This study's object is the university innovation ecosystem as an organizational and structural entity aimed at supporting startups and innovation activities.

The task addressed concerns the fragmentation and lack of coordination among the innovation units of universities, which complicates the commercialization of scientific developments and reduces the effectiveness of innovation-driven growth.

A model of a sustainable university innovation ecosystem has been constructed, incorporating three cycles of interaction among infrastructural components. The proposed model enables a systematic organization of the processes of selection, support, and commercialization of startup projects through the involvement of both internal and external innovation flows. A key component of the model is legal support for startups at all stages, as well as a re-entry mechanism that allows projects to return to the system for refinement and increased market readiness.

The model aligns with the global Sustainable Development Goals (SDGs 4, 9, and 17), which reinforces its strategic orientation. A three-cycle model of a sustainable university innovation ecosystem is proposed and tested, ensuring the integration of innovation units and promoting the effective commercialization of startups.

The uniqueness of the model is its structured architecture, cyclical logic, clear division of roles among innovation units, and the built-in legal mechanism that enables sustainable development and addresses the problem of disconnectedness. The model is applicable for implementation at universities that possess a basic infrastructure for innovation and seek to enhance the effectiveness of research commercialization

Keywords: innovation ecosystem, model architecture, university, sustainable development, startup, commercialization, structural integration, innovation infrastructure

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BUILDING A MODEL OF A SUSTAINABLE UNIVERSITY INNOVATION ECOSYSTEM: MECHANISMS OF INTEGRATION AND COMMERCIALIZATION

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1. Introduction

In the modern world, innovation activity increasingly determines the competitiveness of national economies; universities play a key role in the formation and maintenance of innovation ecosystems. In different countries, regardless of the level of economic development, there is a need to strengthen ties between academia, businesses, and government structures to ensure effective commercialization of scientific results. This is especially relevant in the context of limited resources, global instability, digital transformation, and the challenges of sustainable development.

In many countries (for example, Poland, Estonia, Israel, South Korea, Chile) there are active attempts to structure university innovation ecosystems through the creation of startup centers, science parks, business incubators, technology transfer centers. Despite positive results, university ecosystems often remain fragmented, with insufficiently coordinated interaction between their elements. This creates barriers to the effective launch, support, and scaling of startups.

In this context, the development of structured models of innovation ecosystems of universities, capable of ensuring the integration of key units, support for startups at all stages of the life cycle, and strategic orientation towards achieving the Sustainable Development Goals, is of particular importance. This approach is in demand both in countries with an established innovation infrastructure and in countries that are in the phase of its construction.

One of the key elements of this ecosystem is higher education institutions. An important task of universities is not only the transfer of knowledge but also active promotion of the creation of an innovative environment that ensures sustainable development, integrates science with entrepreneurship, and promotes the transformation of scientific results into practical solutions. Universities, as centers of intellectual development, should be initiators of the implementation of environmentally balanced and effective approaches to management, education, and scientific research.

The evolution of information technologies, the openness of scientific data, and the expansion of international cooperation require universities to constantly improve, be flexible, and able to adapt. In this context, research into the processes of creating and ensuring sustainable development of the university's innovation ecosystem is relevant both for the academic community, as well as for business and society as a whole.

Article 60 of the Law of Ukraine "On Scientific and Scientific-Technical Activities" [1] provides for mechanisms for the participation of state scientific institutions and higher educational institutions in the creation of business associations for the purpose of using intellectual property rights. The practical direction of realizing the innovative potential of universities is the design and development of structures capable of ensuring the commercialization of science-intensive results (innovation centers, technology transfer centers, business incubators), as well as support for startup initiatives within the university environment.

At the same time, there are numerous obstacles to the formation of university innovation ecosystems related to the commercialization of intellectual property created within the framework of state funding. The procedure for such a transfer involves interaction with state structures such as the State Property Fund of Ukraine, the Ministry of Education and Science of Ukraine, which creates significant administrative barriers.

In the EU countries, the practice of commercializing research results at universities is more regulated: universities have a policy that encourages the creation of innovative companies by lecturers and researchers based on their own developments. However, even under favorable conditions, difficulties arise related to scaling models, legal support, and coordination of the roles of different structural units.

Today, higher education and scientific activity at universities are under pressure from growing demands for innovative development, commercialization of research results, and increased competitiveness. The low level of integration of scientific achievements into practice, limited technology transfer mechanisms, and insufficient attention to sustainable development issues create obstacles to the formation of an effective innovation ecosystem. Therefore, the need to devise strategic approaches that could enable the sustainable development of such ecosystems is becoming a priority for modern universities. That is why research into construction of a model for a university innovation ecosystem is extremely relevant.

2. Literature review and problem statement

The university innovation ecosystem encompasses the complex interaction of academic, research, management, and entrepreneurial components within the university and its external environment for the purpose of generating, transferring, and commercializing knowledge. The startup ecosystem is only one of the possible tools for implementing this activity, mostly focusing on supporting entrepreneurial initiatives and newly created innovative companies.

In [2], the results of a case analysis of the organization of the innovation ecosystem at a Brazilian university are reported. It is shown that orchestrating the interaction of departments contributes to efficiency. However, issues related to the scalability of such a model and its legal support remain unresolved. The reason for this is the limitation in financing and the differences in the legislative framework. An option for overcoming related difficulties may be the construction of a universal flexible model taking into account legal support. This is the approach used in [3], but without implementing the cyclical principle.

Thus, in [3] a model of a new generation university ecosystem 5.0 with digital elements is proposed; however, the differences between the functioning of the institutional ecosystem of the university and the support of startup initiatives are not sufficiently detailed. It is shown that the involvement of digital solutions and broad partnerships create additional opportunities. However, issues related to the practical detailing of startup commercialization mechanisms remain unresolved. The reason for this is the predominant attention to the conceptual level without sufficient development of implementation tools. This challenge can be overcome through the integration of specialized legal and business tools.

