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Megapolis as a Symbiosis of Socio-Economic Ecosystems: The Role of Collaboration

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Abstract: In recent years, smart and ecological urbanism and transformations into the new models of city making have become a global mainstream. These are models of the smart city, the eco-city, and the eco-megacity. The article proposes a conceptual approach to the formation of the eco-megacity as a qualitatively new phenomenon in the post-industrial economy. The prerequisites for the transformation of a megapolis into an eco-megacity have been analyzed. The key characteristics of the new phenomenon have been revealed. The role of collaboration as the main factor in increasing the efficiency of interaction processes between ecosystem actors and between ecosystems themselves has been presented. The relationship of the formed ecosystem approaches and the groups of actors during implementation of an institutional project in the megapolis have been determined. It allows for the transformation of a megapolis into an eco-megacity. The ant colony optimization algorithm for studying the symbiosis of socio-economic ecosystems in the megapolis has been proposed. The authors have attempted to contribute to the development of theoretical and methodological aspects of the emerging eco-megacity concept as a new phenomenon of the modern economy.

Keywords: eco-megacity; ecosystem approach; megapolis transformation; ant algorithm; symbiosis; collaboration process; institutional approach

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1. Introduction

Recently, megacities have become local centers of power that play the role of key nodes in the global economy. Here, a certain role is played by economies of scale, since the largest cities have made and are making a significant contribution to the overall results of global reproduction, serving as centers of production, distribution, circulation, and consumption. They act as powerful engines of growth, delivering large-scale incremental value added and generating momentum for innovation, creating new markets, proposing disruptive ideas, and attracting strategically oriented investors for their implementation. This applies both to the core of the development of the modern world and to its periphery, which are rapidly polarizing under the conditions of the new reality [1].

However, the crux of the matter is not limited to economies of scale alone. A megapolis is not just a large city, but a special spatial system occupying a key place in the national economy which has crossed its borders. In order to become a megapolis, a city should pass a certain growth threshold and acquire a new quality. Unlike an ordinary large city, a megalopolis is organically embedded in a variety of global connections, and it also represents a cluster of such connections in the global socio-economic space. The structure of the modern global economy is based on a network of key strategically important places in the global economic space, as well as the priority position being occupied by global urban agglomerations, which concentrate the main possibilities of the evolutionary process and, above all, intellectual capital [2]. Providing the concentration of the most valuable resources, factors, and infrastructure elements in a relatively compact space, a megapolis becomes a platform for the formation of highly productive capital combinations based on breakthrough ideas provided by the owners of intellectual capital. Such opportunities are due to the presence of a set of interconnected infrastructure platforms in its space [3].

The current stage of development is characterized by the intensification of the interaction of complex systemic formations belonging to different levels of the global economy. This also concerns the interaction of the megapolis with ecosystems being formed in its internal environment. The authors consider ecosystems as open systems capable of organically providing their own sustainable self-development and viability based on non-destructive interaction with the environment. Thanks to the specified way of interaction, they are called ecosystems. Most of them are small forms of organizing ties of high adaptability and significant potential for generating renewal impulses, able to organically integrate into a changing environment [4]. Network equality for a set of actors, their self-organization in an innovative environment, and the creation and reproduction of such an environment as a result of the consolidation of rational ties between actors exchanging energy, knowledge, technologies, etc., have become the principles of formation and self-development of ecosystems in the modern economy. The dynamic development of ecosystems, their diversification, and their growing representativeness in various spheres testifies to the adequacy of this form of organizing ties for the requirements of a new reality [5].

Due to the concentration of intellectual capital, the processes of intensive development of ecosystems belonging to various spheres of activity, their interaction, and transformative impact thereof on the functions, structure, organizational mechanisms, and institutions of the megalopolis system are activated in the compact and resource-saturated space of the megapolis. Ecosystems from various areas are involved in these processes. One of the most important generalizing results of such processes is the transition of the megapolis as a systemic spatial formation to a higher level of development. Here, we observe a qualitatively new phenomenon, called an eco-megacity, arise.

As evidenced by a number of studies, research interests are focused on the two most popular typologies of urbanism, namely, the smart city and the eco-city [6–16]. As proposed by Richard Register [17,18], the eco-city concept focuses on ecological aspects and on achieving a balance between social needs and ecosystems through behavioral change. Meanwhile, the smart city movement relies on information technology to produce data on how the city operates, particularly in terms of energy (production, distribution, and consumption) and transport, and uses it to decrease the costs and waste that urban living generates [19–22].

Examining a variety of case studies from different geographical spaces, scholars have shown that alleged smart cities and eco-cities are far from their philosophical ideals, they rarely innovate and instead replicate traditional capitalist strategies of urbanization, and they seldom keep their promises of sustainability [23–25].

This paper is situated precisely in eco-cities studies and complements the above body of work, by expanding it and focusing on the eco-megacity concept as it reflects the phenomenon of the megapolis of Moscow. Since the eco-megacity concept is being formed nowadays, data on this phenomenon are accordingly being accumulated, and attempts are being made both to compare it with already established phenomena and to assess the legitimacy of introducing the corresponding concept into scientific circulation [26].

While developing the eco-megacity concept, we highlight the main processes that make a significant contribution to the formation of this phenomenon:

- diversification of ecosystems in the megapolitan space;
- active interaction of many ecosystems of various profiles;

- formation of the joint needs and interests of ecosystems in the process of their interaction in the megapolitan space;
- formation of an integrated infrastructure platform in the megapolis, ensuring the activity processes of many interacting ecosystems;
- growing interest in ecosystems of building balanced and orderly links with the structures of the megapolis and its management system;
- creation of regulatory bodies for the development of ecosystems in the megapolis management system;
- translation of ecosystems' characteristics for the entire integrity of the megapolis, their organic integration into it, mutually transforming interactions of the whole and its intensively developing parts.

Taking into account the above provisions, it is legitimate to define the emerging phenomenon of the eco-megacity as an integrated subject of socio-economic relations, which arose due to the concentration and combination of various types of environmentally oriented activities and ecosystems in the space of a large city, embedded in the global economy and endowed with the properties of a large spatially distributed ecosystem. Focusing on the subjective nature of this phenomenon, we proceed from the fact that it has a huge creative potential, its own needs and interests, its involvement in the formation and implementation of socio-economic policy, and its ability to sustainable self-development, viewed in terms of integrating environmental, social and governance (ESG) factors [27]. Being an integrated subject, it presupposes the inclusion of a plurality of individual, associated, and corporate participants in its composition. It also assumes the endowment of mechanisms for coordinating their interests, ensuring balanced interaction in the internal environment of the integrated subject. It should be noted that being an integrated subject does not exclude, but, rather, presupposes the possession of the corresponding object property complex, in which the expanded infrastructural component is of priority importance [28].

Consideration of a megapolis as an ecosystem, as a socio-economic phenomenon, and as a modern form of urbanization requires investigation in terms of identifying the peculiarities and characteristics of development.

Having swept the whole world, digital technologies are contributing to the formation of a number of trends, including those relating to how we reassess basic values and understand increasing social, economic, and information inequalities, and environmental disasters. The current COVID-19 pandemic and the crises being provoked mean that countries and cities are experiencing some point of bifurcation concerning their trajectories of development. The importance of studying the phenomenon of a megapolis for the modern challenges facing researchers and policy makers is to consider trajectories of change that are necessary in society as a whole, especially in cities. From this perspective, this conceptual paper considers characteristics and considerations for research focusing on transformative change in a megapolis, and development trends that help us in understanding the complex processes of social development.

A megapolis is an urban construct addressed in numerous modern urban theories, studied by interdisciplinary scholars across the social sciences [29–34].

This article proposes an ecosystem model explaining the processes and interconnections taking place in the megapolis. Various types of ecosystems develop due to the concentration and dominance of the intellectual capital inherent in the space of a megapolis, and the combination of human, technological, informational, and natural elements into a single spatially distributed system. Since the ecosystems of a megapolis are intensively being formed, merging, and interacting with each other, there are many research questions that need to be studied.

First of all, it is necessary to describe complex development trends and patterns of a modern megapolis, and to investigate the prerequisites for the transition from the existing form of a megapolis to the novel eco-megacity concept, starting from the picture of the observed reality. This is required to consider the types of ecosystems formed in the space of a modern megapolis, to determine its key actors, to identify its inherent essential characteristics, to determine the barriers to the interaction of a megapolis with ecosystems formed in its internal environment, and promising directions for the transformation of a megapolis into an eco-megacity.

This article is organized as follows. In Section 2, the authors provide a theoretical overview of different types of urbanization with a focus on megapolises, describe the ecosystem approach, present related approaches, primarily the smart city and the eco-city concepts, and specify their interactions. In Section 3, the factors of megapolis development and its main characteristics are presented. In Section 3.1, some approaches to defining an ecosystem and features of ecosystem maturity that have come to define an eco-megacity are presented. In Section 3.2, the actors in the megapolis system are listed, and some megapolis subsystems are described. In Section 4, the authors propose some methodological foundations for ecosystem research, which require further approbation and test cases for different megapolises, first of all, by the example of the megapolis of Moscow. Considerations in Section 5 constitute some detailed discussion of the role and the mechanism of collaboration based on the project's approach to the megapolis ecosystem. Section 6 highlights the key findings and presents the theoretical contribution and practical significance of the study. In Section 7, some limitations of the research and points for further discussion are proposed, specifically regarding the possibility of further developing the methodological framework for the eco-megacity concept.

