“Digital universities in knowledge creation and transfer: An institutional model for innovation infrastructure in the digital economy”

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DIGITAL UNIVERSITIES IN KNOWLEDGE CREATION AND TRANSFER: AN INSTITUTIONAL MODEL FOR INNOVATION INFRASTRUCTURE IN THE DIGITAL ECONOMY

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Abstract

The rapid digital transformation of universities and the expansion of the digital economy require new approaches to organizing knowledge creation and transfer within innovation infrastructure. This study aims to develop and substantiate an institutional model of innovation infrastructure in the digital economy that conceptualizes digital universities as key actors in knowledge creation and transfer. The research is conceptual and methodological and is based on systematic analysis, structural-functional modeling, elements of graph theory, and quantitative modeling. The proposed model interprets the innovation potential of an actor through the proportional interaction of three complementary components: access to knowledge content, technological provision, and competencies. A weakness in any component may constrain overall innovation potential even when the others are well developed. Illustrative model-based calculations demonstrate this relationship rather than provide empirically verified results. The graph-based representation conceptualizes digital universities as integration hubs coordinating resource flows among innovation actors. The model identifies four interrelated structural blocks of innovation infrastructure: resource and potential, regulatory and technological, methodological, and institutional-managerial. These blocks support the identification of bottlenecks in knowledge creation and transfer and indicate directions for more balanced resource interaction. The study concludes that the effectiveness of innovation infrastructure depends on the proportional development of knowledge content, technologies, and competencies, with digital universities performing a central coordinating function. The proposed approach provides a conceptual and methodological basis for further empirical research on digital universities in innovation ecosystems.

Keywords digital universities, knowledge creation, knowledge transfer, graph-based model, digital transformation, innovation potential

JEL Classification O33, O32, I23

INTRODUCTION

In the context of global digital transformation, higher education institutions are undergoing profound structural and functional changes that redefine their role within the digital economy. Universities are increasingly transforming into key nodes of knowledge creation and transfer, integrating scientific knowledge, digital technologies, and human competencies within broader innovation ecosystems. This transformation is driven by the rapid expansion of digital platforms, the growing importance of data as a strategic resource, and the intensification of global competition in knowledge-based sectors.

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At the same time, the formation of innovation infrastructure in the digital economy requires fundamentally new approaches to organizing the interaction between its core elements. The increasing complexity of innovation processes, the acceleration of technological change, and the growing dependence on digital resources create systemic challenges related to unequal access to knowledge, technological asymmetry, and disparities in the development of competencies among economic actors. These imbalances significantly limit the efficiency of knowledge creation and transfer processes, reduce the adaptability of innovation systems, and constrain the realization of innovation potential at both institutional and macroeconomic levels.

Given the complexity of interactions between knowledge resources, digital technologies, and competencies within innovation infrastructure, this study focuses on the conceptual substantiation and methodological formalization of these interrelations. Particular attention is paid to developing a model-based framework that explains how digital universities can act as institutional integration hubs by coordinating economic actors' access to the key resources required for innovation-driven development.

A key problem addressed in the study arises from the absence of a formalized proportional-balance model that explains the interdependence of content, technologies, and competencies within digital-university-oriented innovation infrastructure. Existing approaches to innovation ecosystems, the Triple Helix, university digital transformation, and knowledge transfer provide an important theoretical basis for understanding the role of universities in innovation processes. However, they insufficiently formalize how the imbalance between knowledge resources, technological provision, and human competencies affects the overall innovation potential of actors in the digital economy. As a result, even significant investments in individual elements of innovation infrastructure do not ensure proportional growth in innovation outcomes.

The contribution of this study lies in extending existing models of innovation ecosystems, the Triple Helix, digital transformation of universities, and knowledge transfer by introducing a proportional-balance logic into the analysis of innovation infrastructure. In contrast to approaches that describe university-industry-government interaction mainly at the institutional level, the proposed framework focuses on the internal balance of three necessary resource components: content, technologies, and competencies. This allows digital universities to be conceptualized not only as participants in innovation ecosystems, but also as integration hubs that coordinate access to these components and support their balanced development.

Another important aspect of the problem is the insufficient understanding of the institutional role of digital universities as coordinators of knowledge flows and integration hubs within innovation ecosystems. Despite their growing importance, the mechanisms through which digital universities influence the structure, balance, and efficiency of innovation infrastructure remain insufficiently formalized. Therefore, this conceptual and methodological modeling study aims to substantiate and formalize an institutional model for the development of innovation infrastructure in the digital economy with the participation of digital universities.

