 2000; Carayannis et al., 2015).
Helix models of innovation	Innovation emerges through the interaction of multiple actors: universities, industry, government, civil society, and nature (Etzkowitz & Leydesdorff, 2000; Carayannis & Campbell, 2012).
Open innovation model	Innovation is fostered through external collaboration, knowledge exchange, and the use of both external and internal ideas (Chesbrough, 2003)..
Innovation ecosystem	Innovation evolves within a network of actors who share resources, knowledge, and infrastructure (Adner, 2006; Autio & Thomas, 2014).

Source: *Authors*

The ecosystem concept, rooted in a biological metaphor, conceptualizes innovation as the outcome of a web of interactions among diverse actors, emphasizing dynamics, reciprocity, and interdependence. Moore (1993, 1996) introduced the term business ecosystem, redefining firms as members of a broader economic community in which they both cooperate and compete. He underscored the dual importance of collaboration and rivalry, arguing that within a business ecosystem, companies co-evolve their capabilities around emerging innovations, working together and against one another to advance new products, satisfy customer needs, and drive subsequent waves of innovation. This idea was later extended to the broader notion of an innovation ecosystem, encompassing networks of organizations and individuals that mutually support and enhance one another through both cooperative and competitive interactions.

Adner (2006) stresses the significance of aligning complementary innovations and cautions against ecosystem risk, the idea that the success of any single innovation depends on whether other actors are ready to innovate in tandem. Autio and Thomas (2014) further highlight the multilayered structure of innovation ecosystems, noting that they operate simultaneously at local, regional, and global scales.

The transition from the business ecosystem to the innovation ecosystem has, however, tended to shift the analytical focus too heavily toward collaboration, often at the expense of recognizing competition. Additionally, the interchangeable nature of artifacts and resources, including technological innovations, has been largely overlooked in many definitions, despite being essential in both natural and artificial ecosystems. Earlier theoretical frameworks have been instrumental in identifying systemic aspects of innovation, such as strategies for shaping interfaces to create complementary advantages among actors. Yet, by concentrating primarily on collaboration while neglecting competition and the material dimension of innovation, these definitions have traded precision for simplicity.

Consequently, they frequently remain either overly broad and vague or, conversely, economically impractical (O'Brien, 2023).

Unlike the concept of the national innovation system, which is largely static and institutionally bounded, defined by national borders and formalized structures (Lundvall, 1992), the innovation ecosystem embodies a dynamic, open, and adaptive framework that enables flexible interaction across diverse social, economic, and technological contexts (Millard, 2018). While helix models, such as the Triple Helix approach, emphasize the roles of specific actors, universities, industry, and government, in shaping innovation processes (Etzkowitz & Leydesdorff, 2000), the ecosystem perspective focuses on emergence: the spontaneous formation of innovation through nonlinear, multidirectional interactions that arise independently of institutional rules or hierarchies (Moore, 1999).

Compared with the open innovation model, which primarily addresses knowledge flows across organizational boundaries (Chesbrough, 2003), the ecosystem framework offers a broader systemic view. In this framework, openness is not only permitted but also functionally enacted through interactive mechanisms of resource sharing, information exchange, and competence transfer (Millard, 2018).

Synthesizing these theoretical approaches provides a more comprehensive understanding of contemporary innovation processes, acknowledging their complexity, layered structure, and deep contextual dependence. The innovation ecosystem thus emerges as the most suitable analytical and operational model for designing development policies that foster inclusivity, resilience, and sustainability. Granstrand and Holgersson (2020) define innovation ecosystems as evolving configurations of actors, activities, artifacts, institutions, and relationships, encompassing both cooperative and competitive links, that collectively determine the innovative performance of individual participants or groups. This systemic lens enables a richer understanding of innovation as a phenomenon shaped by complex interdependencies, multilayered structures, and contextual variability.

In contrast to traditional institutional models built on formal hierarchies and fixed relationships, innovation ecosystems depend not merely on the presence of actors such as universities, accelerators, investors, and research centers, but on the quality of their interrelations, the intensity of their exchanges, and their capacity to co-create value. Their effectiveness arises from the ability of participants to collaborate, adapt to environmental changes, and generate synergistic outcomes, where shifts in one part of the system can trigger reflective and transformative effects across the whole. In this context, constructing an enabling institutional framework, encompassing strategic innovation policy, corporate and research infrastructures, and facilitative mechanisms such as education systems, regulatory frameworks, and financial instruments, becomes a fundamental prerequisite for enhancing innovation capacity and ensuring sustainable socioeconomic development (Millard, 2018).