2. Analysis of Problem Development

The main aspects of transforming a megapolis in the process of interactions with the ecosystems of its internal environment were developed in the context of intensive interdisciplinary research. In biology, the concept of an ecosystem was proposed by Arthur George Tansley in 1935 [35], who interpreted it as a biosystem consisting of a set of living organisms, their habitat, and systems of connections that exchange matter or energy between them. The development of the ecosystem phenomenon was carried out as a result of the scientific synthesis of a number of ideas formed within general systems theory, Marxist theory, evolutionary theory, the theory of ecology, and the concept of sustainable development [36–39]. The products of such a synthesis are the fundamental ideas that an organized cycle of matter and energy is carried out in ecosystems, which ensures systemic self-development; the connections formed therein are organic and balanced, and the processes in such systems do not lead to the destruction of the external environment. The concept of ecosystem development based on these ideas was supplemented by breakthrough results in information and biological technologies, which made it possible to present its fundamental category, on the one hand, as an organic relationship of a set of company services based on a common identification code for participants, and on the other hand, as a sentient organic unit of vitality capable of flexibly interacting with the external environment [40]. Subsequently, the content of this concept was enriched by the theory of the innovation system, which made it possible to, first, reveal the transformative potential of ecosystems at the macro-level, and then, at other organizational levels of ties between economic participants [41]. The establishment of intellectual capital as a key factor in modern transformations has led to the intensive development of this capital theory and, accordingly, to the formation of a special direction in the study of ecosystems, namely, the ecology of ideas and the creative potential of society.

The ecosystem approach gained particular popularity in the context of the digital transformation of the economy and society, when the efficiency of technology, information, and knowledge transfer became the dominant factor in the development of enterprises, organizations, and territories.

Being based on previously conducted theoretical analyses, the authors of this article propose and substantiate the definition of an ecosystem as an open and sustainably self-developing system of economic actors, being self-organized on the basis of a friendly innovative environment formed as a result of the formation of connections between actors and the exchange of knowledge, technologies, and resources [42–45].

A megapolis, being a result of the organic integration of a large urban agglomeration into the global network of connections, has only come to be regarded as a large ecosystem in recent years, which is largely due to its complexity, systemic heterogeneity, and its being embedded into the socio-political structure [46,47]. According to the authors, being an ecosystem, a megapolis is not identical with the concept of a "smart" city, since it includes special infrastructure for the development of numerous ecosystems, mechanisms for sustainable self-development, institutions of collaboration, trusting interactions, ensuring a high quality of life, etc. [46].

A megapolis system is a unique combination of man-made inorganic objects (infrastructure, dwellings, equipment, etc.), organic participants (plants, animals), and a multitude of subjects concentrated in a relatively small space, whose activities lead to the creation, destruction, and change of inorganic objects and organic members in the evolutionary process. The existence of a megapolis as a full-fledged ecosystem is hampered by the fact that its combined activity has a destructive effect on the natural landscape, natural resources, climate, atmosphere, etc. Figuratively speaking, the branches and trunk of a tree destroy its root system and the soil from which it borrows resources [48]. This circumstance has led to the search for opportunities to transform a megapolis into a real ecosystem, and to ensure its sustainable self-development for a deep transformation of this systemic spatial formation [1].

These possibilities are viewed in terms of interactions between a megapolis and ecosystems being formed in its internal environment. The transfer of the fundamental qualities of its own ecosystems to the megapolis system creates the possibility of resolving numerous internal contradictions of this spatial system formation and, above all, overcoming its characteristic deep gaps. One of these gaps is due to the fact that the main flow of resources necessary for a megapolis comes from the external environment, into which a huge mass of its waste is removed. For many Russian megapolises, such as Moscow, St. Petersburg, Yekaterinburg, etc., this gap has become critical in recent years [49]. Another gap is associated with the rapid growth of the need for intellectual potential, and the lack of conditions for its generation and effective capitalization [50]. Deep gaps in the megalopolis system indicate the absence of constituent features of the ecosystem therein, namely, the potential for sustainable self-development; mechanisms of rational, non-destructive interaction with the external environment; institutions of flexible self-regulation, allowing for adaptations to abrupt changes in the conditions of the evolutionary process [5]. Accordingly, the transformation of a megapolis in the process of interactions with the ecosystems of its internal environment makes it possible to acquire the indicated features, and initiate transformation into a qualitatively new state of the eco-megacity.

3. A Megapolis as a Socio-Economic Phenomenon: The Eco-Megacity Concept

Being an ecosystem, a city is significantly different from natural ecosystems. A modern city is a combination of artificial inanimate objects (houses, roads, vehicles, etc.) and a huge number of people who create and modify these objects, which is evolutionarily unique in the history of the earth. Cities arose and exist in natural and native-born landscapes. To some extent, their ecosystem includes elements of the previous natural ecosystem that had existed before the emergence of the city. However, these are only separate elements instead of an integral system.

By natural standards, the urban ecosystem has developed into an insignificant type, while the types of natural ecosystems have been formed over millennia.

In ecosystems, the cycle of matter and energy takes place. There are food chains in natural ecosystems, but these chains are broken in the city. The necessary predominant flow of resources comes from outside the city, and accordingly, a huge mass of waste is taken out of it. The city, as an ecosystem, must receive energy, food, and recycle waste for its existence. It became a problem for the environment when the amount of urban waste could not be processed by the surrounding nature. The city lacks a number of signs of ecosystems.

Nowadays, socio-economic ties between ecosystem participants are complex multi-link chains embedded in networks. Each participant consumes products provided by other participants and creates products for the next links in such chains. The general direction of the chains is such that they meet the needs of evolution. Some of them are value chains, while the rest of the chains create public goods that do not pass through the market. An estimation of such goods is established by the community in which they arise and are consumed.

The largest cities have made and are making a significant contribution to the overall results of global reproduction, serving as centers of production, distribution, circulation, and consumption. "Megacity" is also used to describe big cities that surpass other cities in terms of population and geographic size, the pace of urbanization, and the complexity of the issues they face [51].

In accordance with the United Nations (UN) classification, the main forms of urbanization include agglomeration, conurbation, megapolis, and megalopolis.

Agglomeration is understood as a compact territorial grouping of urban and rural settlements, united into a complex dynamic local system by various intensive industrial, communal, economic, labor, community, cultural and household, and recreational links, environmental protection, and the joint use of a given area and its resources.

Megalopolis is the largest form of settlement, formed under the fusion of a number of urban agglomerations. Its synonym is the term "mega-region", which has become widespread in the English-speaking environment. The term was first used by the Scottish sociologist and town planner Sir Patrick Geddes in *Cities in Evolution: An Introduction to the Town Planning Movement and to the Study of Civics* in 1915 [52].

As for the concept of "megapolis", it was used as the term "mega-city" by urbanist Janice E. Perlman in the mid 1970s, referring to the phenomenon of very large urban agglomerations [53]. Initially, the United Nations used the term "megacity" for cities of eight million or more inhabitants, but since 2018, it has been using the threshold of ten million [54]. A megapolis is the largest form of urban settlement formed as a result of the integration of the main city with adjacent settlements and agglomerations.

The research results for the analysis of the term "megapolis" are shown in Table 1.

Table 1. Various approaches to the definition of a megapolis.

Meaning of the Term	Source
A complex multi-component dynamic system that spatially does not coincide with administrative boundaries	Lappo, G.M. (1997) [55]
A kind of "social laboratory" where humanity was able to "rise" to intellectual life for the first time	Park, R.E. (1974) [56]
A single urban space uniting many sprawling small towns	Lisovets, I.M. (2015) [57]
A dynamic system with production, transport, and cultural links, in which all processes find their specific form of representation	Shchedrovitskiy, P.G. (2005) [58]
A large city or urban agglomeration that is an important economic, political, and cultural center for a country or region, and a center for regional or international infrastructure	Kafidov, V.V. (2015) [59]
Global crossroads of investments and business communications with modern and extensive infrastructure	European Cities Monitor (2005) [60]

However, despite the variety of interpretations of the term "megapolis", there is still no generally accepted definition and unified criteria for the classification of this form of urbanization.

A megapolis can be influenced both by factors contributing to its growth and development and factors contributing to its "dying".

In our opinion, the factors that contribute to the growth and development of a megapolis are as follows:

- a factor of innovation—the level of innovation activity in the megapolis is higher than that in small towns due to the concentration of the country's leading universities, the activity of technology parks, and research centers on its territory;
- a factor of activity diversification—unlike single-industry towns, where types of industrial production depend on the natural resources available on the territory, a megapolis is both the center of industrial production and the center for the provision of services;
- a factor of urbanization—megapolises attract people from small towns and rural settlements due to the emergence of new types of activities, jobs, and a developed service sector.

It should be emphasized that one of the key factors influencing the development of megapolis ecosystems are innovations. Nowadays, open innovation has changed its status from a research interest to a mainstream research area. This real paradigm change is irreversible in terms of its long-term impact [61].

Open innovation is a business paradigm of innovation process that provides more flexible policy in relation to research, intellectual property, user innovation, aggregate innovation, improving the accuracy of market research and customer focus groups, synergy between internal and external innovations, viral marketing, innovation implementation and distributed innovation, low research costs [62]. Doran and Ryan [63] state that access to knowledge and information flowing from the market is particularly important in generating and implementing innovation.

The logical foundations of the field of open innovation are based on the innovating organization's need to establish links that are external to the organization [64]. Open innovation is based on various research streams according to spatial, structural, user, supplier, leveraging, process, tool, institutional, and cultural perspectives [65].

The practical origin of the open-innovation concept highlights a structural tension and can be described as the combination of two differently directed processes: inbound and outbound. The inbound process presents the insourcing of external knowledge through licensing, spinning, acquisition, and collaboration alongside the value chain (cooperation with customers, suppliers, competitors, and other institutions to pursue ideas), which can be utilized in the process of new product development [66]. The outbound process involves the external utilization of internal knowledge [67]. Stakeholder theory [68], especially recent work dealing with the significance of stakeholder engagement, is applied to develop the model that addresses this inherent conflict in open-innovation processes.