The use of a graph-based model is appropriate because innovation infrastructure consists of multiple interconnected actors whose relations can be represented as vertices and edges reflecting access to knowledge, technologies, data, and competencies. The multiplicative function is used to express the assumption that innovation potential depends not on the isolated availability of one resource, but on the simultaneous and balanced presence of all three components. If one component is weak or absent, the overall innovation potential is limited, even when the other components are well developed.

The aim of the study is to develop and substantiate an institutional model of innovation infrastructure in the digital economy that conceptualizes digital universities as integration hubs for knowledge creation and transfer and formalizes the proportional interaction of knowledge content, technologies, and competencies in shaping the innovation potential of economic actors.

1. THEORETICAL BASIS

The problem of digital transformation of higher education institutions has become a central topic in contemporary research, reflecting the growing role of universities in knowledge-based economies. Several studies emphasize that digital transformation represents not only technological modernization, but also a systemic shift in organizational, educational, and institutional models of universities (Verina & Titko, 2019; Gkrimpizi et al., 2023; Gkrimpizi et al., 2024). These transformations redefine the role of universities as active participants in digital innovation ecosystems rather than passive providers of educational services.

For the purposes of this study, the literature is not considered a set of separate research directions, but a conceptual basis for constructing a three-component model of innovation infrastructure. The existing studies can be synthesized around three interrelated dimensions: content, technologies, and competencies. Content refers to knowledge, data, analytical information, educational resources, and international experience. Technologies include digital platforms, software, hardware, data infrastructures, and tools that support knowledge creation and transfer. Competencies cover the skills, expertise, digital literacy, and managerial capabilities required to transform available knowledge and technologies into innovation outcomes.

A significant body of research focuses on the impact of digital transformation on institutional performance and innovation capacity. In particular, Alenezi (2021) and Fernández et al. (2023) highlight the multidimensional nature of digital transformation, which encompasses technological, pedagogical, and managerial changes. Empirical studies demonstrate that the maturity of digital transformation in universities is closely linked to the level of interaction between stakeholders and the integration of digital tools across educational and administrative processes (Bravo-Jaico et al., 2025). At the same time, Antonopoulou et al. (2023) emphasize the importance of adaptability and strategic flexibility in higher education institutions operating under conditions of uncertainty.

These studies provide the theoretical basis for the technological component of the proposed model. Digital transformation creates the infrastructural conditions for innovation by expanding access to platforms, data-processing tools, communication systems, and digital learning environments. However, technological provision alone cannot explain the effectiveness of innovation infrastructure, since digital tools become productive only when they are connected with relevant knowledge content and the competencies of actors who use them.

Another important research direction concerns the role of universities within innovation ecosystems. Universities are increasingly viewed as central actors that contribute to knowledge creation, knowledge transfer, and the development of innovation networks (Taxt et al., 2022; Marchant-Pérez & Ferreira, 2024). This logic corresponds to the broader theoretical tradition of university-industry-government cooperation, the knowledge triangle, and national or regional innovation systems, in which universities perform not only educational, but also integrative, research, coordination, and innovation-supporting functions. This perspective is aligned with the concept of the "Triple Helix," where universities perform integrative and coordinating functions within the innovation system.

In this context, the university should be interpreted not merely as one of the participants in an innovation ecosystem, but as an institutional hub that concentrates knowledge resources, supports their circulation, and connects different actors of the digital economy. This provides the theoretical basis for the content component of the model, since knowledge creation and transfer are impossible without access to relevant scientific, educational, analytical, and data-based resources.

In the context of the digital economy, particular attention is paid to the role of digital innovation ecosystems and the factors that determine their effectiveness. Studies by Liu et al. (2025) and Qiao and Niu (2024) demonstrate that the development of innovation ecosystems depends on the interaction between technological infrastructure, data availability, and human competencies. Similarly, Rachinger et al. (2019) underline the importance of digitalization for business model innovation and sustainable de-

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velopment, highlighting the need for integrated approaches to resource management within digital environments.

These findings directly support the proportional logic of the proposed model. Innovation infrastructure cannot be reduced either to technological infrastructure or to knowledge resources alone. Its effectiveness depends on the simultaneous interaction of digital content, technological provision, and human competencies. Therefore, the proposed approach develops the idea of innovation ecosystems by shifting attention from a general description of actors and networks to the internal balance of resources required for knowledge creation and transfer.

A separate group of studies examines the role of digital technologies in education and their impact on learning processes and institutional development. Paustovska et al. (2024) emphasize the importance of interactive technologies for improving educational outcomes, while OECD (2021) and UNESCO (2023) stress the strategic significance of digital technologies, artificial intelligence, and data-driven approaches in shaping future education systems. At the same time, Williamson et al. (2020) draw attention to the risks of digital inequality and uneven access to technological resources, which can limit the effectiveness of digital transformation initiatives.