In [4], the theoretical justification of the innovation ecosystem is revealed; the results of the theoretical and methodological foundations of the study of the ecosystem of financial recovery and economic development of the territory are reported; the stages that ensure a systematic assessment of various components of its potential are identified. However, there is no clear mechanism for implementing the proposed model in practice under the conditions of post-war recovery and there is no detailing of the role of stakeholders in building this ecosystem. This is due to the lack of empirical data due to the ongoing martial law and the uncertainty of recovery conditions, as well as the authors' focus on theoretical development without practical testing or consultations with business/government representatives.

In [5], the results of analysis of the conditions for the formation of entrepreneurial ecosystems in cities are reported. It is shown that local factors significantly affect the development of innovative structures. However, issues related to the internal structural interaction of universities in such ecosystems remain unresolved. The reason for this is the predominantly macro-level focus of the study, without detailing internal mechanisms. A variant of overcoming related difficulties may be a focus on intra-university processes. This is the approach used in [3], but without taking into account legal and commercial aspects.

Startup development ecosystems as a tool of state innovation policy are considered in [6]; a methodological model of the main characteristics of startup success is built. The research results show that startup ecosystems at universities are becoming an element of the implementation of state innovation policy, a new way of supporting scientific developments and the possibility of their entry into the market. The paper is an analytical review, therefore there are no deep empirical assessments, and no mechanisms for monitoring and assessing the effectiveness of interaction between the state and startups are presented.

The results of the development of the concept for innovation systems are reported in [7]. It is shown that the involvement of different groups of stakeholders increases

the innovation potential. However, the issues related to the practical implementation of such a model at universities in post-conflict regions remain unresolved. The reason for this may be high organizational and financial costs. A possible way to overcome difficulties may be the development of a flexible phased integration model. This is the approach used in [8], but without proper detailing of legal mechanisms.

Analysis of the evolution of the innovation ecosystem of Silicon Valley under the influence of universities is reported in [8]. It is shown that universities are key drivers of the innovation environment. However, the application of this model under European or post-conflict conditions has remained out of focus. The reason for this is cultural and economic differences, as well as different approaches to financing, which can be overcome by devising adapted models taking into account local characteristics. This is the approach that will be proposed in our work; mechanisms for legal protection and sustainable development will also be further integrated.

In [9], the results of research on the roles of participants in the formation of an innovation ecosystem are reported. It is shown that the successful development of the ecosystem depends on a clear distribution of functions between key agents. However, issues related to the long-term stability of interactions between these agents and the stability of models under crisis conditions remain unresolved. The reason for this may be objective difficulties associated with the complexity of tracking the behavior of all participants in dynamics. An option for overcoming related difficulties may be to model sustainable management and integration structures.

The startup ecosystem as an element of the innovation ecosystem, its structure, and areas of support are studied in [10]. In this case, the work lacks a modern approach to the digitalization of ecosystems and does not take into account the role of international platforms (such as accelerators or EU grant programs). It is shown that the involvement of digital solutions and broad partnerships create additional opportunities. Unresolved issues include the practical detailing of startup commercialization mechanisms due to the predominant attention to the conceptual level without sufficient development of implementation tools. Integration of specialized legal and business tools will overcome these difficulties, as shown in [8], but there is no emphasis on sustainable development.

In [6, 11], the evolution of startup ecosystems is studied as part of state innovation policy, but these approaches do not take into account the specificity of the internal logic of the functioning of higher education institutions. The author of [11] studied the creation and scaling of startups and analyzed the features of the formation of startup ecosystems in countries around the world. The research results build on theoretical principles of startup life cycle management based on the identification of the stages of their development. At the same time, there is a lack of analysis of the challenges of scaling startups under the conditions of the Ukrainian market, and insufficient attention is paid to public-private interaction in supporting startups.

Innovations are a key factor in increasing competitiveness both at the level of enterprises and at the level of the country as a whole; they are a driver of economic growth, attracting investments and creating new jobs. Thus, in [12], the results of modeling the choice of an innovation strategy for industrial enterprises are reported. It is shown that the integration of different strategic approaches makes it possible to increase competitiveness. The adaptation of such strategies to the conditions of university startups and academic innovations is unresolved due to the objective difficulties of transferring methods between the business environment and educational structures.

The authors of [13] conducted a comparative analysis of startup ecosystems in Eastern Europe and Ukraine. The development process requires a comprehensive approach and the involvement of all stakeholders, including government, businesses, and the academic sector. All this requires further disclosure of the potential for applying foreign models in the Ukrainian context, taking into account military risk, and there is a lack of in-depth analysis of implementation barriers (regulatory, institutional).

Analytical reports [14, 15] on the global analysis of startup ecosystems outline the problem of fragmentation of the innovation environment in new ecosystems, which hinders the realization of the full potential of startups. The reports emphasize the need for structured models of interaction between institutions, in particular universities, which confirms the relevance of building a system architecture of university ecosystems focused on supporting innovative entrepreneurship.

Paper [16] reports the results of studies that demonstrate the connection between corporate sustainability and financial performance of enterprises in post-war conditions. It is shown that the sustainability of activities directly affects investment attractiveness. However, issues related to the application of results in the field of university startups and ecosystems remain unresolved. The reason for this is the difference in the organizational logic and goals of universities compared to business structures. The creation of university commercialization models integrated with the principles of sustainable development can increase investment attractiveness. This is due to the fact that investors are increasingly paying attention to projects that not only bring profit but also have a positive impact on the environment and society, that is, they comply with the principles of sustainable development.

Work [17] gives the results of a critical analysis of the concepts of an innovation ecosystem. It is shown that there are different approaches to defining and assessing its effectiveness, but there is no single conceptual model for university environments. At the same time, issues related to the practical implementation of concepts in the context of academic structures remain unresolved because of the fundamental impossibility of unifying university systems due to their different missions and organizational cultures. In this sense, the development of an adaptive ecosystem model for individual universities is important.

In general, our review of the literature reveals that despite the large number of studies in the field of innovation ecosystems, either theoretical developments or a focus on the business environment prevail. The specificity of the university innovation ecosystem and its functioning under conditions of limited resources, regulatory complexity, and post-war reconstruction are not sufficiently disclosed.