In contemporary scholarship, innovation ecosystems are described as dynamic configurations characterized by variable actors, activities, and institutional arrangements whose structures cannot be predetermined or uni-

versally replicated. The typology of these ecosystems depends on multiple contextual factors, including the size of the urban area, the number and type of participating entities, their developmental stage, sectoral specialization, and the presence of leading organizations with clearly articulated strategic objectives. Empirical studies suggest that ecosystems functioning at the national or international level—and those supported by formal institutional structures such as incubators, cluster organizations, and technology parks—tend to achieve greater success than local initiatives built primarily on informal community networks (Komorowski, 2019).

FRACTAL INNOVATION ECOSYSTEMS: MULTIDIMENSIONALITY AND MULTILAYERED DYNAMICS OF INNOVATION

The *fractal innovation ecosystem* offers a theoretical framework that mirrors the complexity of the contemporary world. Its capacity to integrate diverse sources of knowledge, broaden the spectrum of participating actors, and interlink innovation with social and ecological dimensions renders it particularly relevant for developing strategies of smart specialization and sustainable innovation policy.

In comparison with the classical innovation ecosystem model, the fractal approach introduces several conceptual and structural innovations that reshape the understanding of how creativity, collaboration, and systemic adaptability interact within complex environments (see Table 2).

Table 2
Innovations of the Fractal Approach

Dimension	Innovation of the Fractal Approach
Structure	Establishes fractal logic with universal patterns of action (Carayannis & Campbell, 2012).
Operational mechanism	Connects systemic interactions with iterative development (Etzkowitz & Leydesdorff, 2000; Carayannis et al., 2015).
Actors	Expands the spectrum of relevant stakeholders (Carayannis & Campbell, 2012).
Knowledge	Innovation emerges from the integration of heterogeneous knowledge sources (Carayannis & Campbell, 2012).
Epistemological frame	Broadens the perspective toward a sustainable understanding of innovation (Max-Neef, 2005; Carayannis & Campbell, 2012).

Source: *Authors*

An analysis of the dimensions presented indicates that the *fractal innovation ecosystem* marks a significant conceptual shift from traditional models of innovation ecosystems. Whereas classical approaches primarily emphasize coordination among actors and the complementarity of resources within a single level, whether industrial, network-based, or platform-oriented, the fractal approach introduces a multi-level, self-similar logic that allows the same innovation principles to be applied simultaneously at the micro, meso, macro, and meta levels (Carayannis & Campbell, 2009; 2012).

A further novelty of the fractal framework lies in its integration of helix models into the broader ecosystem structure. In addition to conventional actors, enterprises, universities, and the state, the fractal system incorporates the wider public, as well as cultural and ecological dimensions, emphasizing the interdependence and spiral dynamics of innovation processes. This integration enables the coexistence of multiple levels and types of actors, representing an evolutionary advancement beyond earlier, more static ecosystem models.

A defining characteristic of the fractal innovation ecosystem is its *epistemological scope*. It adopts the logic of helix innovation systems through the simultaneous application of disciplinary, transdisciplinary, and hybrid paradigms of knowledge creation. Innovation is no longer perceived merely as a product of market mechanisms or technological coordination but as the outcome of diverse and interrelated knowledge sources and approaches. This epistemological diversity allows for a more profound understanding of how innovations emerge and evolve within complex, dynamic systems-particularly in the context of global challenges and sustainable development imperatives.

The fractal innovation system also introduces a new paradigm of innovation *decentralization*, enabling local capacities to develop autonomously while maintaining coherence with broader strategic frameworks. In the Serbian context, this approach implies the strengthening of regional innovation centers, fostering stronger links among universities, local governments, and the civil sector, all while remaining aligned with national innovation objectives.

Fractal innovation ecosystems thus embody a new paradigm for understanding and managing innovation, grounded in the principles of *self-similarity, scalability,* and *emergence*. These principles facilitate more effective modeling and analysis of innovation processes within complex contemporary economic and social environments, providing fertile ground for further empirical research and practical applications in both national and international innovation policy frameworks.