The issue of digital inequality is important for explaining the competence component of the model. Even when knowledge and technologies are formally available, actors may be unable to use them effectively if they lack digital literacy, professional skills, innovation-oriented thinking, or organizational capacity. This corresponds to the logic of absorptive capacity, according to which the ability to identify, assimilate, and apply external knowledge depends on the internal capabilities of actors. In the proposed model, this role is reflected through the competence component, which determines whether access to content and technologies can be converted into real innovation potential.

Besides, recent research highlights the importance of balancing key components of digital transformation. Safarli et al. (2024) argue that disproportionate development of technological, informational, and human resources leads to inefficiencies and reduced innovation outcomes. Similarly, Kozhyna (2022) emphasizes the role of inclusive approaches in ensuring equal access to resources and opportunities in the digital economy.

These arguments are central to the conceptual logic of this study. They show that innovation infrastructure should be analyzed not only through the presence of individual resources, but also through their proportional development. If content is available but technologies are weak, knowledge cannot be effectively disseminated. If technologies are developed but competencies are insufficient, digital tools do not generate expected innovation outcomes. If competencies exist but actors lack access to relevant data and knowledge, their innovation potential remains constrained. This provides the theoretical justification for the multiplicative interpretation of innovation potential, where the weakness of one component limits the overall result.

Despite the extensive body of research, several important gaps remain. First, most studies consider individual aspects of digital transformation or innovation ecosystems without providing an integrated framework that captures the interdependence between knowledge, technologies, and competencies. Second, there is a lack of quantitatively grounded models that allow for assessing the balance and efficiency of innovation infrastructure in the digital economy. Third, the institutional role of digital universities as key integration hubs in knowledge creation and transfer processes remains insufficiently formalized.

The identified research gap is not limited to the absence of an integrated framework. More precisely, it concerns the lack of a formalized proportional-balance model that explains how content, technologies, and competencies jointly determine the innovation potential of actors within digital-university-oriented innovation infrastructure. Existing studies substantiate the importance of digital transformation, university innovation ecosystems, stakeholder interaction, and access to digital resources, but they do not sufficiently formalize how imbalances between knowledge resources, technological provision, and competencies influence the effectiveness of innovation infrastructure.

Building on this gap, the present study develops a conceptual and methodological model that links the institutional role of digital universities with the proportional interaction of three key components of innovation infrastructure: content, technologies, and competencies. This theoretical basis directly leads to the graph-based and multiplicative modeling logic used in the following section.

2. RESULTS

The concept of creating a favorable innovation infrastructure for the digital economy with the participation of digital universities is based on the formation of conditions that ensure knowledge creation and transfer by providing innovation actors with access to key resources necessary for the development of new technologies, products, and services. Differences in the conditions of access to these resources lead to variations in the opportunities and mechanisms through which economic effects from innovation activities are achieved.

In a digital society, information technologies serve as a primary driver of innovation, enabling both the creation of new products and services and the improvement of production. New knowledge is generated through the utilization of global intellectual potential, access to which is facilitated by digital platforms, global networks, and the IT infrastructure of universities. At the same time, the accelerating pace of technological change and rapid obsolescence of technologies necessitate the continuous identification of new sources of innovation, including digital data made available through the deep integration of IT across all areas of activity, such as the Internet of Things and university analytical systems.

Within the digital economy, innovation activity depends on intellectual potential, IT infrastructure, and data accumulated through the interaction of digital technologies and competencies formed in the university environment. Digital universities ensure systematic creation, accumulation, and transfer of knowledge and data, thereby establishing the conditions for econom-