Nowadays, open innovation is easier since research, technology, and product development have become more global in a connected world. This concept emphasizes the aspects of cooperation with external entities undertaken to generate innovation. A megapolis is integrated in many international connections, as it represents a complex system consisting of many subsystems that provide cooperation in the socio-economic space. The boundaries between the socio-economic ecosystems of a megapolis and its environment have become more penetrable. Innovations can easily be transferred in and out between actors, which has an impact on the level of the consumers, firms, industry, and society. Thus, a megapolis becomes a platform for the formation of innovation based on breakthrough ideas and technologies.

A megapolis is a city that has passed a certain threshold of measures in its development and has entered into a new qualitative state. Its key characteristic is integration into global connections and being a significant place in the global social and economic space.

The intensive development of relations between actors in the space of a modern megapolis, the presence of expanded opportunities for creating combined infrastructure platforms, similar opportunities for generating qualitatively new ideas and advanced technologies, and organizational mechanisms and institutions create favorable conditions for the formation and development of different profile ecosystems in this space.

The huge size and complexity of megapolises pose social and environmental challenges. Their ability to develop sustainably depends largely on how they receive, distribute, and manage their energy and material resources. For the sustainable development of a megapolis, it is necessary that the social, economic, and physical development of a megapolis should be stable.

Main characteristics of a megapolis are shown in Figure 1.

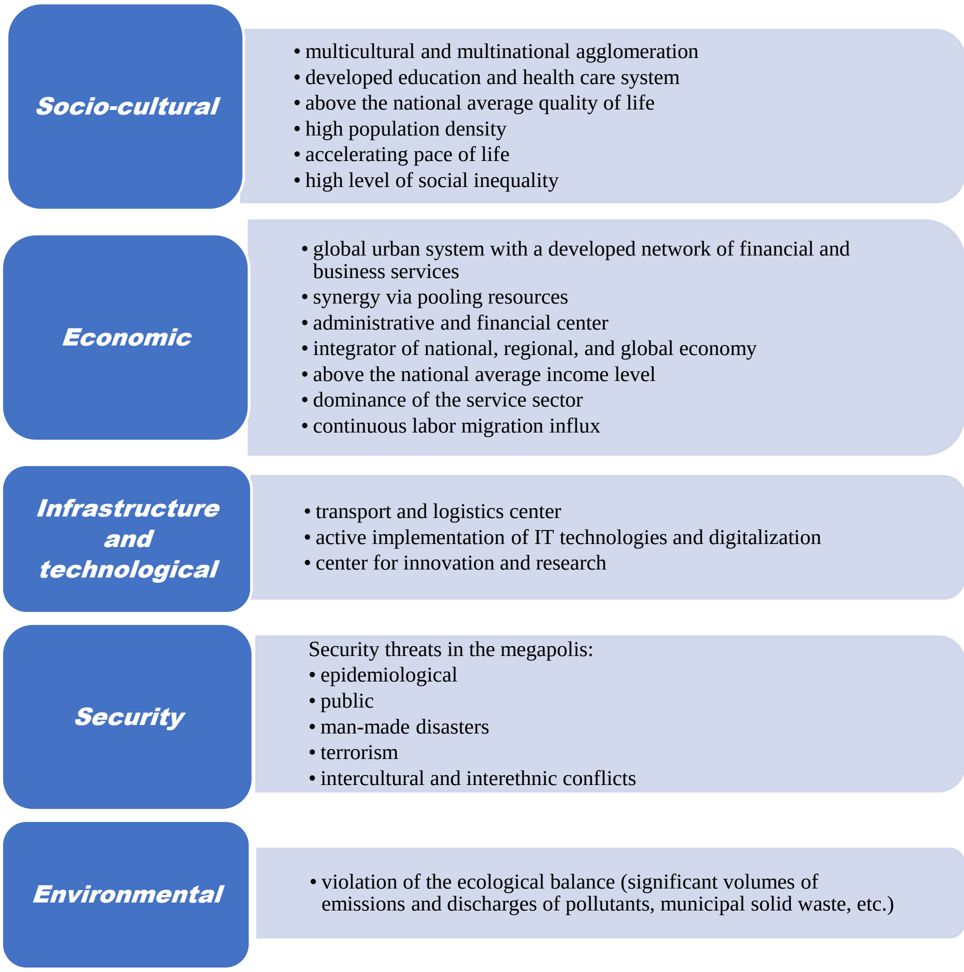

Figure 1. Characteristics of a modern megapolis. Source: Own elaboration.

Megapolises are traditionally considered to be centers of social inequality measured using the Gini coefficient (equity index). For example, the stratification of society in New York in 2019 is estimated at 55%; it reaches 43% in London and 41.5% in Moscow. Another characteristic feature of a megapolis from a social point of view is gentrification, which denotes socio-cultural changes therein. As the cost of living rises, low-income residents are forced to move out of the megapolis, resulting in higher average incomes and making the megapolis attractive to wealthy individuals and business owners, which in turn further increases the cost of living.

Due to the concentration and domination of intellectual capital, the intensive development of ecosystems takes place in the megapolitan space. This spatial systemic formation moves to a higher level of development and becomes a special integrated subject of socio-economic relations.

This is a qualitatively new phenomenon that has arisen in the megapolis, and the emergence of which is proven by the following objective processes:

- diversification of ecosystems in the megapolitan space;
- active interaction of many ecosystems of various profiles in the given space;
- formation of joint needs and interests of ecosystems in the process of their interaction in the given space;
- formation of an integrated infrastructure platform ensuring the activity processes of numerous ecosystems;
- growing interest of ecosystems in interaction with the structures of the megapolis;
- creation of regulatory bodies for the development of ecosystems in the megapolis management system;
- translation of ecosystems' characteristics to the megapolis and their organic integration into its system.

We single out a number of characteristics of Russian megapolises interacting with ecosystems in their internal environment and encountering the built-in limitations of the national socio-economic system based on the power–property relationship:

- embedding the megapolis in the vertical of power, which determines the dominance of vertical processes in its internal environment, and also puts the resources of a huge urban agglomeration at the service of state power;
- projecting the rental strategic orientation of the Russian economy onto the megapolis, which creates incentives for expanded rent seeking, and undermines the development of ecosystems, innovation processes, and the promotion and implementation of sustainable development goals;
- burdened with physically and morally worn-out infrastructure, an acute shortage of modern infrastructure that meets the needs of ecosystem development and the formation of competitive advantages demanded by the new reality;
- possessing a set of scientific and educational centers, being the legacy of the Soviet period, which correspond to the periphery of the global scientific and educational subsystem and therefore requiring modernization and further innovative development;
- formation of imaginary ecosystems focused on vertical ties and the ugly transformation of the goals, needs, and results of real ecosystems (SberBank, which grew up in the course of the bank's expansion, is a vivid example of this process).

Taking into account the above characteristics, the formation and development of an eco-megacity in the Russian economy presupposes the implementation of deep institutional and economic transformations, including the adaptation of its supporting attitude to the requirements of the new reality, and a change in the rental strategic orientation of development.

3.1. Types of Ecosystems Formed in the Space of a Modern Megapolis

Considering the concentration both of subjects endowed with highly developed competencies and the resources and factors of the expanded reproduction of such competencies in the megapolitan space, the authors highlight the following ecosystems as the most promising ones:

- technological ecosystems focused on technology development;
- scientific and educational ecosystems focused on the development of competencies;
- social ecosystems focused on the development of societal forms.

Currently existing interpretations of the term "ecosystem" can be classified according to the approaches presented in Table 2.

Table 2. Various approaches to the definition of an ecosystem.

Approach	Meaning of the Term	Examples
Ecosystem as a horizontal model for uniting actors	An ecosystem (entrepreneurial, sectoral, innovative, or digital) is a voluntary set of enterprises, complexes, and cluster developments, formed through collaborative interactions based on long-term agreements of participants such as a relationship contract. This provides cluster members with an equality of positions in decision making, allowing them to arrive at an agreed strategy of actions for each specific project [69].	Horizontal ecosystems can be considered the evolutionary development of clusters. Examples of such ecosystems are the intelligent ecosystems of *Silicon Valley* in the USA and *Skolkovo* in Russia.
Ecosystem as a combination of two formats of inter-firm links for uniting actors	An ecosystem is a combination of vertical–horizontal sectoral interactions of players as participants in product chains and their horizontal institutional interactions as participants in collaboration. Typically, the vertical grouping of companies occurs at certain stages of product manufacturing in the added value chain, and horizontal industry links are formed at each level of the chain [70,71].	Ecosystem model of cross-industry interactions that provides management of the high-tech industry's development of aircraft systems in the Russian Federation [72]. Vertical interaction is carried out at the level of subjects implementing state industrial policy (Government of the Russian Federation, industrial sector, regions). Horizontal interaction is carried out through partnerships of enterprises and corporations, scientific organizations, consulting firms, startups, etc.
Ecosystem company	An ecosystem is a product creator company, a brand carrier company that forms the philosophy of offering goods and services and unites a group of enterprises and organizations. In practice, a common ecosystem product is not the result of the activities of a single enterprise, but always represents a complex of efforts of various legal entities, which may not even be parent and subsidiary enterprises, but are united by partnership agreements. This, in turn, creates several specific features that form difficulties, for example, in the field of border formation and the statistical accounting of similar markets and their sectors [73].	The principles of self-organization, collaboration, and cooperation act only to the extent defined by the platform owner. Notable examples of ecosystem companies include *Microsoft* and the *Alibaba Group*. In Russia, these are *Yandex* and *SberBank*.
Ecosystem as a cooperation mechanism	An ecosystem is the ecosystem mechanism through which businesses combine their goods and services to create brand new products [74–76]. Through partnership, a common strong and comprehensive product, which is more in demand by the consumer, is formed in any area. The value from using such a set of goods and services is much higher as a general offer than a separate one.	This definition does not reflect the organizational model of the union of actors, but rather the way of unity, which is the basis for the organizational models discussed above.
Ecosystem as a digital platform and/or digital infrastructure	An ecosystem involves not just the creation of innovative infrastructure (scientific centers, technology parks, development institutions, etc.), but its involvement in the development of collaboration between various legally independent partners [77].	These are digital platforms of industrial sectors integrated into pools with a cross-industry nature of interaction. Digital platforms are pools to produce raw materials, financial platforms, logistics and regulatory platforms, platforms for the production of technological equipment, etc.