All this gives grounds to argue that most studies focus on theoretical or generalized models, do not offer practical tools for the implementation, monitoring, and scaling of innovation ecosystems, etc. The construction of such an ecosystem would make it possible to cover both internal processes of management, knowledge transfer, and interaction between departments, and external interaction with businesses, investors, and government agencies. Within such

a model, startup structures can be considered as one of the tools for implementing the functions of the ecosystem but not as its synonym or dominant component.

3. The aim and objectives of the study

The purpose of our study is to build a model of a sustainable innovation ecosystem of a university, which enables effective interaction between key innovation units and promotes effective commercialization of startup projects, taking into account the global goals of sustainable development. This could allow universities to improve organizational and structural approaches to managing innovation activities, increase the efficiency of bringing developments to the market, establish cooperation within the ecosystem and create institutional conditions for sustainable innovative development. In this case, a sustainable innovation ecosystem is understood to be an ecosystem as a set of interconnected elements of infrastructure, organizations, processes, and people that act to set up and commercialize startup projects and technological advancements.

To achieve the goal, the following tasks were set:

– to identify the features of existing practices at universities with an extensive innovation infrastructure in the innovation ecosystem;

– to substantiate the architecture of a sustainable innovation ecosystem of the university by determining its structural components, functional relationships between key units, as well as mechanisms for integrating startups and supporting their commercialization processes within the university environment;

– to verify the model based on practical testing.

4. The study materials and methods

The object of our study is the university's innovation ecosystem as an organizational and structural formation focused on supporting startups and innovative activities.

As part of the study, the main hypothesis was put forward, according to which the unification of the university's innovation units into a single structured model of a sustainable innovation ecosystem could improve the efficiency of the commercialization of startup projects.

A number of assumptions were accepted in the process of our study. First, the university has sufficient institutional, scientific, and infrastructural potential for the implementation of innovative activities. Second, the units of the innovation ecosystem are capable of effective interaction under the conditions of the introduction of agreed regulations.

However, for the integrity of the model, several simplifications were adopted, in particular, the financial component (sources of funding, budgeting mechanisms, and risk assessment) is considered indirectly in the study.

This approach allowed us to focus the study on building a practically oriented, systemic model of the innovation ecosystem, relevant to the conditions of Ukrainian universities.

To solve the first task, the induction method was used to generalize information obtained from primary sources – university websites and documents, to study and systematize the advantages and disadvantages of universities in the innovation environment.

Within the framework of the second task, the conceptual modeling methodology was used to design the architecture of a sustainable innovation ecosystem of the university. The architecture is built on the basis of a three-cycle approach, which involves the interaction between research, educational, and entrepreneurial activities as elements of a single functional system. To fill the model with empirical data, the case study method was used: the activities of the innovation infrastructure at the National Technical University "Kharkiv Polytechnic Institute" were analyzed, which includes the Startup Center, the Science Park, the research department, and other units.

The proposed model was tested by analyzing real cases of startup projects initiated in the university environment within the framework of the third task. This allowed us to verify its applied effectiveness in the context of solving the problems of commercialization of innovations and integration of innovation units of the university into a single ecosystem.

Such a comprehensive approach is aimed at forming a holistic understanding of how the innovation ecosystem evolves, is managed, and coordinated in the context of interaction between science, businesses, and the state.

5. Results of building a model of a sustainable innovation ecosystem of a university

5. 1. Practices of universities with an extensive innovation infrastructure

Higher school is constantly faced with the need to adapt to market changes, an integral part of which are organizational and structural changes (structural transformations, creation of new innovation units, startup centers, business incubators, etc.). The irreversibility and orderliness of such changes over time allows us to identify them as sustainable organizational development, which must necessarily be focused on preserving the desired properties and achieving pre-established requirements, that is, meet the sustainability criterion. Planning and targeted implementation of changes should be focused on ensuring increased efficiency of innovation activity through the implementation of a comprehensive approach to managing sustainable organizational development by management as a management entity. The complexity of the approach should be based on the adaptation of the structural innovation ecosystem in accordance with the conditions of the external environment. This is what determines the relevance and urgency of the need for an adequate theoretical and conceptual understanding of the causes and prerequisites, mechanisms, and tools for supporting the sustainability of the newly created innovation ecosystem when implementing organizational transformations in the development process.

Creative entrepreneurship among universities and students has gained popularity, which has contributed to the creation of startup centers, parks, and incubators at educational institutions of Ukraine. In particular, this allows them to become part of the startup movement and develop their own innovative products within the framework of the educational process.

Among the organizations that are actively involved in the development of startup ecosystems at universities, the following can be distinguished: "Tech Startup School" at the National University "Lviv Polytechnic" [18], "Sikorsky Challenge" at the National Technical University of Ukraine "Kyiv Polytechnic Institute" [19]. In addition, this is the Kharkiv National University of Urban Economy named af-

ter O. M. Beketov (Beketov Startup School junior; Beketov Startup School; Beketov Business Incubator; Beketov Science Park; technology transfer center "Megapolis") [20].

Enabling the functioning of such startup ecosystems is carried out through the creation of a comfortable innovative environment for the production and implementation of innovative products and successful startups. This helps innovators, under the guidance of mentors, go from a startup idea to building a business model, finding investors, and commercializing an innovative project.

Analysis of the «Tech Startup School» at the National University «Lviv Polytechnic» [18] revealed that the university has reasonably developed innovation departments, but the concept of creating an innovation ecosystem at the university is not proposed. Analysis of the innovation ecosystem «Sikorsky Challenge» at NTUU «Kyiv Polytechnic Institute» [19] allows us to conclude that this ecosystem is relatively developed but does not take into account some modern trends, for example, sustainable development goals.

When analyzing the activities of innovative startup units at the Kharkiv National University of Urban Economy named after O. M. Beketov (KNUMG), it was revealed that there are no interconnections between the elements of the startup [20]. The existing units (Beketov Startup School junior; Beketov Startup School; Beketov Business Incubator; Beketov Science Park; Technology Transfer Center "Megapolis") do not have structural interaction.