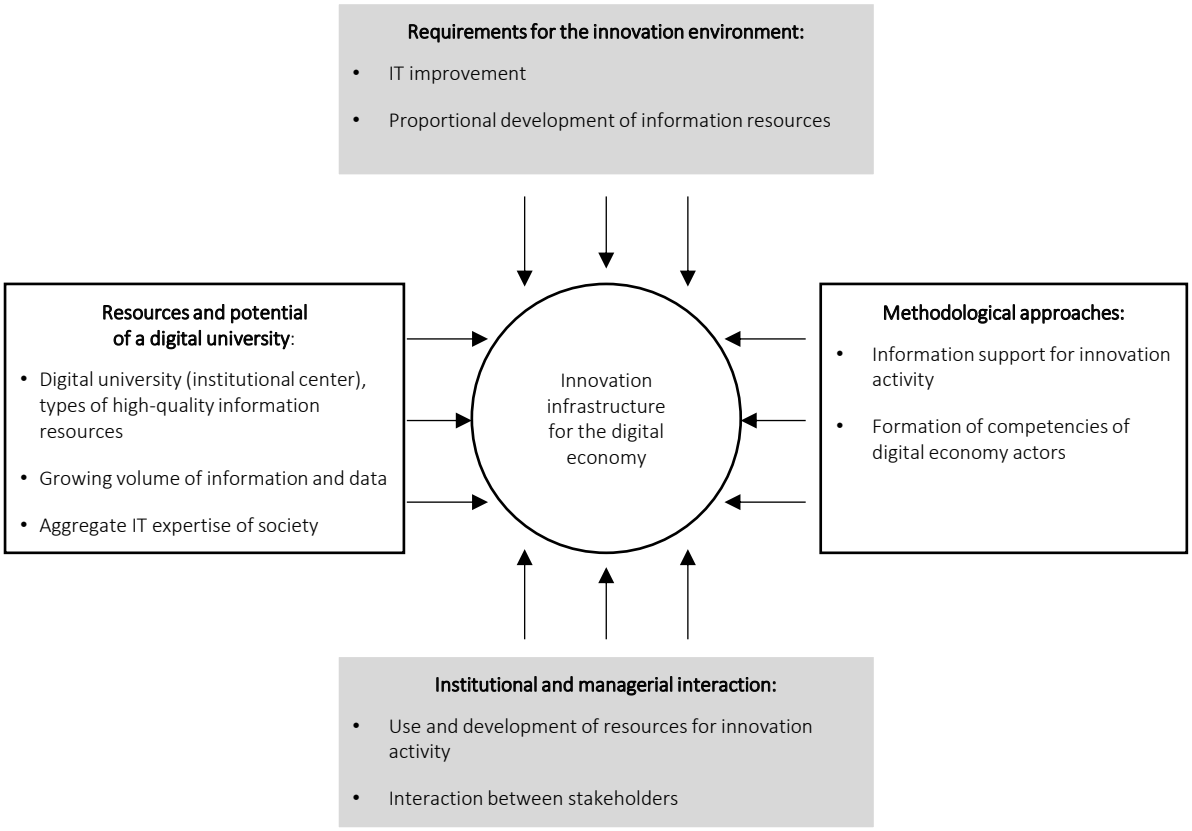

Figure 1. Block diagram of digital university participation in innovation infrastructure formation through resource, technological, methodological, and institutional-managerial interactions

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ic actors to transition to the digital economy through innovation development.

It is determined that the core information resources for innovation activity are those continuously developed and updated in accordance with the requirements of the digital economy. Accordingly, the key requirements for innovation infrastructure include the advancement of information technologies and the proportional development of knowledge and information resources, as illustrated in Figure 1.

Analysis of the results obtained allows us to identify four interrelated blocks that form the innovation infrastructure of the digital economy with the participation of digital universities. The first block, resource and potential, covers the high-quality information resources available to digital universities, growing volumes of data, and the accumulated IT expertise of society. The second block, regulatory and technological, defines the requirements for the innovation environment, among which the improvement of information technologies and the proportional development of information resources are priorities. The third block – methodological – provides information support for innovation activity and the formation of competencies of digital economy actors, which directly affects the quality and relevance of innovative solutions. The fourth block – institutional and managerial – contains mechanisms for the use and development of resources for innovation activity and coordination of interaction between participants in the innovation ecosystem.

In the context of this study, the proposed institutional model of innovation infrastructure is based on a differentiated understanding of the main categories that describe the interaction between digital universities and the innovation environment of the digital economy. Innovation infrastructure is interpreted as a set of resource, technological, methodological, institutional, and managerial conditions that support innovation activity, whereas an innovation ecosystem represents a broader network of actors, institutions, relations, and feedback mechanisms involved in innovation processes. Within this logic, knowledge creation is associated with the generation, systematization, and renewal of scientific, educational, analytical, and data-based resources, while knowledge transfer reflects their dissemination, adaptation, and practical use by other actors. Accordingly, an actor of the digital economy is understood as any participant that uses digital resources, technologies, or competencies in innovation activity, including universities, enterprises, startups, public authorities, civil society organizations, and consumers.

The developed conceptual approach to creating an innovation environment for the digital economy with the participation of digital universities can be formalized in the form of a graph model. The graph-based model is chosen because innovation infrastructure consists of multiple interconnected actors whose relations can be represented as channels of access to knowledge, technologies, data, and competencies. This enables to describe not only the composition of the innovation environment, but also the directions and functions of resource flows between its participants.