The concept of the fractal innovation ecosystem rests on three core dimensions that define its structure and functionality: *self-similarity, scalability, and emergence* (see Table 3). These dimensions do not function independently but interact in an interconnected and synergistic manner, collectively oriented toward generating innovative value. Their application enables decentralized yet coordinated innovation processes guided by shared systemic principles.

Table 3.
Core Dimensions of the Fractal Innovation Ecosystem and Their Key Characteristics

Dimension	**Knowledge transfer**	**Exchange of knowledge, technology, and resources between sectors**
Self-similarity	Pattern repetition across multiple levels Modular structure Structural coherenceLearning from feedback	Innovation units operate according to the same principles at different scales, facilitating connectivity and knowledge exchange (Carayannis & Campbell, 2009; Arthur, 2009).
Scalability	Adaptability to scale Efficient expansion Preservation of functionality	Systems can expand without losing efficiency, while maintaining the core logic of the innovation process (Carayannis & Campbell, 2012).
Emergence	Unexpected outcomes Actor synergy Self-organization	Complex innovations arise spontaneously from the interaction of simple elements, without central control (O'Brien et al., 2023).

Source: *Authors*

Within the fractal innovation framework, self-similarity ensures structural stability by reproducing successful patterns across different levels of the system. Scalability enables the expansion of innovation capacities without compromising identity or functionality, while emergence generates new value through the spontaneous interaction of diverse actors. In this model, innovations are not the product of centralized planning but arise organically from decentralized units that share common principles and operational logics.

Self-similarity refers to a system's capacity to reproduce analogous patterns at multiple levels of organization, from local initiatives to global innovation networks. As a foundational property of fractal systems, self-similarity describes how recurring patterns emerge across scales, from wholes to their constituent parts. where each "cell" of the system retains the essential functions and relationships of the larger whole (Warnecke, 1993).

In the context of a fractal innovation ecosystem, self-similarity does not imply the identical replication of forms but rather the recognition of structural and functional analogies that recur across contexts. For instance, the operational dynamics of a small startup community may mirror those found in large-scale technology clusters, reflecting core principles such as collaboration, knowledge sharing, and adaptability (Arthur, 2009).

Viewed through the lens of self-similarity, the fractal innovation ecosystem can be understood as a network of interconnected entities that operate according to shared principles yet differ in scale, intensity, and local specificity. This structure allows successful models to be replicated and adapted across diverse environments without loss of coherence. Moreover, self-similarity facilitates the identification of potential synergies and points of friction, as behavioral patterns can be anticipated based on earlier experiences in other parts of the system (Holland, 1995).

Beyond its analytical function, self-similarity carries *normative* potential. It suggests that innovation policies can be designed to stimulate local initiatives that reflect and reinforce broader systemic objectives, thereby enabling decentralized yet coordinated development. The fractal perspective thus provides a foundation for adaptive strategies built on network dynamics, open collaboration, and the evolutionary expansion of innovation capacities (Carayannis & Campbell, 2012).

Scalability, as a defining dimension of the fractal innovation ecosystem, denotes the system's intrinsic ability to expand, evolve, and transform while preserving its structural integrity and functional coherence. Its application supports the design of innovation strategies that are simultaneously locally grounded and globally connected, ensuring sustainability, resilience, and evolutionary potential within contemporary socio-technological environments.

Scalability also enhances system resilience. In fractal ecosystems, innovation processes are distributed across networks of interconnected actors rather than concentrated within centralized structures. This distribution enables the system to maintain functionality even in the face of disruption, as local nodes can reorganize and assume broader systemic roles. Consequently, fractal ecosystems are particularly suited to turbulent and uncertain environments, where adaptability, responsiveness, and agility are decisive factors of success.

Emergence embodies unpredictability, creativity, and the spontaneous generation of complexity. Within fractal innovation ecosystems, innovations rarely follow predefined strategic plans; instead, they arise through serendipitous encounters, experimentation, and unplanned synergies. This inherent uncertainty is not a limitation but a strength, allowing the system to generate outcomes that transcend initial expectations and open new developmental trajectories.

In practice, emergence manifests through the spontaneous creation of innovative solutions, business models, and technological paradigms resulting from dynamic interactions among entrepreneurs, researchers, institutions, and users. These interactions evolve within networks of collaboration characterized by feedback loops and adaptive learning. Hence, innovations emerge not from centralized design but as expressions of the system's *collective intelligence*.