The movement of emergence and development processes of ecosystems in a megapolis, as well as the megapolis itself, is not unambiguous. Considering various ways of societal development, such as post-capitalism and post-imperialism, we can talk about similar development options for a megapolis, reflecting the laws of the society.

To evaluate the "friendliness of the technological space", suggested by Vladimir Ivanov [78], the authors propose to develop an index of ecosystem maturity in the following main directions, reflecting the positivity and creativity of the processes taking place in the megapolis:

- the level of technology development;
- economic well-being;
- natural and ecological balance;
- the level of cultural and educational development.

The maturity of the megapolis ecosystem is determined by the balance and harmonious development of all these components. Following this logic, ecosystem immaturity is an indicator of dominance of a single direction. So, for example, the predominance of vertical–horizontal ecosystems dominated exclusively by the goals of economic well-being can turn a megapolis into a technological single-industry city, when development tends towards an increase in social, economic, and information inequality, and an increase in environmental problems.

The mature ecosystem of a megapolis should not be identified with the concept of a "smart city" either. This concept originated in foreign urban studies in the late 1990s and was aimed primarily at the development of technologies and infrastructure. The British Standards Institution (BSI) describes a "smart" city as effectively integrating physical, digital, and human systems in an artificially created environment in order to provide a sustainable, prosperous, and inclusive future for citizens [79]. A technological approach to urban development is clearly visible here. Russian experts (Ministry of Construction, Housing, and Utilities of the Russian Federation, and Institute for Cybersecurity and Information Protection) see digitalization as the main task of building a "smart" city, linking urban infrastructure into smart grids, covering them with information and communication technologies (ICT) and the Internet of things (IoT), etc. A smart city has, of course, a high level of technological development of the processes therein, the development of digital platforms, and an abundance of digital services available to residents. However, at the same time, it is necessary to understand that digital technologies are still only tools for achieving certain goals, and the digitalization of public life is not equivalent to an increase in the level of its quality.

Thus, ecosystem maturity is an indicator of the harmony of technological development with natural (ecological), human, and natural values. It means that it can be used to judge the processes of post-industrialism taking place in society.

A megapolis with a high level of ecosystem maturity is proposed to be called an eco-megacity. We introduce our own definition of an eco-megacity as a symbiosis of ecosystems that forms the friendliness of a technological space, characterized by the properties of self-organization, co-evolution, and adaptability, initiating and integrating the processes of the cooperation, collaboration, and competition of all actors in order to provide a comfortable and safe environment for the interaction of all actors of the megapolis, their sustainable development, and a high level of quality of life for each resident of the megapolis.

3.2. Megapolis as an Eco-Megacity

It is natural to analyze and evaluate the transformation processes of a megapolis into an eco-megacity in terms of the modular version of the systems approach proposed by George Kleiner [80], which makes it possible to represent the megapolis system via the combination of object, process, design, and environmental subsystems. These subsystems are in a certain proportional equilibrium in relation to each other, changing and influencing the evolution of other subsystems.

The object subsystem of a megapolis has spatial localization, and theoretically, the lifetime of objects is not limited. From the standpoint of systems analysis, we refer actors, which can be conditionally classified into the following groups, to the object subsystem of a megapolis:

- State (federal) institutions of power: legislative and executive bodies, judicial, tax, customs authorities, etc.
- Big business: headquarters of transnational corporations, industrial holdings, banking and financial groups, international logistics companies, etc.
- Small- and medium-sized businesses: industrial enterprises, service enterprises, individual entrepreneurs, start-ups, engineering and consulting companies, etc.
- Innovative infrastructure of the megapolis: scientific and technological complexes, design organizations, private and state business incubators, technology transfer centers, engineering centers, etc.
- Public and non-profit organizations: associations, public chambers and councils, charitable foundations, representative offices of the largest religious associations/denominations, hospitals, etc.
- Financial institutions: Central Bank, Treasury, Chamber of Commerce and Industry, currency and stock exchanges, scientific and venture funds, etc.
- Representative offices of international organizations: the United Nations (UN), the Organization for Economic Co-operation and Development (OECD), the World Bank, the World Health Organization (WHO), the Eurasian Economic Commission (EEC), embassies, etc.
- Culture and education: educational institutions, universities, museums, theaters, galleries, etc.

Members of each group can operate as actors in one or more different emerging ecosystems. Domestic and international experience shows that there is some practice of forming ecosystems depending on the groups of actors nowadays (Figure 2). However, this practice will probably still be significantly modified depending on a number of factors: institutional, socio-cultural, political, strategic, etc. It is the principles of the interaction of these actors with each other, the pace of development of ecosystem integrations, and the level of collaboration between them that will have the most direct impact on the transformation of a megapolis into an eco-megacity.

Moscow, as a megapolis in Russia, is "a state within a state". There are many reasons for this: the historically established practices, the vertical power structure of the center with the regions, the concentration of political and economic resources, the large distance between cities, the significant demographic potential, and much more.

The following ecosystems can be considered as examples of Moscow ecosystems:

1. Ecosystem of culture and recreation. Ecosystem subsystems are:

– *Zaryadye Park*, which includes the Virtual Tour platform, Polet Media Complex, Northern Tunnel Art Space, Media Hall 360;
– *Park Ecosystem*, consisting of Lianozovsky, Tagansky, Sokolniki, Dubki, Druzhba, Northern River Station parks, etc.;
– *Moscow Culture Online platform*, which includes a whole range of cultural events online.

The actors of this ecosystem are the Government of Moscow, the Contemporary Arts Development Fund (CADF), charitable foundations, and financial institutions.

2. *Skolkovo* innovation ecosystem is an ecosystem with a full-fledged urban infrastructure, including residential buildings, an international gymnasium, a university, a Technopark, and significant scientific and technical centers of large corporations. The task of the ecosystem is to create a self-managing and self-organizing fund that contributes to the strengthening of companies to successfully compete in the international market, as well as the formation of an innovative and entrepreneurial environment for the emergence and development of innovative companies. The actors of the ecosystem are scientists, businessmen, over 150 investor companies, 100 industrial partners, and more than 2000 startups.

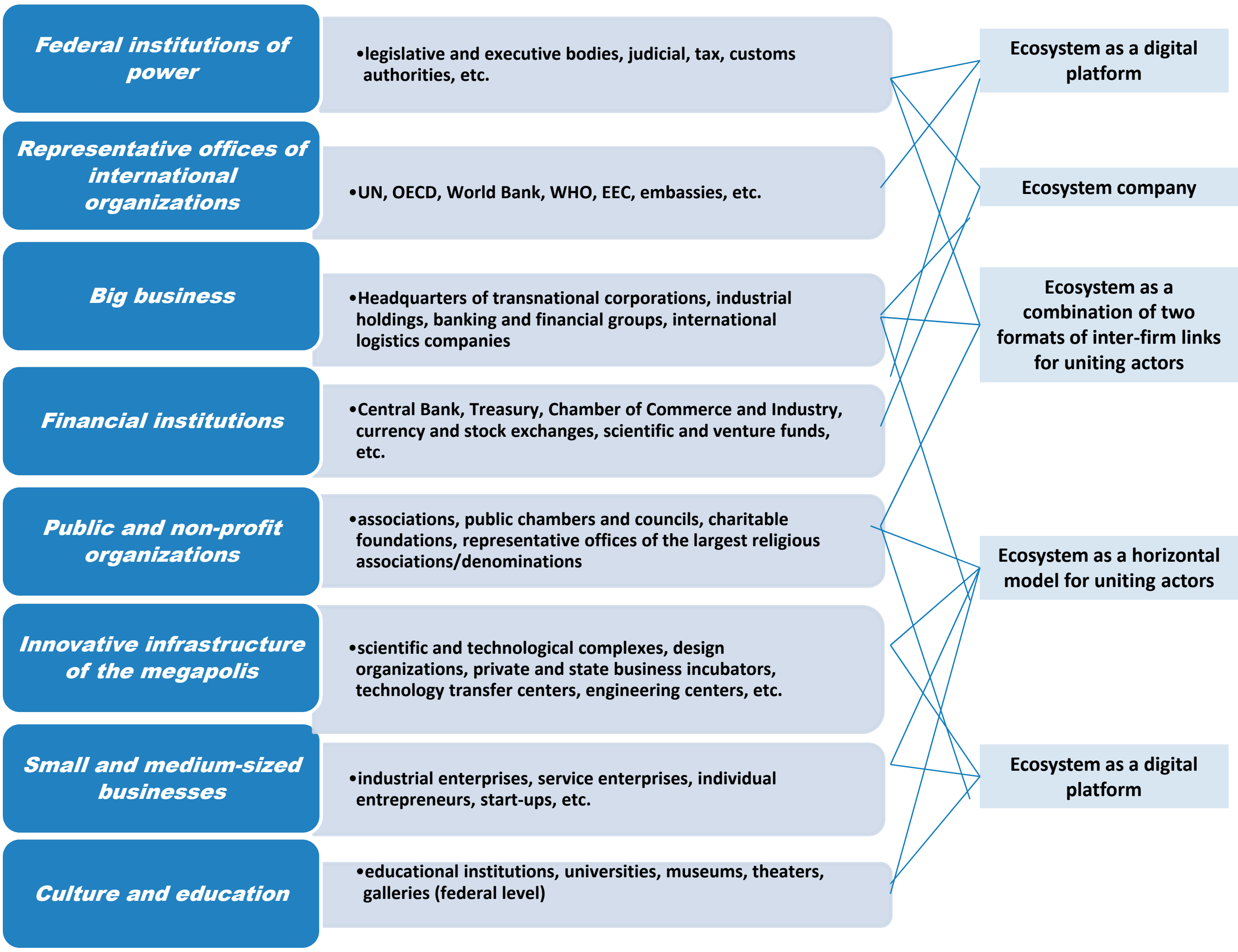

Figure 2. The relationship of the formed ecosystem approaches and the groups of actors in the megapolis.