In addition to the Ukrainian experience, the practices of leading universities in the world that have implemented comprehensive models of innovative development are of considerable interest. For example, Stanford University (USA) is one of the most famous examples of integrating university infrastructure into a regional innovation ecosystem. Through the creation of the Stanford Research Park [21], active cooperation with venture investors, and support for teaching entrepreneurship, the university has become the core of the formation of Silicon Valley. Its model involves not only technical support for startups but also the full integration of educational, research, and business initiatives within a single institutional environment. Another example is Aalto University (Finland), which has combined engineering, economics, and art into a single innovation system. Its infrastructure includes the Aalto Startup Center [22], the student entrepreneurial association Aaltoes, incubators, design factories, and accelerators. The university has built a holistic model that covers all stages of the innovation process – from the birth of an idea to its commercialization, involving mentoring, training programs, and international partnerships.

In the UK, an example of an integrated innovation ecosystem is the SETsquared association [23], which unites five universities (Bath, Bristol, Exeter, Southampton, and Surrey). The SETsquared model includes joint business incubators, acceleration programs, advisory support for startups, and active participation of universities in regional innovation policy. This format enables not only effective technology transfer but also scalability of entrepreneurial initiatives.

A summary of available open data shows that universities are implementing innovative forms of startup support based on internal structures: startup schools, business incubators, technology transfer offices. The main tasks of these units are idea generation, mentoring, business model development, investor search, partnership creation, and promotion of project commercialization.

However, the vast majority of universities implement the development of startup ecosystems in a fragmented manner, without a single concept or structured model of interaction between units. In a number of cases, there is an insufficient level of integration of elements of innovation infrastructure, as well as a lack of systemic connection with global sustainable development goals.

Thus, the generalization of existing practices indicates the presence of positive examples of the functioning of innovation infrastructure at universities, but at the same time demonstrates the need for more integrated and conceptually consistent models of the university innovation ecosystem.

5. 2. Substantiating the architecture of a sustainable innovation ecosystem of the university

The proposed architecture consists of three interconnected modules that reflect the main cycles of development of startup projects:

1) initiation – generation of innovative ideas, team formation, initial examination;

2) development – acceleration, mentoring, legal support, preparation of a business model;

3) commercialization – market entry, technology transfer, scaling support, re-entry for refinement.

This study analyzes the current scheme of work of innovation units at the National Technical University "Kharkiv Polytechnic Institute" (hereinafter referred to as NTU "KhPI"), which is shown in Fig. 1.

The organizational structure of the university includes three innovation departments and the TISC office (Technology and Innovation Support Center):

1. Research and Development Department [24], the main goal of which is to obtain and use new scientific knowledge in order to create, implement, and use socially useful scientific and practical results in Ukraine and on the world market.

2. Startup Center "SPARK" NTU "KhPI" [25], the main task of which is to support startups of young entrepreneurs at all stages of development: from idea development to commercialization.

3. LLC "Science Park NTU "KhPI" [26], the general mission of which is to integrate intellectual resources into the process of creating knowledge-intensive, innovative products competitive in domestic and foreign markets and ensuring sustainable development of society.

However, in many universities of Ukraine, including NTU "KhPI", there is a problem of bringing technological advancements to the market and accompanying them to the commercialization market because of the imperfection of the legislation. To solve this issue, it is proposed to create an ecosystem and establish practical interaction with LLC "Science Park NTU "KhPI". Such interaction will be implemented through the following Global Sustainable Development Goals (SDGs): SDG 4 "Quality Education", SDG 9 "Industry, Innovation and Infrastructure", and SDG 17 "Partnerships for Sustainable Development".

The strategic scheme of the sustainable innovation ecosystem of NTU "KhPI" is shown in Fig. 2.

Thus, the substantiated architecture of the sustainable innovation ecosystem of the university determines the logic of the internal organization of innovation activities, ensures coordinated interaction between departments, and creates conditions for the effective integration of startups and commercialization of developments within the university environment.