This emergent process facilitates the organic evolution of innovation through unpredictable yet productive exchanges. It fosters experimentation, openness, and evolutionary growth, positioning the fractal innovation ecosystem as particularly well-suited to complex and volatile envi-

ronments where agility, adaptability, and creativity are essential success factors. The fractal structure of the system allows patterns of innovative activity to recur and scale across multiple levels, from local communities to global networks, where emergent properties do not dissipate but rather transform and adapt to new contexts. For example, a local initiative in the field of the circular economy may generate models later applied successfully in international contexts, retaining core principles while developing new functionalities through interaction with broader institutional and cultural environments (Carayannis & Campbell, 2012).

For this reason, emergence within the fractal innovation ecosystem should not be regarded as a byproduct but as a *central mechanism of evolution*. It enables systems to adapt, transform, and grow in response to environmental shifts without depending on rigid hierarchies or centralized control. The fractal perspective on innovation thus reinforces principles of decentralization, openness, and experimental culture, where value creation arises primarily from interaction rather than command.

Together, the three dimensions, self-similarity, scalability, and emergence, enable innovation ecosystems to remain dynamic, flexible, and continuously evolving. Much like naturally occurring fractals that sustain recognizable patterns while constantly transforming, fractal innovation systems harmonize stability with change.

In addition to these core dimensions, auxiliary dimensions play a critical role in fine-tuning the operation of fractal innovation ecosystems. While they do not embody the system's structural logic, they ensure its practical functionality within specific contexts, objectives, and resource constraints. Table 4 summarizes the most frequently cited auxiliary dimensions identified in the literature.

Table 4
Auxiliary Dimensions of Fractal Innovation Ecosystems and Their Key Characteristics

Auxiliary Dimension	**Key Characteristics**	**Explanation**
First intersection	Knowledge transfer	Exchange of knowledge, technology, and resources between sectors
Adaptiveness	Flexibility in changing conditions Learning from feedback	The system adapts to external changes and internal challenges through iterative processes and reflection (Carayannis & Campbell, 2009; O'Brien et al., 2023).
Interconnectivity	Networked actor connections Horizontal and vertical communication	Enables the exchange of knowledge, resources, and ideas across different levels and sectors within the ecosystem (Carayannis & Campbell, 2012).

Transparency	Process openness Clear rules and information accessibility	Builds trust among participants and facilitates collaboration through accessible data and open standards (Nambisan & Baron, 2013).
Resilience	Resistance to disruptions Rapid recovery and reorganization	The system can withstand stressful situations and reorganize quickly without losing core functionality (Matic & Matic, 2022).
Participativeness	Inclusion of diverse actors Democratic decision-making	Ensures that diverse voices are acknowledged, enhancing the relevance and legitimacy of innovation processes (Carayannis & Campbell, 2009).
Temporality	Consideration of time cycles Long-term and short-term planning	The system balances immediate needs with strategic goals, taking into account developmental rhythms (O'Brien et al., 2023).

Source: *Authors*

Auxiliary dimensions of the fractal innovation system do not operate independently but intertwine and reinforce one another, making the fractal innovation ecosystem capable of evolving within an inherently complex and unpredictable environment. Their integration enables the system to be simultaneously resilient, open, and adaptive, creating fertile ground for the emergence of relevant, sustainable, and socially desirable innovations.

KEY ELEMENTS OF THE CORE DIMENSIONS OF THE FRACTAL INNOVATION ECOSYSTEM OF THE REPUBLIC OF SERBIA

This section highlights how Serbia's innovation ecosystem increasingly mirrors the structure and logic of a *fractal innovation system*, where successful development models repeat across different levels of organization, from national strategies to regional parks and individual startups. The key characteristic, *self-similarity*, manifests through the consistent replication of operational patterns and collaboration models across scales, ensuring systemic coherence, adaptability, and scalability.

Self-Similarity of the Fractal Innovation Ecosystem in Republic of Serbia

At the *macro level*, Serbia shows strong innovation inputs but moderate output performance (47th vs. 60th in the Global Innovation Index 2024), suggesting unused potential and a "fractal gap" between resources and outcomes. National strategies such as the *Smart Specialization Strategy* and the *Artificial Intelligence Development Strategy (2020–2025)* define the systemic framework that cascades down through the ecosystem.

At the *meso level*, *science and technology parks* in Belgrade, Niš, Novi Sad, and Čačak replicate the Belgrade park's model of mentorship,

internationalization, and financing, creating structurally similar innovation nodes. The Belgrade Science and Technology Park, with over *240 supported tech companies*, exemplifies this self-similar logic by fostering collaboration between universities, the private sector, and public policy.