3. The *MISiS* ecosystem of the National University of Science and Technology MISiS is a part of the scientific and educational ecosystem of Moscow. Its actors are JSC Ural Electrochemical Plant, RF State Research Centre JSC RPA CNIITMASH, JSC UZGTS, JSC GIREDMET, LLC Investstroy, FSBI TISNCM, LLC Technoceramica, JSC VNIIInstrument, etc. The ecosystem results are a set of implemented projects in the field of engineering and reindustrialization technologies.

4. *Mos.ru* social ecosystem. This platform is integrated with all the main network resources of the metropolis and helps to solve almost any issue related to life in Moscow. For example, to make an appointment with a doctor, to enroll a child in school, to arrange a car sale, to get support for families with one or two children, to receive information about the subway, to get medical help, etc. Mos.ru ecosystem subsystems are:

- *Pulse of the City*, where you can find out the latest news on the life of the capital and get information about various city events and promotions;
- *About Moscow*, which contains the entire history of Moscow, from its mention in the annals of the XII century to the present day;
- *City of the Future*, which presents plans for further development;
- *Facts of the City*, including city statistics in recent years: how many roads and how many apartments were built; where Moscow is located in world rankings, and how the capital will look in three years.
- *Documents* that represent a complete list of legislative acts in force on Moscow's territory.

Being a "large system", the economy can be considered as a cenosis or "community of objects (pieces, individuals), each of which has individual properties and can be identified (correlated) with any species; a community characterized by transcendental internal connections, formed by many elements and subjectively identified as a whole" [81]. Vladimir Gromovsky substantiated that physical and chemical, biological, technical, informational, and social cenoses have similarities in their structures. Thus, economic cenoses (communities of organizations in various industries) obey the same laws as biocenoses do [82]. It can be concluded that various economic entities (enterprises, industries, clusters, etc.) are only a kind of cenosis, and they form an ecosystem in unity with the external environment [83].

From this point of view, ecosystems are a kind of a megapolis that is a cenosis, reflecting the processes taking place therein. Likewise, a megapolis, as part of a country's cenosis, reflects the changes taking place in society. Therefore, the actors, shaping effective ecosystems in their cooperation, also form the strong potential of the megapolis, ensuring its development and positive impact on the country and the society as a whole. However, at the same time, each actor of the ecosystem, as well as individual species in the biological ecosystem, ultimately share the fate of the entire network, despite the presence of strong competitive advantages. From this point of view, the megapolis should not only influence society and the country as a whole, but also contribute to the development of smaller entities and territories that are part of the general cenosis (the country as a system), wherein these subjects and territories, forming their potentials, can adopt the models and technologies of development that have been developed in the megapolis, or become actors of already formed ecosystems, influencing the positive development of the cenosis common with the megapolis.

It follows that within the framework of ecosystems of different scales and levels, mutually beneficial collaboration between ecosystems, their actors, and stakeholders is necessary for the implementation of the creative development of the general cenosis.

The environmental subsystem of a megapolis. A megapolis exists in a certain environment, and its quality affects the processes occurring therein. The environmental system is not limited either in time or in space. The quality of the environment is determined by the level of development of institutions ("hard and soft", according to the classification of Douglass C. North) [84], which create conditions for the unhindered interaction of market participants. At the same time, a technological barrier has recently appeared between the traditional (natural) habitat and humans which is constantly increasing. The creation and use of new technologies that do not correspond to the level of cultural development of society and to generally accepted values can lead to negative consequences. That is why it is advisable to evaluate development processes of the megapolis environment not only via the degree of manufacturability and digitalization, but via the cultural, educational, natural, and ecological balance, which reflect the positive development of the society. The same approach concerning harmonization and the balancing of various targets is reflected in the system of Sustainable Development Goals (SDGs) adopted by the UN in 2015.

The process subsystem of a megapolis has no spatial restrictions, but it is limited in time. The mission of the process subsystem is to support the effective interaction of the megapolis actors both in achieving their development goals and in the entire megalopolis as a whole. The flows and processes of interaction between the actors of the megapolis ensure the connectivity of its space and are implemented in the following directions:

- individuals (work, rest, migration, etc.);
- goods (production and intermediate consumption between enterprises);
- services (financial, educational, health, etc.);
- limited capital (investments, taxes, property);
- waste and environmental pollution (solid waste, emissions, water pollution);
- natural resources;
- knowledge (technology, information, experience, social technologies);
- culture (social norms, values, lifestyle, identity).

The process subsystem of a megapolis is focused on the nature and dynamics of the interactions of ecosystem actors (with each other and with potential participants), creation and diffusion of knowledge flows, transformation of this knowledge into innovations, and diffusion of innovations throughout the economy. In general, the mission of the process subsystem is to support effective interaction in the megapolis, but the implementation of this mission is impossible without relying on other subsystems.

The study of a megapolis both as a static system and one in development through the prism of ecosystems involves adding the drivers of ecosystem formation, being individual projects, to the object, process, and environmental components of the megapolis. Consider **the design subsystem of a megapolis** as the reason for the unification of various actors into ecosystems. Analyzing the ecosystem model, the authors of this article have emphasized the so-called "pacemakers", that is, projects that consolidate actors around them, necessary for the ecosystem to emerge [43,44]. In contrast to the object and environmental components, projects are temporary in nature; they are implemented through processes and can have different goals, uniting a variety of actors and stakeholders. Ecosystems can be formed for the functional areas of projects, for example, innovative, industrial, cross-sectoral, recycling, entrepreneurial, territorial, etc. The actors of a megapolis can simultaneously function as actors of different ecosystems in various project roles [44].

Thus, the theoretical study of a megapolis as an integrated system, based on a systemic methodological approach, makes it possible to substantiate the directions of its transformation into an eco-megacity.

4. Models and Methods for Studying the Symbiosis of Socio-Economic Ecosystems in a Megapolis

Based on the above principles, we single out two approaches to assessing the tightness/strength of ecosystem collaboration in a megapolis. If we consider the ecosystem of a megapolis as a combination of meso- and micro-level ecosystems, then the assessment of collaborative relationships is possible through the entropy of a complex system composed of the object entropies of its components [85].

An application of the entropy approach allows both for understanding specific features of a particular ecosystem characteristic and assessing the adequacy of the tools used in the predictive modeling of a megapolis ecosystem. In general, the entropy of a complex system is equal to the sum of the object entropies of its constituents. This important property allows carrying out the decomposition of a complex system during its evaluation.

There are several types of entropies and methods for their calculation in modern science. Joint entropy or entropy of association is designed to calculate the entropy of interconnected systems. A metropolis ecosystem consists of interconnected ecosystems. Accordingly, it is advisable to determine the entropy of an ecosystem through the entropy of association [86].

If there are n dependent systems, the union entropy will be equal to:

$$H\ (x_1; x_2;\ x_3; \ldots x_n) = H(x_1) + H\left(\frac{x_2}{x_1}\right) + H\left(\frac{x_3}{x_1 x_2}\right) + \cdots H\left(\frac{x_n}{x_1 x_2}\right) x_n) \tag{1}$$

where H is the union entropy of megapolis ecosystems; $x_1;\ x_2;\ x_3; \ldots x_n$ are meso- and micro-level ecosystems being part of a megapolis (entrepreneurial, technological, environmental, etc.).

The entropy of the first system is included completely; so is the entropy of the second system, taking into account that the first system is defined; so is the entropy of the third system, provided the first two are defined, etc. The entropy of each subsequent system is calculated under the condition that the state of all previous ones is known.

To calculate the entropy of association, it is necessary to determine the entropy of micro-level ecosystems based on the adapted Shannon equation:

$$(x) = -\sum_{i=1}^{m} P_i log_2 \quad (2)$$

where P_i is the collaboration potential of the i-th ecosystem; m is the number of ecosystems.

Collaboration potential can be assessed using expert evaluation scales, normalized in the range from 0 to 5. In the absence of reliable information on indicators, the assessment is carried out on a limited range of indicators. The reference gradation is defined as follows:

- $0 \leq$ No interaction between ecosystems < 1.
- $1 \leq$ Interaction between ecosystems is purely informational < 2.
- $2 \leq$ Collaboration between ecosystems is partially project-based, resource-balanced and intellectual < 3.
- $3 \leq$ Project collaboration < 4.
- $4 \leq$ Complete resource and project collaboration < 5.

After receiving expert assessments in points, we determine the coded values of the control points (y_{ij}), taking into account the lower and upper limits of the value (y_{min} = 0, y_{max} = 5) using the Harrington desirability scale [87] (Table 3).

Table 3. Modified Harrington desirability scale.

Gradations of Collaboration Types between Ecosystems in Accordance with the Harrington Desirability Scale				
(1.00–0.80) Very Good	**(0.8–0.63) Good**	**(0.63–0.37) Satisfactory**	**(0.37–0.20) Poor**	**(0.2–0) Very Poor**
Complete resource and project collaboration	Project collaboration	Collaboration is partially project-based, resource-balanced, and intellectual	Interation between ecosystems is for informational purposes only	Lack of interaction between ecosystems

The bond strength of the ecosystems is defined as the geometric mean of the coded values (y_{ij}; d_i) [88].

The entropy of association determines the totality of possible states for the megapolis ecosystem: stationary equilibrium; stationary non-equilibrium; non-stationary equilibrium; non-stationary non-equilibrium. For open ecosystems that are constantly interacting with each other, a sign of stability is a quasi-stationary equilibrium state or a stationary non-equilibrium state, when the ecosystem entropy is constant but not equal to its maximum value under the considered conditions.