Formally, the innovation infrastructure can be represented as a directed graph $G = (V, E)$, where V is the set of vertices and E is the set of directed edges. In this model, the vertices V are all actors of innovation activity in the digital economy: digital universities, enterprises, startups, government and public organizations, consumers, etc. A separate subset of vertices $U \subset V$ represents digital universities as key integration hubs that possess or provide access to the main resources of innovation activity: new knowledge and digital content, information technologies, digital data, and competencies.

The edges E of the graph represent connections between actors, i.e., channels of access to or exchange of innovative resources. If there is a directed connection from actor i to actor j ($i \rightarrow j$), this means that actor j can receive certain innovative resources from actor i, for example, knowledge, data, consulting, technological support, or educational services. In such a network, the digital university acts as a provider and coordinator of information, technological, and competence-related resources for other participants. The connections outgoing from the vertex corresponding to the digital university simulate the provision of information support, digital data, technological infrastructure, and competence formation for other actors of innovation activity.

The proposed graph model is based on several assumptions. First, each actor involved in innovation activity requires access to three categories of resources: content, technologies, and competencies. Second, these resources are complementary rather than fully substitutable. Third, the availability of each resource can be expressed by a normalized indicator within the interval [0;1], where 0 means the absence of access or provision, and 1 means the maximum level of availability. Fourth, the weakness or absence of at least one component limits the overall innovation potential of an actor, even if the other components are sufficiently developed.

Based on this model, a favorable innovation environment should provide each actor of innovation activity with access to at least three key categories of resources:

- content – new knowledge, international experience, analytical information, and digital data;
- technologies – digital platforms, software, hardware, and data infrastructures;
- competencies – skills, expertise, digital literacy, and the ability to use knowledge and technologies in innovation processes.

In a graph model, this corresponds to each vertex having connections leading to the sources of these resources. Digital universities integrate these connections, acting as hubs through which diverse resources become accessible to a wide range of participants. Therefore, the function of a digital university is not limited to knowledge production; it also includes coordinating resource access, supporting competence development, and reducing asymmetries between actors in the innovation infrastructure.

For analytical interpretation, it is proposed to introduce three indicators of resource availability for each actor *i:*

C_i – level of access to content (knowledge and data); T_i – level of technology provision; k_i – level of formed competencies (skills and knowledge of specialists).

The indicators are normalized to an interval from 0 to 1. The integral indicator of innovation potential F_i is defined as the product of these three values:

$$F = C_i \cdot T_i \cdot k_i. \quad (1)$$

The use of a multiplicative rather than an additive function reflects the complementarity of the three components. In an additive model, a high value of one component could compensate for the weakness of another. However, in innovation infrastructure, access to technologies cannot fully compensate for the absence of relevant knowledge content, and strong competencies cannot generate innovation outcomes without access to data, knowledge, or technological tools. Therefore, the multiplicative form better reflects the logic of proportional balance.

This multiplicative form takes into account that the absence or very low level of at least one key resource (C_i, T_i, k_i approaching 0) significantly restricts the creation of innovations, since the product also tends towards 0. Conversely, balanced growth of all components (C_i, T_i, k_i approaching 1) increases the integrated innovation potential $F(C_i, T_i, k_i)$. This model formalizes the principle of proportional development of the innovation environment: only a coordinated combination of content, technologies, and competencies allows for an increase in the effectiveness of innovation activity.

If the development of the environment is disproportionate – for example, investments are made mainly in technology T_i, while access to data and knowledge C_i or the level of staff competence k_i remains low – the integrated innovation result will be limited. Theoretical model-based calculations may illustrate this logic: when one component lags behind, even significant development of another component does not produce a proportional increase in the integrated innovation potential. This is consistent with the argument that disproportionate development of elements of the innovation environment leads to a mismatch between resources and the needs of actors, and as a result, investments in individual elements do not provide a significant increase in innovation returns. Accordingly, the model suggests that the integrated effect increases most consistently when all

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three areas – digital content, technological infrastructure, and participant competencies – develop in a balanced manner.

The combined action of these components forms an integration mechanism for the development of an innovation environment. This mechanism ensures the coordinated development of resource, technological, methodological, and managerial components through the coordinating role of a digital university, which acts as a network hub. In other words, a digital university connects various participants and resources, creating a unified network system of knowledge, technologies, data, and competencies necessary for innovation.