At the *micro level*, the *Innovation Fund's programs,* such as *Mini Grants* and *Matching Grants,* extend this pattern by applying uniform design principles and evaluation mechanisms across all project stages. This standardization provides predictability and coherence while retaining flexibility in implementation.

The *Belgrade–Novi Sad innovation corridor* further demonstrates fractal replication, ranking among Europe's top 40 ecosystems for overall performance and top 20 for talent. The continued rise of *ICT exports* (€4.13 billion in 2024) shows how coherent, self-similar local systems contribute to macro-level success by strengthening knowledge and value chains.

The emerging *BIO4 Campus* represents a new macro-module, expanding Serbia's fractal architecture into life sciences. By integrating faculties, institutes, and laboratories under shared collaboration models, it multiplies local micro-modules, spin-offs, startups, and labs, while connecting them to global innovation networks.

Viewed through the lens of *complex systems theory*, Serbia's innovation ecosystem evolves through repeatable, stable institutional forms that enhance resilience and adaptive capacity. Yet, the persistence of *"bad fractals",* misalignments between universities and industry or between national and regional priorities, can fragment systemic coherence. Overcoming these gaps demands policy and regulatory harmonization aligned with EU frameworks.

In conclusion, Serbia's innovation landscape already reflects a *self-similar fractal geometry* characterized by recurring structures, strategic focus areas (S3, AI), modular science parks, replicable grant schemes, and strong international links. The next phase requires refined *"fractal tuning"*: building stronger feedback loops, ensuring open data exchange, and investing in mechanisms that convert inputs (talent, infrastructure) into outputs (patents, market value). Such alignment would consolidate the country's position within the global innovation ecosystem and enable sustainable, systemic evolution.

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Scalability of the Fractal Innovation Ecosystem in Serbia

The scalability of the innovation ecosystem in the Republic of Serbia refers to the system's ability to expand, adapt, and respond to the growing needs of innovative actors, from startups to large enterprises. This dimension represents a key prerequisite for the country's long-term development and competitiveness in the global innovation landscape.

According to the European Innovation Scoreboard 2024, Serbia is recognized as an "emerging innovator," with an overall innovation index of 69.1, or 62.8% of the EU average, an increase of 4.4 points compared to the previous year (European Commission, 2024). Notably, there has been a rise in the number of small and medium-sized enterprises introducing product and process innovations, as well as a continuous increase in private sector investment in innovative activities. These indicators point to a strengthening capacity for scaling business models and technologies.

Digitalization, including widespread internet access and modern IT solutions, further accelerates the expansion of innovative ideas and enables their faster implementation in practice. Indicators of digital skills and broadband penetration show significant growth, with a digitalization index of 64.1 and broadband penetration of 87.6% in 2024 (European Commission, 2024).

A particular potential lies in the concept of the fractal innovation ecosystem, which enables successful models from urban centers such as Belgrade, Novi Sad, or Niš to be transferred to less developed regions, such as Eastern Serbia, without requiring complete institutional reconstruction. This fractal logic implies the repetition of efficient patterns with local adaptation, preserving the system's core functionality while allowing a flexible response to specific regional needs.

In this context, fractality is not merely a theoretical metaphor but an operational principle of scalability, allowing stable organizational forms (institutions with clear interfaces, standardized procedures, repetitive funding programs) to be replicated across different scales of the system, while maintaining coherence and resilience. This approach positions scalability as both a *developmental mechanism and a resilience strategy*: it promotes distributed innovation capacity, reduces regional asymmetries, and ensures that the national innovation ecosystem functions as an interconnected, evolving network capable of continuous self-renewal and expansion.

The scalability of Serbia's innovation ecosystem extends beyond institutional frameworks, it fundamentally depends on the system's capacity to recognize, integrate, and amplify local innovative impulses. This process reveals the synergy between fractal structure and emergent dynamics, where innovation arises not from centralized planning but from bottom-up initiatives that emerge organically within communities (Table 5).

Table 5.
Examples of Scalability in the Fractal Innovation Ecosystem in Serbia

Level	Example	Scalable Elements
Local	Science and technology park Niš, startup incubators in Čačak and Kruševac	Replication of the Belgrade STP model: collaboration with universities, mentoring support, incubation
Adaptiveness	Flexibility in changing conditions Learning from feedback	The system adapts to external changes and internal challenges through iterative processes and reflection (Carayannis & Campbell, 2009; O'Brien et al., 2023).