The influence of changing external factors increases the overall uncertainty (entropy) of the ecosystem. Accordingly, the ecosystem is more stable if it has more collaborative relationships and adaptive capabilities. Creating new connections between ecosystems with the greatest potential is the optimal strategy from the point of view of the entropy approach, since it requires minimal energy consumption. Furthermore, under conditions of global instability, the megapolis ecosystem can achieve local stability due to fluctuations in the micro-level ecosystems making it up.

To assess the tightness/strength of ecosystem collaboration at the micro-level, some models based on simulating the collective behavior of various groups of living organisms, in particular, swarm intelligence [89], as well as ant colony optimization algorithms have been chosen (Figure 3).

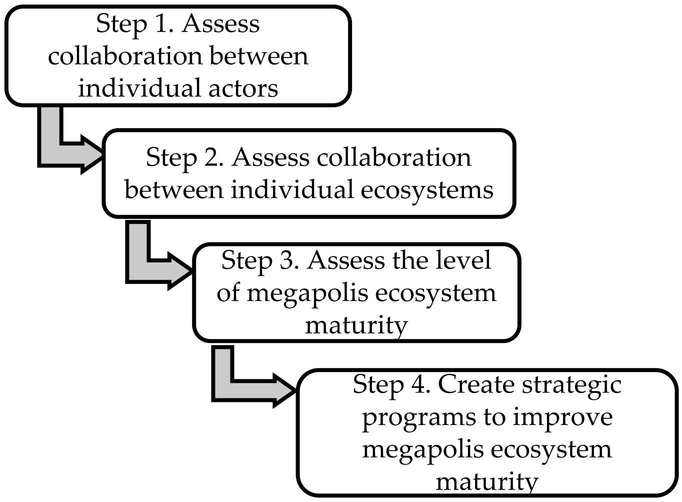

Figure 3. Methodological framework for assessing ecosystem collaboration. Source: Own elaboration.

Considering the characteristic features of the behavior of ecosystem collaboration participants, one should pay attention to some aspects of the emergence of contacts (interests) between them, which create prerequisites for the subsequent cooperation and mutual penetration of teams. As a rule, these contacts are initiated by individual actors who participate in external projects and attract external customers with their capabilities and results.

In the problem under consideration, where the city acts as a socio-economic symbiosis, the behavior of the collaboration participants requires careful study. Due to the complex nature of the behavior of participants (actors), it is proposed that a choice be made in favor of methods and models inspired by various natural (biological) systems. These include methods for solving complex (multidimensional, discrete) problems, united by the so-called theory of natural computing models (natural computing). To solve the considered problem, some models based on simulating the collective behavior of various groups of living organisms, in particular, swarm intelligence [81], as well as ant colony optimization (ACO) algorithms have been selected from a fairly large list of models of artificial biological systems. The first version of ACO algorithm for the approximate solution of the traveling salesman problem was developed by Marco Dorigo in 1992 [90]. These algorithms have an important property of adaptability—if any route becomes unavailable, then a replacement will be found in the form of an alternative route. These algorithms are based on the peculiarity of the behavior of an ant colony that searches for a path from an anthill to a food source. When looking for a path to a food source, ants mark the path they have traveled, and these marks play the role of a positive feedback to the system: the more ants move along the marked path, the more attractive it becomes for other ants. As a result, after some time, most of the ants begin to move from the anthill to the found food source along the same path. Ants use a method of communication based on a mechanism of indirect spontaneous interaction called stigmergy. Distinctive features of this method are: the exchange of information between ants is carried out by changing the environment; information is local and one can access and read it only by moving to a certain point in space. The task of implementing a certain cross-industry project as a symbiosis of ecosystems will be explored through networking. Network models are part of graph theory, being a section of discrete mathematics. We have modeled the project implementation process similarly to the problem of finding the shortest path from the project start point to the end point through the network, where the nodes are connected by edges. The edges are non-directional, which means one can move in both directions from vertex i to vertex j, and vice versa. There is a constraint that prohibits returning to the starting vertex and leaving the final vertex. The solution method is based on partitioning a set of vertices into selected and joined vertices:

- At the first step, the initial vertex is included into the set of selected vertices, and the connected vertices belong to the set of joined vertices.
- At the second step, a vertex is chosen from the set of joined vertices, the path to which is the shortest one from the initial vertex.
- At the third step, the edge (or related path) leading to the chosen joined vertex is labeled. Any other edges leading from the selected vertices to the joined vertex are removed from further consideration.
- At the fourth step, the chosen joined vertex is added to the selected vertices.
- At the fifth step, a search for new joined vertices and a transition to the second step are carried out.

Now let us consider the determination of weights by which the edges connecting the vertices of the network are weighted. It is assumed that the more useful the interaction between node i and node j in solving project problems is, the greater should be the value of the weight related to the edge connecting vertices i and j. To determine the weights, a family of approximate techniques called ACO algorithms is used to solve complex optimization problems.

Suppose the implementation of a certain project, for example, on the formation of innovative infrastructure in a metropolis, includes a symbiosis of industry and business ecosystems. Then, we will assume that ants are actors participating in the implementation of the intercross project of ecosystem symbiosis. The vertices of the network are the stages of the project, and the edges are information, knowledge, and resources that are exchanged by actors during the project's implementation. The choice of actors, projects, and ecosystems is influenced by pheromones, that is, marks in the edges that enhance or weaken the transfer of information, knowledge, and resources. Pheromones can be accumulated partnership experience, reputation, trust, etc.

The description of the project as a symbiosis of ecosystems is the construction of a multi-level network in which ants are launched at several sub-levels corresponding to the utility options acquired during the interaction of actors located in the nodes of the project. The weight of the edge is set as a result of summing the scores obtained at individual levels, weighted by the indicator of importance of the utility level $y_i = \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} \cdot k_j$.

N ants are placed at arbitrary vertices of the network and bypass the network, building a step-by-step solution to the problem. The choice of an edge for transition to a new vertex is made according to the constraints of the problem and the current distribution of the pheromone along these edges. In this case, it is required to initially distribute the utility estimates of actors—the concentration of pheromone on the edges. The ant, being at node i of the network, can move at the next step to node j if there is an edge $(i,\ j)$ in the network.

The choice of an edge to move along is made by each ant on a probabilistic basis, based on the concentration of pheromone on the edges emanating from vertex i—the greater the concentration of pheromone is, the more likely is the choice of this edge.

At the same time, other factors determined by the specifics of the task also influence the choice of edge. For example, if there were difficulties during the interaction of actors in the previous project, which led to a noticeable deviation of the project in terms of time, quality, or cost, the edge leading to this vertex is excluded from the list of possible candidates for relocation. This technique preserves the possibility of forming long cycles when the utilities of the interaction of actors change over time.

If each ant is located at vertex i and, when moving along the network, it keeps a list of vertices X that it has already visited, and when choosing the next vertex, it relies on marks on outgoing edges and on the values of the lengths of these edges, then the probability of moving to the j-th vertex is determined as:

$$p_{il}^{k} = \begin{cases} \frac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum_{l \notin X_k} \tau_{ij}^{\alpha}\eta_{ij}^{\beta}},\ if\ j \notin X_k \\ 0, if\ j \in X_k \end{cases} \quad (3)$$

where α and β are parameters affecting the relative importance between the label value and the heuristic information $\eta_{ij} = 1/d_{ij}$, where d_{ij} is the edge length.

Heuristic information is understood as an assessment of the usefulness of the interaction of actors at a certain level of utility. Since several levels of utility are used, several matrices that describe the quality of interaction between actors for each level are introduced. After the completion of the project, these matrices are updated based on actor feedback.

Following the ants having returned to the anthill, the values of the labels on the edges of the graph are updated. Each ant only updates the edges it has moved along. The label value is calculated as follows:

$$\tau_{ij} \leftarrow \rho\tau_{ij} + \sum_{k=1}^{N} \triangle\tau_{ij}^{k} \tag{4}$$

where ρ is the coefficient of disappearance of the label over time; $\triangle\tau_{ij}^{k}$ is the contribution to the label left by the k-th ant.

$$\triangle\,\tau_{ij}^{k} = \begin{cases} \frac{Q}{D_k},\ if\ k\ went\ along\ the\ edge\ (i,j) \\ 0,\ otherwise \end{cases} \tag{5}$$

Q is some fixed value. The shorter the ant's path, the more significant marks it will leave on the edges along which it moved. The iterations are repeated until some stopping criterion is met: the number of iterations is exhausted; the required accuracy is achieved; the algorithm is converged to some solution. After the completion of the ACO algorithm, the weights used to weigh the edges connecting the network vertices are applied to find the shortest path from the initial to the final vertex, being the best option for implementing a cross-industry project.

The ACO algorithm makes it possible to predict the effectiveness of cross-industry projects as symbioses of different ecosystems through simulation modeling. In addition, information about the weights allows judging the potential opportunities of a cross-industry ecosystem: a decrease in the value of the sum of the network weights indicates a more effective interaction of actors and an increase in the multivariate choice of partners when conducting cross-industry projects.

Let $V = \{v_0, \ldots, v_n\}$ be a set of project nodes where the actors are located.