Figure 2 presents a generalized scheme of interaction between a digital university and the innovation environment of the digital economy. In this model, the digital university is positioned as a central integration hub that combines three key components of innovation infrastructure: content, technologies, and competencies. Content includes knowledge resources, data, analytical information, and international experience; technologies include digital platforms, software, hardware, and data infrastructures; competencies refer to the skills and expertise required for the effective use of knowledge and digital tools. The interaction between the digital university and innovation actors is represented as a system of bidirectional flows. On the one hand, the digital university provides enterprises, startups, government institutions, public organizations, and consumers with knowledge transfer, data exchange, technological support, and competence development. On the

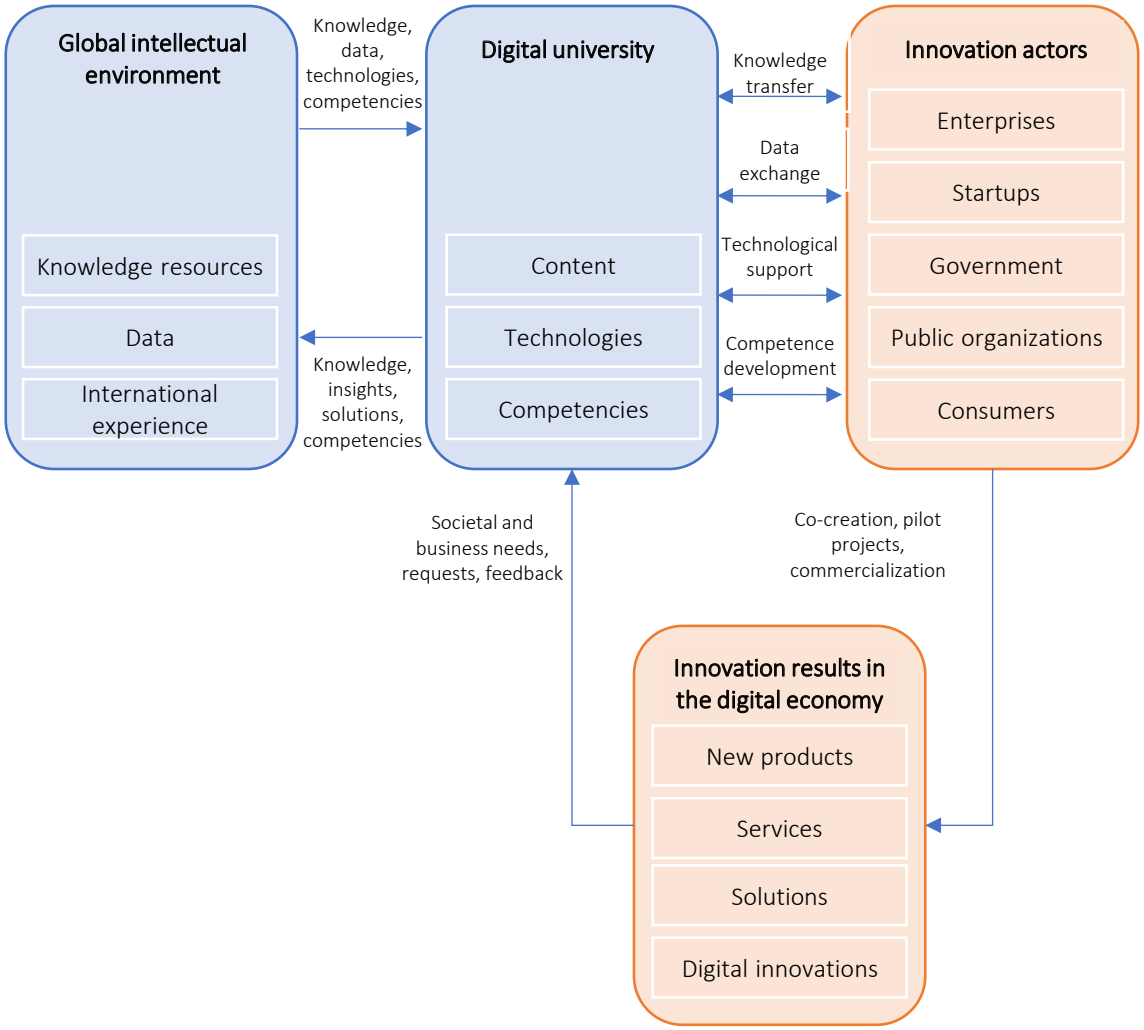

Figure 2. Interaction between a digital university and the innovation environment of the digital economy

other hand, innovation actors generate practical requests, societal and business needs, feedback, and applied problems that return to the university environment and influence further knowledge creation and methodological support.

Thus, the proposed scheme reflects not a one-way transfer of knowledge from universities to the economy, but a continuous circulation of knowledge, data, technologies, and competencies between the digital university and innovation actors. This interaction creates the conditions for co-creation, pilot projects, commercialization, and the implementation of innovation results in the digital economy, including new products, services, solutions, and digital innovations.