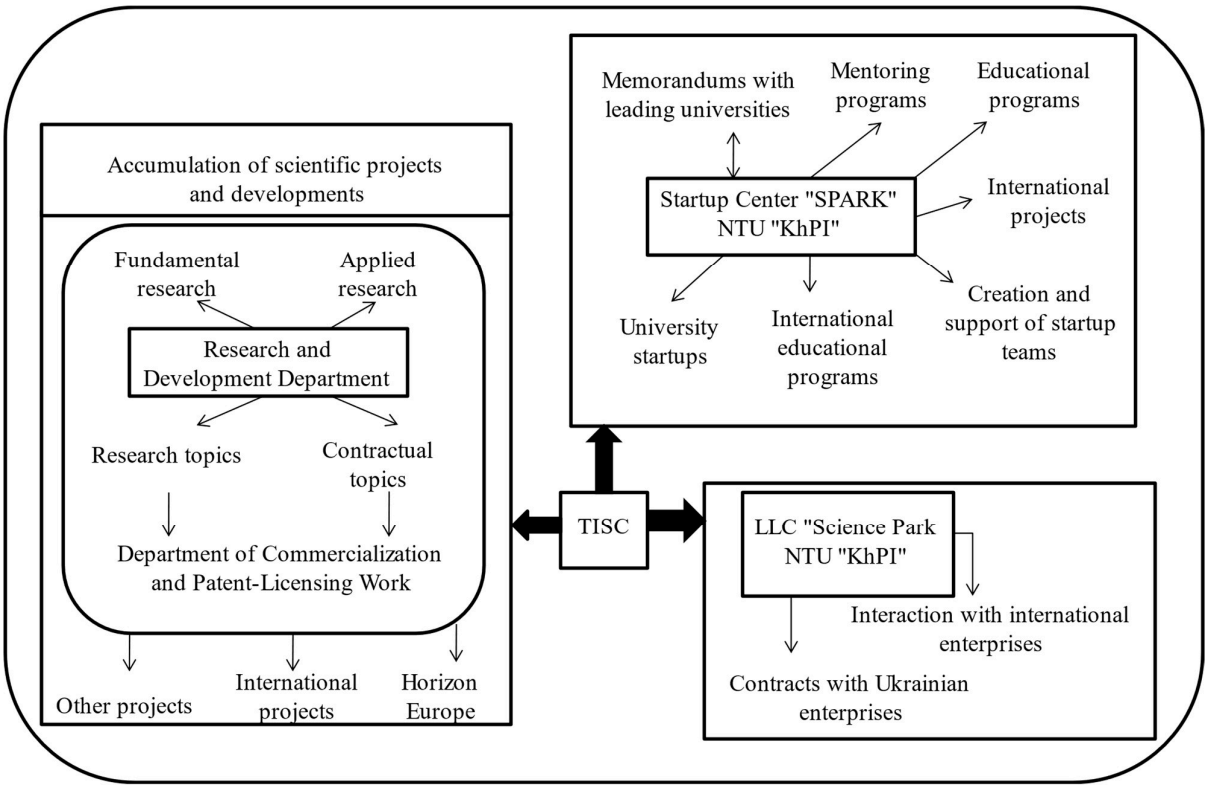

Fig. 1. Scheme of interaction between innovation units at the National Technical University "KhPI"

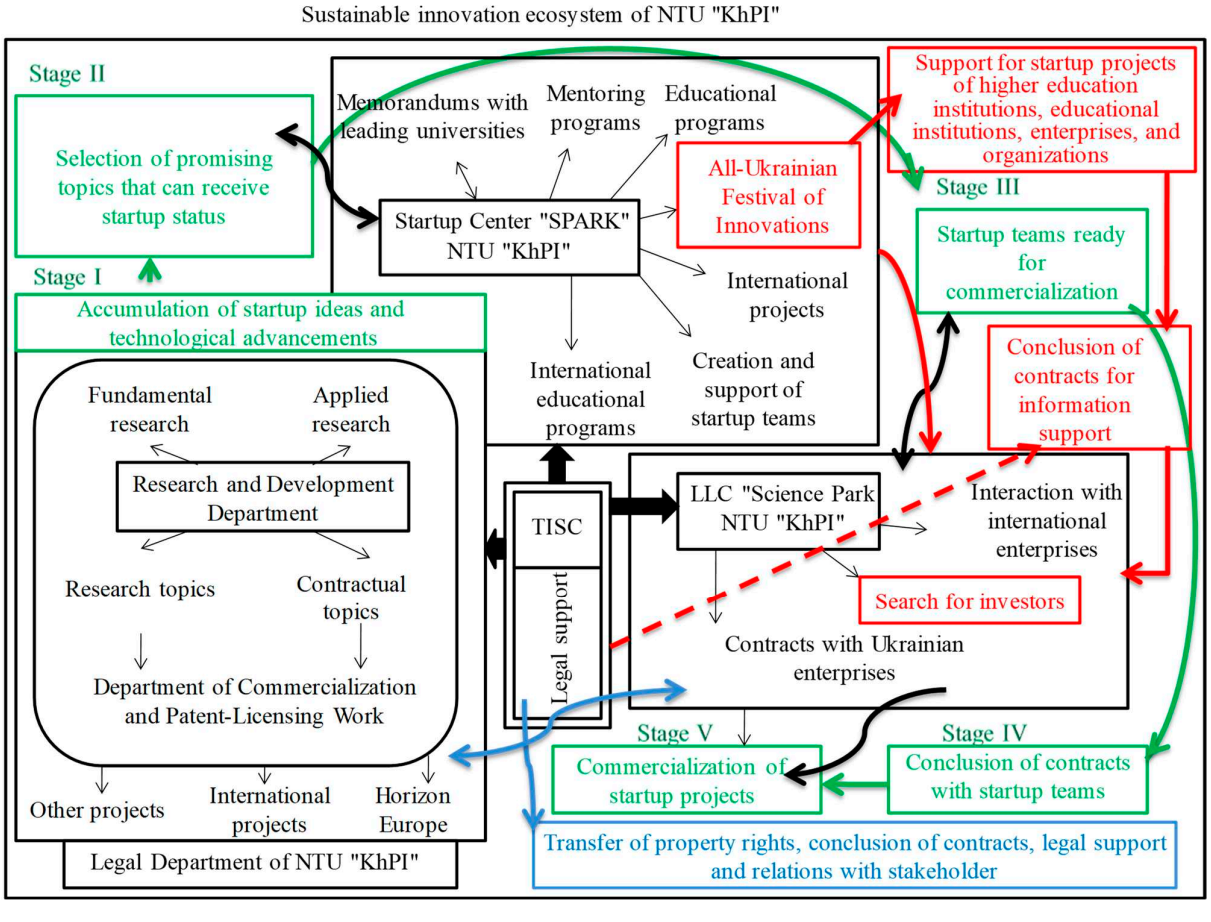

Fig. 2. Strategic scheme of a sustainable innovation ecosystem planned for implementation

The architecture of the proposed model of the sustainable innovation ecosystem of the university reflects an interconnected complex of structural components focused on the implementation of three interdependent cycles. The first cycle in the diagram is depicted in green, the second cycle in red, and the third cycle in blue. An important point is the introduction into the organizational structure of the sustainable innovation ecosystem of an additional element for legal support or the provision of legal consulting services at all cycles and stages of the commercialization of startups and technological advancements. After all, it is important to protect the intellectual property of a product or technology by obtaining patents, copyrights, or other forms of protection.

In the first cycle of commercialization, startup projects go through five stages (Fig. 3):

Stage 1 – accumulation of startup ideas and technological advancements takes place in the university's research department. The purpose of accumulation of startup ideas is to create conditions for collecting, evaluating, and developing potentially successful business concepts.

Stage 2 – selection of promising topics that can receive startup status. If a startup needs mentoring support, acquiring additional knowledge, or a startup does not have a team at all and needs help in forming it or finding certain specialized services, it is envisaged to transfer it to the Startup Center. In order to support a startup, the Startup Center provides such services as market research, compilation of a business plan, analysis of the target audience or consumer portrait, etc.

Stage 3 – selection of projects ready for monetization. At this stage, the startup enters LLC "Science Park "KhPI", where the search for investors, business angels, and interested stakeholders begins.

Stage 4 – conclusion of contracts with startup teams: for this purpose, an independent assessment of the value of property rights to intellectual property objects of NTU "KhPI" will be carried out and an agreement will be signed on their transfer to LLC "Science Park NTU "KhPI".