For each vertex $v_i \in V' = V \backslash \{v_0\} = \{v_1, \ldots, v_n\}$, the amount of work $q(i) > 0$ and the duration of work $s(i) > 0$ are given. The usefulness of the interaction between actor v_i and actor v_j is defined as the distance between them $d(i,j)$. The smaller the distance between the actors is, the more desirable their interaction is. The set of values $d(i,j)$ is represented as a symmetric matrix dimension $(n+1)^2$. The total amount of work performed in the project is set to Q. The maximum length L_m of the traversed path during the project's execution is determined. The purpose of solving the problem under consideration is to find the set $R = \{r_1, \ldots, r_k\}$ of permissible K sequences of project implementation of the minimum total length. Thus, to solve the problem, it is necessary to split the set {1,..., n} into subsets r_k and set the traversal order on each subset. Let $r_k(i) = w_i,\ i = 0, 1, \ldots,\ n_k, n_{k+1}$ be the order of involvement of n_k actors $\{w_1, \ldots, w_{nk}\} \in V'$ in the sequence k. The length of the project execution sequence k is as follows:

$$D(r_k) = \sum_{i=0}^{n_k} d(r_k(i), r_k(i+1)) \tag{6}$$

The sequence k is valid if the constraint on the total amount of work performed in the project

$$q(r_k) = \sum_{i=0}^{n_k} q(r_k(i)) \leq Q \tag{7}$$

and the maximum distance traveled within the sequence of work, taking into account the time spent on the work, is not violated:

$$\sum_{i=0}^{n_k} d(r_k(i), r_k(i+1)) + \sum_{i=0}^{n_k} s(r_k(i)) \leq L_m \quad (8)$$

Let us define the task of minimizing the total length of the work sequences for all the projects:

$$f(R) = \sum_{r_k \in R} \sum_{i=0}^{n_k} d(r_k(i), r_k(i+1)) \rightarrow min \quad (9)$$

As mentioned above, being included in the ecosystem, each actor starts to interact with other actors, acting in different roles, for example, as a supplier or a consumer of services and resources.

It is proposed to consider the task of assessing the strength of the relationship between participants in contract manufacturing chains in a network form.

To assess the collaboration potential at the level of interaction between actors in the ecosystem, it is proposed to use the modified Harrington desirability scale. For example, for the indicator Joint Participation in Projects, Very Good levels of interaction (complete resource and project collaboration) mean that the considered actors carry out from 80 to 100% of their projects together. Good levels of interaction (project collaboration) mean that the considered actors carry out from 63 to 80% of their projects together. Satisfactory levels of interaction (collaboration is partially project-based, resource-balanced, and intellectual) means that the considered actors carry out from 37 to 63% of their projects together. Poor levels of interaction (interaction between actors is purely informational) mean that the considered actors carry out 20 to 37% of their projects together. Very Poor levels of interaction (lack of interaction between the actors) mean that the considered actors carry out from 0 to 20% of their projects together.

The results of calculations for all indicators are summarized and converted into a reference gradation normalized in the range from 0 to 5.

Further, this information is used at the next level to estimate the collaboration tightness of the megacity ecosystems through the entropy of association.

The next step is to study the quality of interaction between actors (participants of collaborations). In this regard, it is proposed to focus on the development and analysis of crisp and fuzzy non-deterministic dynamic models based on Petri nets, using information about the neighborhood of the current solution, with the possibility of adaptation. These models allow for the fuzzy nature of the values in the nodes and the links between the nodes of a dynamic organizational system. The development of identification algorithms and the solution of reachability problems with partially specified parameters are also required.

5. Collaboration as a Trend in Eco-Megacity Formation. A Case Study of the Megapolis of Moscow

Based on the above methodological approaches, we have evaluated the level of collaboration for Moscow megapolis ecosystems. For this purpose, the three largest ecosystems were selected that implemented joint projects for the integration of science and industry.

1. *Skolkovo* innovation ecosystem was created for scientists, businesses, venture investors, and industrial companies creating successful international projects. It was formed to promote entrepreneurial and research activities in the fields of space, computer, medical, and nuclear technologies. The Skolkovo ecosystem has a full-fledged infrastructure, which includes residential buildings, universities, and scientific and technical centers. The ecosystem consists of four main actors (Figure 4):
    - Skolkovo Institute of Science and Technology, formed with the support of the Massachusetts Institute of Technology;
    - International gymnasium, carrying out the educational process in accordance with the Federal State Educational Standards;

- The largest Technopark in Eastern Europe, with an area of 96,000 square meters;
- Center for Intellectual Property.

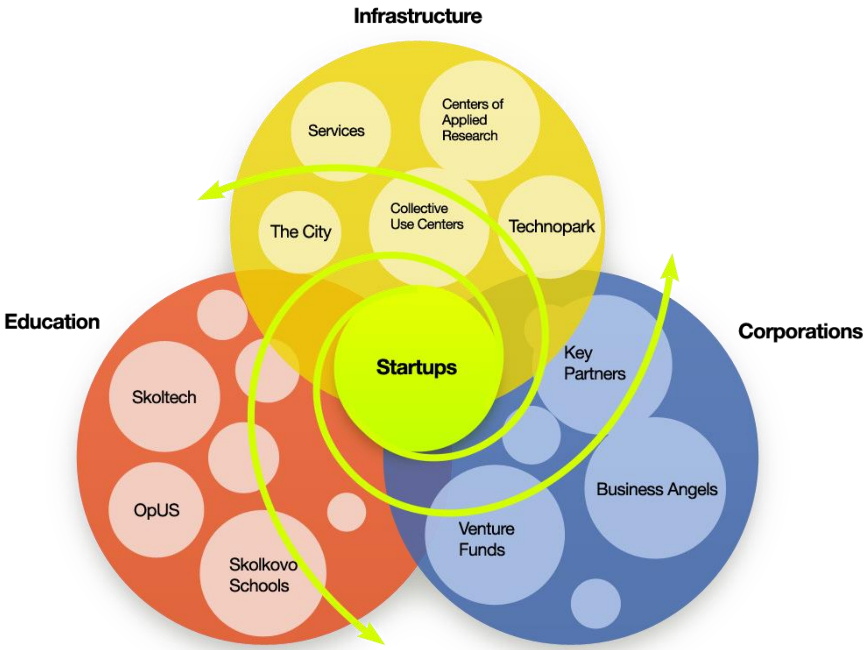

Figure 4. Skolkovo ecosystem. Source: Skolkovo Ecosystem. Available online: https://skolkovo-resident.ru/ekosistema-skolkovo/ (accessed on 10 May 2022).

A key feature of the ecosystem is that any participant can leave the project at will.

2. *Vorobyovy Gory* innovation ecosystem of Lomonosov Moscow State University was created in order to implement the priorities of scientific and technological development of Russia; to increase the investment attractiveness of research and development and to commercialize the results thereof; to expand the access of citizens and legal entities to participate in promising and commercially attractive scientific and technical projects. The main actors of the ecosystem are the Government of Moscow, Lomonosov Moscow State University, and nine clusters:
    - *Lomonosov*—a flagship cluster, a launch pad for the first residents;
    - *Nanotech*—nanotechnology and research of new materials, nanomachinery;
    - *Engineering*—robotics, special-purpose technologies and machine engineering, energy saving and efficient energy storage;
    - *Biomed*—biomedicine, pharmaceuticals, biomedical research and testing;
    - *Cosmos*—space exploration and astronautics;
    - *Infotech*—information technologies and mathematical modeling;
    - *Geotech*—geonomy and ecology;
    - *Interdisciplinary cluster*—interdisciplinary humanities research and cognitive sciences, sports, innovative sports technologies, and artificial intelligence technologies;
    - *Educational (management) cluster*—location of the management company and offices.
3. *MISiS* innovation ecosystem of the National University of Science and Technology MISiS was created to solve scientific and technical problems of the industry, to ensure cooperation between science and industry for the purpose of innovative development of industrial enterprises. As part of its transformation into a global center for engineering education and science, MISiS will make its contribution to the development of Moscow as a megacity by connecting it with other similar research and educational centers. The main actors of the ecosystem are engineering and consulting companies, a technology transfer center, scientific laboratories and centers, industrial enterprises, and state corporations.

Skolkovo, Vorobyovy Gory, and MISiS innovation ecosystems are jointly implementing the following projects:

Project 1. *Digital Business*—the creation and development of a universal software platform for data mining to generate and commercialize digital solutions for innovative ecosystems based thereon.
Project 2. *Quantum Hub*—the creation of network prototypes for quantum computers, the development and implementation of quantum data protection.
Project 3. Establishment of the laboratory infrastructure for the Technological Valley of Lomonosov Moscow State University. The collaboration potential was assessed on the basis of expert assessments using the Harrington scale for converting qualitative parameters into quantitative ones. Representatives of business and scientific communities, government authorities, and industrial partners of ecosystems acted as experts.

The strength of the ecosystem connection is defined as the geometric mean of the coded values (y_{ij}; d_i). Let us calculate the values of control points (y_{ij}) and the parameter value of the dependence between ecosystems for Project 1.

$$y'(1) = -\ln\ln(1/0.37) = 0.00576$$

$$y'(10) = -\ln\ln(1/0.8) = 1.4999$$

The equation $y' = a * y + b$ acts as a mechanism for transfering y into y'. The final equation will take the form: $y' = 0.16576y - 0.16025$.

Similarly, the parameter for Project 2 and Project 3 has been estimated. The generalized Harrington desirability function (optimization criterion) for the j-th ecosystem is defined as the geometric mean of particular desirabilities. The results are presented in Table 4.

Table 4. Interpretation of standard marks on the Harrington scale for ecosystems.

Projects	Skolkovo Ecosystem		Vorobyovy Gory Ecosystem		MISiS Ecosystem		Generalized Harrington Desirability Function (D)
	y_{ij}	d_1	y_{ij}	d_2	y_{ij}	d_3	
Project 1	1.374	0.781	1.248	0.769	1.325	0.763	0.81
Project 2	1.115	0.716	0.857	0.645	1.373	0.767	0.73
Project 3	1.125	0.681	0.752	0.583	1.149	0.721	0.60

According to the Harrington scale, Project 1 is classified as *very good*; therefore, the ecosystems have a complete resource and project dependence. Project 2 is classified as *good*, which indicates the presence of a project dependency between ecosystems. The dependence between ecosystems is for informational purposes only in Project 3. The integral indicator of the collaboration level for the three ecosystems was as follows:

$$D_j = \sqrt[3]{0.81 \cdot 0.73 \cdot 0.6} = 0.7079$$

The closer the indicator of the collaboration level is to 1, the better it is for the ecosystem in terms of its sustainability.