It is important to note that the innovation environment creates favorable conditions for innovation activity, provided that its development is based on principles that support innovation in the digital environment. One of these principles is access to international experience, which becomes particularly important under conditions of global competition and rapid technological change. The development of innovations that correspond to current scientific, technological, and market trends requires access to knowledge about leading international achievements, emerging technologies, and accumulated intellectual experience. In this context, digital universities can facilitate the integration and dissemination of relevant scientific, educational, analytical, and technological information, thereby expanding the resource base available to innovation actors.

The principle of focusing on the needs of the innovation process implies that the selection and use of digital resources and technologies should correspond to the specific objectives and resource requirements of innovation actors. Given the growing volume and diversity of digital data, priority should be assigned to those resources and technological solutions that are most relevant to particular innovation activities. Digital universities can contribute to this process by coordinating access to specialized knowledge, data, expertise, and technological support.

The principle of integrated use of societal IT infrastructure emphasizes the importance of a comprehensive approach to available technological resources across different areas of economic and social activity. Their effective integration can expand the technological opportunities available to innovation actors, while broader access to IT resources becomes particularly important under conditions of rapid technological obsolescence and increasing requirements for competitiveness.

The principle of equal access to digital data defines data as a key resource for innovation. Universities, particularly digital ones, can act as providers of platforms that ensure open and secure access to aggregated and anonymized data, thereby supporting the development of innovation potential in the economy.

The principle of flexible formation of competencies is driven by the need for rapid adaptation of personnel to changing technological conditions. Digital universities can act as centers for integrating developers, consumers, business representatives, and public institutions into joint innovation and project initiatives, thereby promoting continuous learning and the formation of relevant competencies.

The principle of proportional development of the innovation environment emphasizes that effective innovation requires a balanced combination of three components – content, technologies, and competencies. Disproportionate development of these components may create structural constraints that reduce the ability of innovation actors to transform available resources into innovation outcomes.

Within the proposed conceptual model, adherence to these principles can contribute to creating more favorable conditions for innovation activity in the digital economy. The innovation environment can perform its key function by providing actors with more balanced access to the resources required to realize their innovation potential, while digital universities act as institutional coordinators of knowledge, technologies, data, and competence development. Such interaction creates conditions for strengthening knowledge creation and transfer and supporting the broader digital transformation of the economy.

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3. DISCUSSION

The proposed institutional model of innovation infrastructure is consistent with contemporary scientific approaches to understanding the role of universities in shaping innovation ecosystems in the digital economy. At the center of this model is the interpretation of the digital university as an institutional hub capable of combining knowledge creation, knowledge transfer, technological support, and competence development. This interpretation corresponds to the Triple Helix approach, in which universities are considered important actors in the interaction between education, business, and government, as well as coordination nodes between different institutional sectors. The digitalization of higher education strengthens this role by expanding universities' capacity to accumulate, process, and disseminate knowledge, data, and technologies.

Within the proposed conceptual logic, the digital university is considered not only as a participant in the innovation ecosystem, but also as an infrastructural center that coordinates access to three key resource components: knowledge content, technological provision, and competencies. This makes it possible to specify the channels through which universities influence innovation development, which are associated in the contemporary literature with knowledge creation, human capital development, innovation culture formation, start-up support, and cooperation with the business sector.

An important element of the proposed approach is the formalization of the principle of proportional development of innovation infrastructure. Previous studies indicate that an imbalance between available resources and actors' needs may reduce investment efficiency and limit innovation returns (Safarli et al., 2024). The proposed institutional model of innovation infrastructure develops this idea through the function $F(C_i, T_i, k_i)$, which reflects the interdependence between access to content, the level of technological provision, and formed competencies. In this interpretation, the weakness of one component limits the integrated innovation potential, even when the other components are sufficiently developed.

This proposition is important for explaining resource bottlenecks in innovation infrastructure. One-sided expansion of the technological base without adequate access to relevant knowledge content or without a sufficient level of competencies does not ensure the expected increase in innovation activity. Similarly, the availability of knowledge and skills cannot be fully realized without digital platforms, data infrastructures, and communication tools. Therefore, the logic of the model emphasizes not the mere availability of resources, but their balanced interaction.

The proposed approach also corresponds to studies in which universities are regarded as important elements of innovation ecosystems and regional development. In particular, Taxt et al. (2022) and Marchant-Pérez and Ferreira (2024) emphasize the role of universities in knowledge creation, knowledge transfer, and the development of innovation networks. In this context, the proposed model complements existing approaches, as it shifts the focus from describing the university as a participant in the ecosystem to explaining the mechanism of organizing resource flows between actors of the digital economy.