Stage 5 – commercialization of startup projects and technological advancements takes place. Commercialization of startup projects and technological advancements is the process of transforming an idea or concept into a successful, profitable business.

The first cycle of startup commercialization in the innovation ecosystem model is shown in Fig. 3.

Color marks help visually highlight the cycles during which startups enter this model (at any stage).

The second cycle of the proposed model involves interaction with external startup teams (not from NTU "KhPI"). They contact the Startup Center "SPARK" of NTU "KhPI" in order to receive appropriate support for the startup, additional consultations, participation in educational programs, events, interaction with international partners organized by the Startup Center (Fig. 4). External startups, for example, can enter through the All-Ukrainian Festival of Innovations (Fig. 4).

The next step within the second cycle is to conclude agreements for information support with legal support. Then the startup data is transferred to LLC "Science Park NTU "KhPI", where startups are directly monetized. If additional mentoring or services are needed, the startup team has the opportunity to contact the startup center, improve its qualifications and return to commercialization. This is made possible by the cyclical nature of the proposed model.

The third cycle involves the interaction of the research part of the university with LLC "Science Park of NTU "KhPI" (Fig. 5).

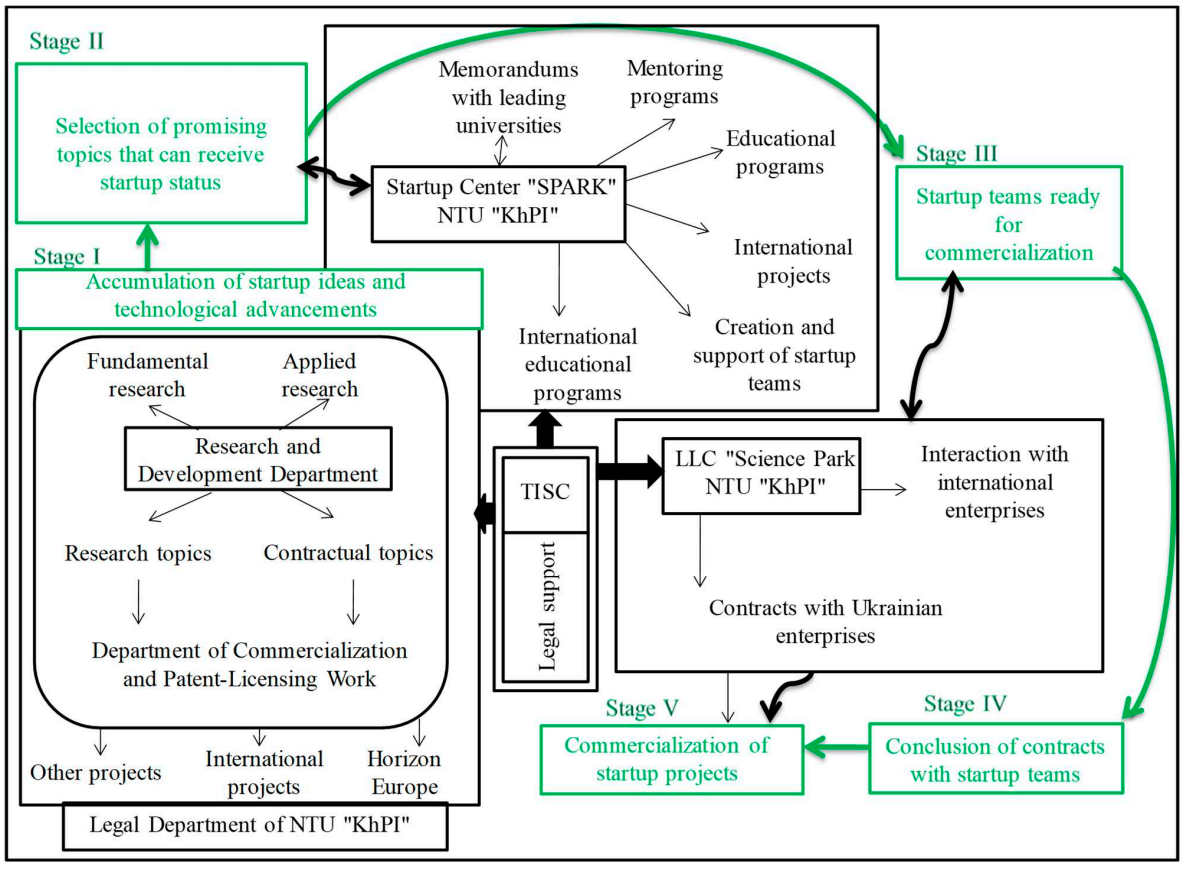

Fig. 3. First cycle of startup commercialization in the innovation ecosystem model