Regional	Smart specialization in Vojvodina (ICT, bioeconomy), Southeast Serbia (healthcare, energy)	Thematic focus, connection of local actors, use of national instruments
National	Innovation fund, StarTech, Digital Serbia	Standardized funding and support mechanisms available across all regions
International	Participation in Horizon Europe, EUREKA, bilateral projects	Local capacities integrated into global flows through consistent structural patterns

Source: *Authors*

At the heart of this process lies emergent innovation, initiatives born from local needs, resources, and creative collaborations. Local examples, such as factories partnering with technical schools to co-develop new technologies or agricultural cooperatives applying digital tools to optimize production, illustrate how micro-level innovation can generate scalable models. These initiatives hold systemic value by fostering new knowledge networks and cross-sectoral linkages, turning local experimentation into a national development engine.

Transdisciplinary collaborations, or example, partnerships between the IT sector and healthcare or education, increasingly originate from local ecosystems. Projects such as rural healthcare applications developed in Niš demonstrate how localized expertise can evolve into scalable solutions with both community and national relevance. Similarly, innovation hubs in smaller cities like Zrenjanin and Valjevo function as fractal replicas of larger urban centers, preserving key collaboration principles while adapting to specific local contexts. These decentralized nodes enhance inclusivity, adaptability, and systemic resilience, creating a multi-layered, self-similar network of innovation.

Furthermore, open calls and innovation challenges organized by public institutions frequently generate unexpected solutions from informal teams, students, and individuals, reflecting the emergent nature of Serbia's innovation base. Such bottom-up mechanisms broaden participation and ensure that the ecosystem continually renews itself through spontaneous creativity and diversity of actors.

Thus, the scalability of Serbia's fractal innovation ecosystem is not defined by size or resources alone but by its ability to multiply local creativity, knowledge, and collaboration through interconnected decentralized structures. This approach strengthens systemic resilience, promotes inclusive regional development, and builds a foundation for sustainable adaptation to future challenges.

The emergence of Serbia's fractal innovation ecosystem is no longer a theoretical notion, it is increasingly visible in practice. Through decentralization, local initiative, and horizontal collaboration, Serbia is shaping an innovation environment that evolves organically while maintaining the potential for global integration. Innovation is thus not imposed from above but emerges from local interactions, reflecting the country's movement toward sustainable, inclusive, and resilient growth (Rindova et al., 2010).

This emergent model is rooted in creativity, experimentation, and networked collaboration, rather than rigid hierarchies. Cities such as Niš, Čačak, and Novi Sad have independently developed vibrant startup communities driven by entrepreneurial motivation and shared interest, often without centralized coordination (OECD, 2021). These micro-ecosystems, functioning as fractal units, are interconnected through events, hackathons, and partnerships that facilitate rapid knowledge exchange and mutual learning.

The success of one local hub stimulates the creation of others, reinforcing the self-replicating (fractal) expansion logic. The Science and Technology Park in Belgrade, for example, served as a model for the development of similar centers in Niš and Čačak (Innovation Fund, 2022). Meanwhile, Serbian startups increasingly engage in international markets, attracting investment and forming global collaborations, which further extends the fractal network beyond national borders (European Commission, 2023).

For this emergent system to flourish, local autonomy is crucial. Innovation centers must have the freedom to adapt their development pathways according to local strengths and identities. Equally important are transparency, open data flows, and a culture of experimentation, where mistakes are seen as opportunities for learning rather than failure. Universities play a pivotal role as both knowledge producers and development partners, bridging science, business, and public policy (OECD, 2021).

Examples from Subotica and Užice show that local entrepreneurs, often without institutional backing, are creating coworking spaces and event networks that later integrate into national innovation frameworks. Experienced founders frequently act as informal mentors, forming organic, self-sustaining support networks. Meanwhile, digital platforms and online communities expand collaboration beyond geographical constraints, allowing innovation to evolve within a fluid, adaptive digital ecosystem.

The emergence of Serbia's fractal innovation system thus confirms that innovation can grow from the periphery to the center-from communities that connect, learn, and co-create shared value. This bottom-up architecture not only enhances national innovation capacity but also positions Serbia as an active contributor to the global innovation landscape, rooted in flexibility, collaboration, and systemic evolution (See Table 6).