The issue of openness and inclusiveness of innovation infrastructure is also of particular importance. The principle of equal access to digital data and technologies corresponds to the problem of digital inequality discussed by Williamson et al. (2020) in the context of educational technology use. Unequal access to digital tools, data, and knowledge may limit the effectiveness of even well-designed digital transformation initiatives. In the proposed model, digital universities can function as platforms that mitigate such imbalances by expanding access to knowledge, data, technological resources, and opportunities for competence development.

The logic of the model is also consistent with studies on digital innovation ecosystems and digital business transformation. Liu et al. (2025) and Qiao and Niu (2024) emphasize the importance of technological infrastructure, data availability, and human capabilities for digital transformation and innovation ecosystem development. Rachinger et al. (2019) underline the role of digitalization in business model innovation and sustainable development. The proposed model systematizes

these interrelations within a proportional-balance framework, where digital transformation is considered not only as technological renewal, but also as the coordinated development of content, technologies, and competencies.

The practical relevance of the proposed institutional model of innovation infrastructure lies in its potential use as an analytical basis for developing digital economy policies and university innovation strategies. The European University Association (EUA, 2022) defines universities as important drivers of sustainable innovation ecosystems and as intermediaries between academia, business, and society. Within the proposed model, this intermediary function is specified through the network-based integration of resources and actors. From this perspective, investments in university digital platforms, open data infrastructures, and skills development programs may be more effective when implemented not separately, but as interconnected elements of a unified innovation infrastructure.

Prospects for further research are related to a deeper quantitative and applied assessment of the proposed model. In particular, it would be appropriate to estimate the parameters of the graph model, including the weight coefficients of edges E for directed connections ($i \rightarrow j$), which may reflect the intensity or quality of resource exchange between specific actors. Such parameters may include the frequency of joint projects between universities and businesses, the volume of data transferred, the number of joint educational or innovation initiatives, and the scale of competence development programs. This would enable to model the dynamics of the innovation environment more accurately and to assess the consequences of managerial decisions related to the creation of digital platforms, competence centers, or university-based innovation hubs.

At the same time, the issue of the optimal configuration of such a network remains open. The innovation environment may be formed around several strong digital university hubs or may develop as a distributed network of many interconnected participants. The proposed concept outlines the analytical significance of the hub role of digital universities; however, the specific organizational forms of such interaction may vary depending on the institutional, regional, and sectoral context. This creates a basis for further research aimed at identifying the most effective mechanisms for integrating education, science, business, government, and society in the digital environment.

CONCLUSIONS

The study aimed to substantiate and formalize an institutional and graph-based model for the development of innovation infrastructure in the digital economy with the participation of digital universities. The proposed conceptual and methodological approach allows digital universities to be interpreted as key integration hubs for knowledge creation and transfer. Within the model, their role is associated with the coordination of three interrelated components of innovation infrastructure: content, technologies, and competencies. The graph-based representation enables to describe the interaction between digital universities and other actors of the digital economy through resource flows, access channels, and institutional connections.

The model-based analysis suggests that the innovation potential of an actor depends on the proportional development of three components: access to content C_i, technological provision T_i, and competencies k_i. The multiplicative function ($F_i = C_i, T_i, k_i$) reflects the assumption that these components are complementary rather than fully substitutable. Therefore, the weakness of one component may limit the integrated innovation potential, even when the other components are relatively well developed.

The proposed model also provides an analytical basis for identifying possible structural imbalances and resource bottlenecks in innovation infrastructure. In this context, the balanced development of knowledge resources, technological systems, and human competencies can be considered a necessary condition for strengthening knowledge creation, knowledge transfer, and innovation activity in the digital economy.

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The study contributes to the conceptual understanding of digital universities as institutional centers that coordinate the interaction between knowledge, technologies, data, and competencies. Further research may focus on empirical testing of the proposed model, including the estimation of graph parameters, the measurement of resource flows between actors, and the assessment of the model's applicability in specific regional, sectoral, or institutional contexts.

AUTHOR CONTRIBUTIONS

Conceptualization: Natalia Pokorny.
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Formal analysis: Natalia Pokorny.
Funding acquisition: Natalia Pokorny.
Investigation: Natalia Pokorny.
Methodology: Natalia Pokorny.
Project administration: Natalia Pokorny.
Resources: Natalia Pokorny.
Software: Natalia Pokorny.
Supervision: Natalia Pokorny.
Validation: Natalia Pokorny.
Visualization: Natalia Pokorny.
Writing – original draft: Natalia Pokorny.
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