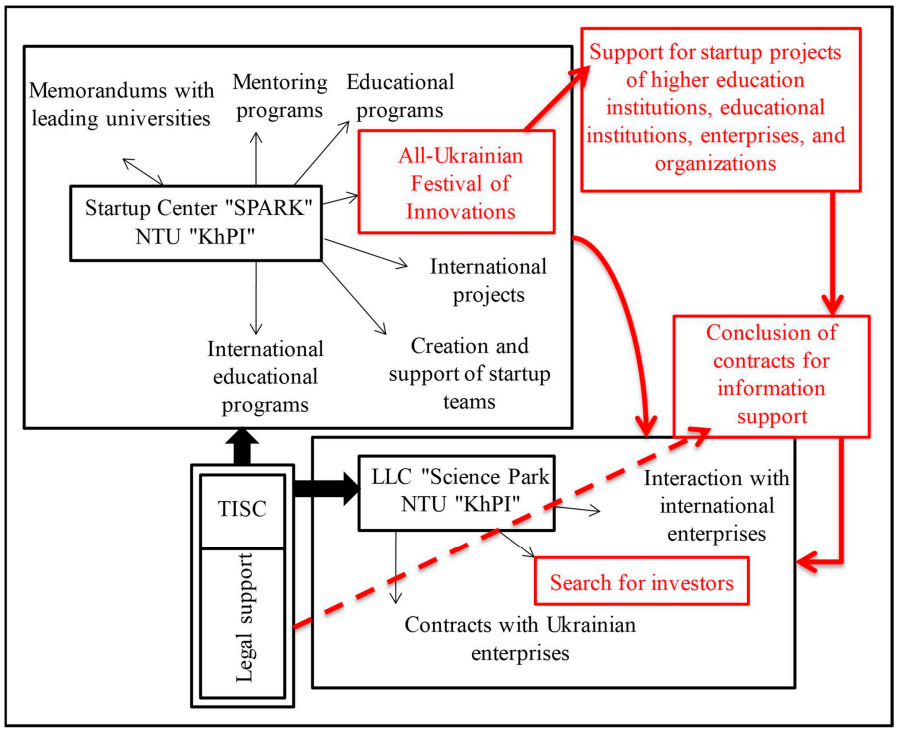

Fig. 4. Second cycle of startup commercialization in the innovation ecosystem model

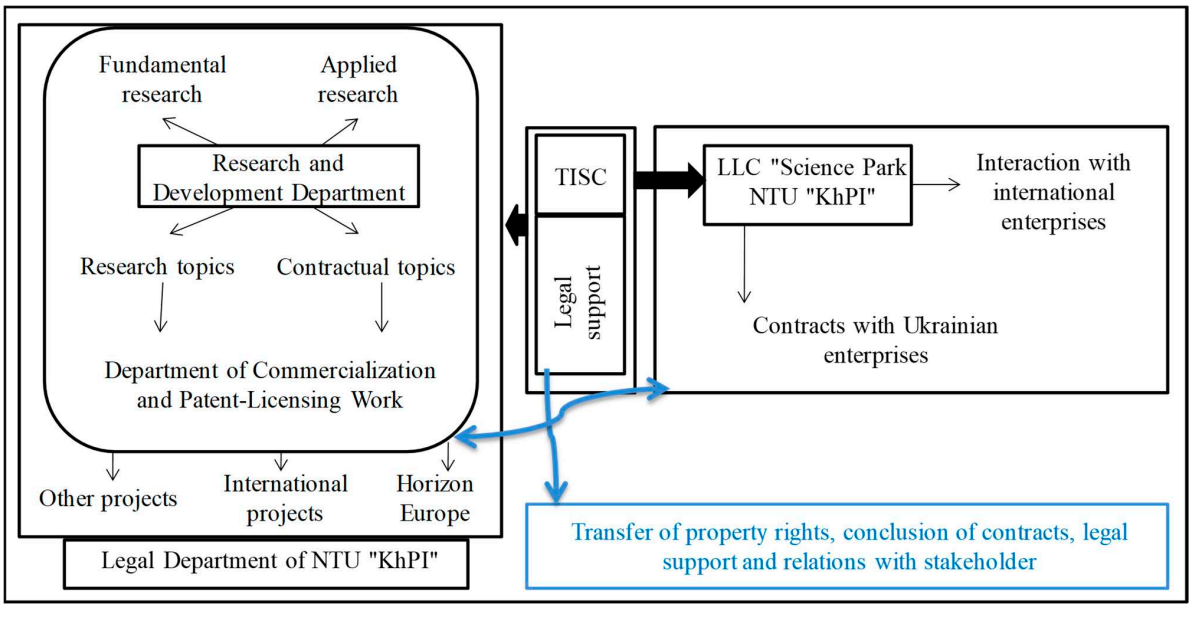

Fig. 5. Third cycle of startup commercialization in the innovation ecosystem model

This cycle involves the selection of startup projects and technological advancements that do not require additional mentoring and further training in this area. They begin to interact directly with LLC "Science Park "KhPI NTU", where the transfer of property rights, conclusion of contracts, and interaction with stakeholders take place. Thus, owing to the proposed model of a sustainable innovation ecosystem, which is planned for implementation, an important scientific and practical task of commercialization of startup projects and technological advancements has been effectively solved.

5. 3. Verification of the model based on practical testing

To verify the practical feasibility and adaptability of the proposed model of a sustainable innovation ecosystem of the university, it was tested on the example of real startup projects initiated within the university environment. This approach allows us to identify how the model corresponds to the features of the internal innovation process at the university, in particular in terms of interaction between departments, knowledge transfer, and commercialization of scientific developments.

It should be noted that the proposed model was tested on the example of a large investment project "Ensuring sustainable development of the city of Kharkiv under the conditions of post-war reconstruction". The project involves reducing CO_2 emissions within the city of Kharkiv and allocating three priority zones with CO_2-neutral facilities and high energy efficiency: the city center, Northern Saltivka, and the

Kharkiv Polytechnic Campus. Relevance of the project: significant destruction caused by Russian military aggression against Ukraine, and measures to implement the strategy of industrial and innovative development of the city of Kharkiv. For a long time, Kharkiv was in the zone of active hostilities. More than 2,500 apartment buildings were destroyed in the city. Enterprises, educational institutions, scientific laboratories, museums, hospitals, etc. were destroyed. In particular, NTU "KhPI" suffered from Russian aggression: the sports complex, academic building, and student dormitories were destroyed [27].

The proposed projects for the sustainable development of the city are also Solar energy, Individual heat points, Electric transport, Turboexpander technologies.

An example of setting up a spin-off company of NTU "KhPI" is the development of fluorescent paving slabs and paving stones, which has undergone several stages of commercialization according to the proposed model of an innovative ecosystem with the involvement of international investments (cycle 3, Fig. 5). The idea of the project is to widely introduce in the city paving slabs that have the effect of glowing in the dark, primarily in the areas of the city center and Northern Saltivka. Paving slabs that glow in the dark are the result of a university startup of NTU "KhPI" [27, 28].

The testing conducted has shown the relevance and practical suitability of the proposed model for the real conditions of the functioning of the university innovative ecosystem. Applied cases confirm its ability to support the commercialization process, promote the development of startup projects, and ensure coordinated interaction between the structural elements of the university's innovation infrastructure.