Table 6
Examples of Emergence in the Fractal Innovation Ecosystem in Republic of Serbia

Domain	Examples of Emergent Phenomena	Explanation of Emergence
Startup Scene	Tenderly*, Joberty**, Anari AI***	Innovations arise from local creativity and networked collaboration, without centralized planning.
Regional development	Science and technology parks in Niš, Čačak, and Novi Sad	Local actors spontaneously form new models of collaboration between science and industry.
Transdisciplinary projects	Smart cities, e-health, integration of ICT, healthcare, education, and ecology	Innovations emerge from the fusion of different sectors, without prior institutional structures.
Digital transformation	AI, blockchain, and IoT solutions in domestic companies and universities	Technological innovations develop through spontaneous learning and experimentation.
International integration	Horizon Europe, EUREKA, bilateral projects	Local capacities are integrated into global flows, generating new forms of knowledge and collaboration.

Source: *Authors*

* *Tenderly* is a platform from Belgrade that simplifies the development of blockchain applications, especially on the Ethereum network.
** *Joberty* is a platform for employment and experience sharing in the IT industry. IT professionals can anonymously rate companies, share interview experiences, and find information about salaries and workplace culture. On the other hand, companies can advertise job openings and build their employer brand. Joberty is present in several countries across the region.
*** *Anari AI* is a startup from Novi Sad that has developed the first virtual factory for AI chips in the cloud.

CONCLUSION

The fractal innovation ecosystem represents a contemporary theoretical and practical framework that enables a deeper understanding of complex, multilayered, and dynamic innovation processes. By analyzing its core dimensions, self-similarity, scalability, and emergence, it becomes clear that this approach surpasses the limitations of traditional models, offering a flexible and adaptive architecture suited to the conditions of modern society and economy.

Unlike rigid, centralized structures, the fractal model allows innovation to be understood as a process that emerges spontaneously from the interactions of local actors. Preserving the identity of innovation patterns while enabling their expansion across broader systemic levels creates space for development strategies based on decentralization, network connectivity, and self-organization. This approach fosters inclusivity, resilience, and sustainability within innovation systems.

In this sense, the fractal innovation ecosystem is not merely a theoretical construct but a practical tool for designing future innovation strategies—strategies that are both locally rooted and globally relevant. Its application supports the creation of inclusive, agile, and resilient innovation environments capable of responding to the challenges of digital transformation, climate change, and social turbulence that define the 21st century.

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FRAKTALNA DINAMIKA INOVACIONOG EKOSISTEMA: PRIMER REPUBLIKE SRBIJE

Rezime

Rad istražuje teorijski okvir fraktalnih inovacionih ekosistema kao savremen pristup razumevanju strukture i dinamike inovacionih procesa, sa fokusom na tri ključne dimenzije fraktalnosti: samosličnost, skalabilnost i emergentnost u kontekstu Republike Srbije. Koncept fraktalnosti omogućava dublje sagledavanje složenih, samosličnih i višeslojnih obrazaca koji oblikuju inovacione mreže i njihovu adaptivnu dinamiku. Reč je o modelu koji integriše ključne koncepte nacionalnih inovacionih sistema, heliks inovacionih modela i paradigme otvorenih inovacija, te objašnjava mehanizme putem kojih lokalni obrasci oblikuju globalne strukture i omogućavaju širenje inovacija bez gubitka identiteta.

Empirijski primeri iz Srbije potvrđuju relevantnost i primenljivost fraktalnog pristupa. Lokalni tehnološki parkovi, startap zajednice u manjim gradovima, neformalna mentorstva i digitalne platforme za saradnju pokazuju sposobnost ovog modela da oblikuje politike koje odražavaju lokalne specifičnosti, a istovremeno doprinose globalnoj konkurentnosti. Fraktalna logika omogućava prenos uspešnih obrazaca iz urbanih centara u manje razvijene regione bez potrebe za institucionalnom rekonstrukcijom, čime se obezbeđuje skalabilnost uz očuvanje funkcionalnosti.

Zaključuje se da fraktalni inovacioni ekosistem predstavlja relevantan teorijski i praktični okvir za razumevanje i unapređenje inovacija u savremenim ekonomskim uslovima.

Ključne reči: fraktalni inovacioni ekosistem, samosličnost, skalabilnost, emergentnost, inovacije, Republika Srbija.