The relationship strength between actors can be assessed through the dynamic component of behavior, which manifests itself in the activity of a set of actors and the emergence of effective patterns for solving certain problems. The search for optimal ways of interaction within the ecosystem has led to the discovery of its elements, where the relationship strength between actors is especially strong.

Consider the features of the proposed methodology applied to the case study of Moscow innovation ecosystem. Its structure is shown in Table 5.

Table 5. The composition of the innovation system actors.

Participants in Moscow Innovation Ecosystem	Number of Participants
Scientific and innovation organizations, total:	1074
- Scientific organizations	821
- Small innovative organizations	253
Educational institutions, total:	285
- Universities	145
- Colleges	119
- Children's technoparks	21
Industrial enterprises, total:	25,614
- Manufacturing enterprises	25,574
- Industrial complexes	40
High-tech IT companies	38,773
Support infrastructure, total:	1614
- Nanotechnology centers	4
- Engineering centers/Prototyping centers	69
- Multiple access centers	142
- Pilot test sites	172
- Business accelerators	29
- Business incubators	12
- Development institutions	20
- Coworking spaces	173
- Technoparks	47
- Centers for youth innovative creativity	55
- Business service centers	16
- Certification bodies/Test laboratories	733
- Technology transfer centers	11
- Special economic zone	1
- Unique scientific installations	128
- Digital business space	1
- Creative business services center	1

The innovation ecosystem includes the Moscow innovation cluster and twelve sectoral clusters. The innovation cluster numbers 25,033 members and 9542 partners. The participation structure by the type of activity is as follows: services—51%; wholesale and retail trade—18%; industry—12%; information technology—6%; scientific research—5%; education—3%; others—5%. The participation structure by the size of the organization is as follows: micro- and small enterprises—71%; individual entrepreneurs—14%; large enterprises—13%; medium-size enterprises—2%. The innovation cluster provides its members and partners with the following services: Navigator on Support Measures, Venture Investments, Pilot Sites, Partner Search, Hackathons, Moscow Accelerator, Contract Manufacturing Exchange, Business Premises, Concierge Service, Projects and Needs, Inter-Sectoral Clusters, Factoring.

Recently, the Contract Manufacturing Exchange service has been actively developing in the innovation cluster. This is the manufacture of piece and serial parts according to drawings or 3D models, as well as their subsequent processing, carried out at the capacities of an accredited manufacturer in accordance with customer requirements and in compliance with the entire technological cycle. As a rule, when developing complex innovative products, it is necessary to place a significant number of orders at the capacities of various independent manufacturers. To launch a new product or expand production, there is no need to buy machines or equipment and hire additional staff. All contractors accredited at the Exchange are required to confirm the availability of the necessary equipment and compliance with technological and production cycles. At present, 151 mechanical processing manufacturers, 123 instrumentation manufacturers, and 332 light industry manufacturers are registered at the Exchange.

To evaluate the efficiency of the model, a set of five test cases of varying complexity depending on the number of actors (from 50 to 150) has been used.

The obtained efficiency values for the search for optimal solutions for the indicated tasks are shown below. The calculations were carried out using an Intel-Xeon E5-2650 v2 microprocessor (2.60 GHz). Table 6 shows minimum, maximum, and average values of the program's operation (for 30 launches, in second) when finding optimal solutions.

Table 6. Values of performance indicators for the search for optimal solutions.

Task	n	t_{min}	t_{max}	t_{avg}
PE01	50	0.5	16.7	1.7
PE02	75	1.2	31.2	2.3
PE03	100	1.7	55.6	12.6
PE04	150	2.6	252.2	39.3
PE05	120	2.1	105.8	27.2

In all cases, optimal solutions were obtained. The following parameter values were used in the calculations: $\alpha = 2.0$, $\beta = 1.0$, $\rho = 0.2$, $N_{ants} = 30$. The time for solving the same problem can differ significantly from case to case due to the stochastic nature of the proposed method.

6. Discussion and Conclusions

The article proposes a conceptual approach to the formation of an eco-megacity as a qualitatively new phenomenon in the post-industrial economy. The authors make their assumptions through observation of reality, namely, current trends and tendencies in the development of the megapolis of Moscow.

Examining a variety of case studies from different geographical spaces, scholars have shown that alleged smart cities and eco-cities are far from their philosophical ideals, they rarely innovate and instead replicate traditional capitalist strategies of urbanization, and they seldom keep their promises of sustainability [26,91–93]. This fact forms the gaps between ideas and reality in individual cases of smart and eco-city projects [91]. Our research complements the above body of work by focusing on an aspect of ecosystems' collaboration within a modern megapolis as a core of the concepts of smart and eco-cities and a driving factor for successful ecosystem transformations.

Our study derives from the eco-city concept by expanding it and focusing on the concept of the eco-megacity and contributes to its further theoretical and methodological development.

Currently, while the eco-megacity phenomenon is emerging, the corresponding data are being accumulated, and attempts are being made to compare it with already established phenomena and to assess the legitimacy of its introduction into scientific circulation. Deep gaps in the megapolis system indicate the absence of constituent features of the ecosystem therein: the potential for sustainable self-development; mechanisms of rational, non-destructive interaction with the external environment; institutions of flexible self-regulation, allowing for adaptations to abrupt changes in the conditions of the evolutionary process [5]. Accordingly, transformation of a megapolis in the process of its internal environment interaction with the ecosystems makes it possible to acquire the indicated features and initiate a transformation into a qualitatively new state of an eco-megacity.

The conducted theoretical study of the megapolis as an integrated system in terms of the modular version of the systems approach proposed by Kleiner [80], representing the ecosystem of the megapolis through the combination of object, process, design, and environmental subsystems, allowed the authors to substantiate its further transformation.

The authors presented the role of collaboration as the main factor in increasing the efficiency of interaction processes between ecosystem actors and between ecosystems themselves, having revealed its constituent features. In general terms, the potential of the institutional approach for ordering the relations developed in the process of collaboration between ecosystems has been indicated. The soft institutions that are demanded by the collaboration of ecosystems have been identified, which makes it possible to ensure the transformation of a megapolis into an eco-megacity. The features of the project's approach to implementation to ensure the collaboration of ecosystems in the space of the megapolis are highlighted.

The authors propose a novel approach to the study of the ecosystem transformation of a megacity, which is based on the idea of developing collaboration as a fundamental basis for the transformation of a megacity into an eco-megacity. The implementation of this approach made it possible to form the concept of the socio-economic diversification of a megapolis based on the concentration of intellectual capital and the possibility of digital transformation.

The main practical contribution of the conducted research is that the results of the study at the municipal level can be used in strategic documents for economic development to improve the regulatory framework that ensures the implementation of the socio-economic policy of the Russian Federation.

It should be further emphasized that the proposed methodology for studying the symbiosis of socio-economic ecosystems in a megapolis is based on the following assumptions and limitations:

(1) restrictions on indexing grid nodes and the order of their traversal;
(2) the result depends on the validity of the trajectory optimization formulation;
(3) the assumption of minimizing repeated and diagonal traversals of nodes or edges;
(4) the assumption of the ant algorithm's convergence;
(5) non-convergence—even after many iterations, different solutions are being investigated simultaneously, which allows you not to get stuck in local optima.

7. Future Research

In the future, the authors propose testing the proposed methods and mathematical tools on real cases by assessing and modeling collaborations within multiple ecosystems of the megapolis of Moscow, since data on this phenomenon are accordingly accumulated. To develop collaborations between the ecosystems, a project approach should be used. The next step is to study the quality of the interaction of actors (participants of collaborations). When developing models of dynamic organizational systems, the problem arises of choosing an adequate mathematical model of quality (utility). This is due to the complex structure of relationships between the elements of the system being built, the evolution of the object of study in time, and partial uncertainty, which manifests itself in the different reactions of actors to the same situation at different points in time.

In future research, the authors are planning to extend the case study by taking into account other megapolises. This will help us in drawing general and specific features for each case assessed and expanding on the generalization of the conclusions and propositions made in our research to make them widely applicable.

Further research into a megapolis in terms of its ecosystem is supposed to be carried out using the method of entropic stability analysis proposed by the authors in previous works [42]. This approach makes it possible to determine the structure of dependencies of both actors included in a single ecosystem and the ecosystems within the eco-megacity.

Besides, in the future, the authors plan to assess the potentials of megapolis ecosystems based on the calculation of indicators for the corresponding components of the ecosystem's maturity (the level of technology development, economic well-being, natural and ecological balance, the level of development of culture and education) using the method of the analytic hierarchy process (AHP) developed by Thomas L. Saaty (1989) [94].

Another promising approach to the study of megapolis ecosystems is represented by the theory of macrogenerations by Ilya Prigogine [95]. Using the example of US ecosystems, he showed that there are several macrogenerations at any given time in the simulated ecosystem, each of which moves along its own trajectory and, having reached its maximum development, begins to gradually fade away. Synchronization of life cycles of macrogenerations in a megapolis is of particular importance from the standpoint of sustainable development.

Finally, speaking of ecosystems as a horizontal cooperation of actors and an evolutionary development of traditional network structures, it is necessary to study the processes of networkization in terms of the theory of scale-free networks. Baruch Barzel and Albert-Laszlo Barabási [96] suggested that networks form a kind of framework for their corresponding complex systems, and proved that scale-free networks are very resistant to accidental damage or external accidental influences. However, deliberate damage to one or more nodes with a large number of connections (degree centrality) leads to the disintegration of the network [97]. In future research, it is advisable to apply this approach to model the optimal network structure of ecosystems in the eco-megacity space.

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