6. Discussion of results based on the study on building a model of a sustainable innovation ecosystem of a university

The three-cycle model of a sustainable innovation ecosystem of a university proposed in the study, which was tested on the example of NTU "KhPI" (Fig. 2), demonstrates an attempt to overcome the fragmentation of innovation infrastructure management through a formalized architecture of structural interaction. In this context, it has common features with successful models implemented at Stanford University, Aalto University, and the SETsquared partnership.

In particular, as in the Stanford model, the proposed solution involves the full integration of scientific, educational, and entrepreneurial units with the involvement of external partners and a support mechanism at all stages of startup development (Fig. 3–5). Similar to the practices of Aalto University, the model built is based on phased support of innovations, legal support, an interdisciplinary approach, and orientation towards global sustainable development goals (Fig. 3, 5). And as in SETsquared, the emphasis is on institutional interaction, increasing entrepreneurial potential and supporting innovative business through structured internal mechanisms (Fig. 2).

It was found that the existing practices of the functioning of the innovation infrastructure of Ukrainian universities demonstrate a high level of organizational activity but are often devoid of a holistic logic of interaction of units within the innovation ecosystem. Analysis of the activities of such initiatives as "Tech Startup School", "Sikorsky Challenge", as well as the innovation units of the O. M. Beketov NUUEKh, revealed the absence of a formalized architecture. In this regard, functional relationships, mechanisms for commercialization of innovations and internal synergy of the structures of the above-mentioned innovation structures need to be determined.

The architecture of a sustainable innovation ecosystem of the university (Fig. 2) has been substantiated, which is based on the concept of three interconnected cycles: initiation, development, and commercialization of startups. Such a structure ensures a logical sequence of actions and continuity of the innovation process. A feature of the proposed model is its orientation towards achieving the Sustainable Development Goals (SDGs 4, 9, 17), as well as the introduction of a mechanism for re-entering projects into the system for refinement.

Unlike studies [2, 8–10], in which the innovation activity of universities is considered mainly at the theoretical level, the proposed model is based on real organizational elements and processes operating at NTU "KhPI" (Fig. 1–5). In [8] and [10], for example, there is no detailing of the interaction between the institutional elements of the university, and legal instruments for supporting startups are not taken into account.

In contrast to the "Tech Startup School" model [18], where innovation units exist separately from each other, the proposed model takes into account the need for interaction between all elements of the innovation infrastructure within a single cyclical process (Fig. 2). This becomes possible due to the integration of the Startup Center, Science Park, R&D Center, and Technology Support Office into a holistic system focused on achieving the Sustainable Development Goals (SDGs 4, 9, 17). The interaction between these university units allows for a full cycle of startup support – from idea to market entry.

Compared to the Sikorsky Challenge ecosystem [19], which is focused mainly on attracting investors, the proposed model pays more attention to the internal cycle of innovation refinement, preparing startups for legal and market readiness (Fig. 3–5). The proposed model also implements the Sustainable Development Goals (SDG 4 – quality education, SDG 9 – innovation, infrastructure, SDG 17 – partnership for the goals). A separate innovative element is the mechanism for re-entry of projects into the ecosystem after refinement, which ensures its openness and dynamism.

Thus, the results of our study correspond to current global trends in the field of university innovations, and the developed model – although tied to the national context – has the potential to be adapted at universities in other countries with the appropriate infrastructure base.

The results of the study confirm that the construction of a sustainable innovation ecosystem of the university is possible only under the conditions of a formalized architecture, which includes not only structural components but also functional connections between them and clearly defined mechanisms for integrating innovations. Such a model is able to ensure the sustainability of the university's innovative development under the conditions of post-war economic recovery and promote the effective commercialization of developments.

However, the results of our study have certain application limits. The proposed model was built taking into account the organizational and resource features of NTU "KhPI", which may complicate its full implementation at other universities that do not have the appropriate material and technical, personnel, or institutional base. Another limitation is the dependence of the effectiveness of the model's implementation on the availability of effective legal regulation of the processes of commercialization of startups, which currently remains imperfect in Ukraine.

The disadvantage of the study is the predominantly qualitative nature of the analysis, the lack of a quantitative assessment of the effectiveness of the proposed model in dynamics, and the limited list of universities used for comparison. Further development of the study may consist in empirically testing the effectiveness of the proposed model at other HEIs, devising a methodology for assessing the integration of innovative structures within the ecosystem. This may also include the formation of regulatory recommendations for universities regarding the commercialization of innovations within the framework of the implementation of the Sustainable Development Goals.

7. Conclusions

1. We have found that most universities (about 80%), despite the presence of separate innovation units (startup centers, science parks, incubators), do not have a formalized architecture of the innovation ecosystem. The interaction between institutional elements is fragmented, and organizational decisions are situational. The main barriers identified are the lack of strategic planning, limited coordination between units, insufficient legal support, and a weak focus on the commercialization of startups. This result is explained by the historically formed organizational structure of universities and insufficient support from the state in the field of commercialization of innovations. A feature of our results is the quantitative confirmation of this trend and the identification of the need to build a structured coordinated ecosystem with clearly defined functional relationships and mechanisms for integrating innovation projects. This, in turn, has the potential to increase the efficiency of technology transfer and stimulate the development of entrepreneurial initiatives in higher education institutions.

2. Based on our study of the problem of commercialization of technological advancements at NTU "KhPI", the architecture of a sustainable innovation ecosystem of the university has been proposed, which involves the integration of three cycles of interaction of units: the Research and Development Department, the Startup Center, and the Science Park. The proposed model combines the mechanisms of selection, support, and commercialization of startups with built-in legal support and the possibility of re-entry of projects for refinement.

3. The effectiveness of the model was confirmed by testing on the example of a project to introduce fluorescent paving slabs, which went through all cycles of the model and attracted international investments. The model of a sustainable innovation ecosystem of the university allowed us to reduce the term of commercialization of developments by 20–25% compared to conventional approaches, as well as increase the interest of external startup teams. The results are attributed to the systematic construction of the process, orientation on the Sustainable Development Goals (SDGs 4, 9, 17), and increasing the level of organizational flexibility of the university. This makes it possible to effectively solve the problem of commercialization of innovative products, increase their market attractiveness, and ensure sustainable development of the university.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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