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A system dynamics approach for the development of a Regional Innovation System

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Abstract

Regions play an important role in the global economy by driving research and innovation policies through a major tool, the Regional Innovation System (RIS). The RIS is a social system that encompasses the systematic interaction of the various organizations that comprise it, to improve local knowledge and innovation. It consists of interconnections of various public and private sector institutions, whose activities and interactions create, introduce and diffuse innovations. This paper outlines the methodology employed in developing and validating a mathematical model of Regional Innovation Systems, utilizing the system dynamics approach. To provide a demonstration of the aforementioned concept, the proposed model will then be implemented in the RIS of two specific regions in Greece, namely Western and Central Macedonia. Within this context, various policies will be formulated to modify the indicators of Smart Technology, with the objective of assessing their influence on the overall regional development of the aforementioned regions. The model focuses on the functional structure of the RIS, separating it in six diverse, interacting subsystems consisting of different components, captured by a total of 38 different factors which can be quantitatively assessed.

Keywords: Innovations, Regional development, Systems thinking, Smart technologies, Policy making

Introduction

The concept of innovation can be better understood through the study of systems (Doloreux & Parto, 2004). Even in the largest companies, innovation does not take place in a vacuum, with no contact with the outside world, but it is shaped by the relationships and connections among different organizations of different types (Pavitt, 1995). Human capital, research institutes and universities, the technology transfer organizations and other intermediary organizations, consultants, development organizations, financial and investment organizations, knowledge and material infrastructures, markets and consumers and businesses are all drivers and components of innovation (P. Cooke et al., 1997). An innovation system consists of interconnections of public and private sector institutions, whose activities and interactions create, introduce and diffuse innovations (Pavitt, 1995).

Despite technological progress and increasing globalization, geographical location is still the primary feature of innovation systems. Location is the main benchmark for assessing innovation performance and implementing innovation strategies. It is acknowledged that a company's capacity to innovate is impacted by external sources of knowledge and technology. Consequently, companies, situated in various areas subject to varied external circumstances, may display significant variations in their ability to innovate, even if their internal circumstances and research and development expenses are comparable. This realization resulted in the substitution of neo-classical frameworks with evolutionary approaches which perceive innovation as a systemic phenomenon that relies on interactions at the meso-level between companies and other players, as well as interactions at the micro-level within the firms themselves (McCann & Ortega-Argilés, 2013).

Innovation systems can be classified according to different criteria, such as specific industrial sectors, or their geographical size. There are national, supranational, regional, local, sectoral or cluster-type innovation systems (Cooke et al., 2004). The national innovation system is probably the first concept to be examined in the literature (Dore, 1988). However, since 2000, academics tend to place greater emphasis on the regional innovation system, since this represents the "perfect" scale for localized capabilities such as institutional endowment, infrastructure, knowledge and skills, to meaningfully interact with each other (Martinidis, 2017; Martinidis et al., 2021).

Regions need to adapt to the demands of contemporary society and the global market by leveraging their unique strengths to foster development through goal setting, networking, active participation, learning, and fostering innovation and creativity (Garau, 2015; Vanolo, 2013). Each region possesses distinct attributes, strengths, and industrial strategies that set it apart from others (Sleuwaegen & Boiardi, 2014). In smaller countries, regions must carve out niches where they can gain a competitive edge on the global stage. To achieve this, they explore additional resources, employ unconventional methods to tackle socio-economic challenges, recognize their strengths, and utilize them to unlock their potential for innovation, aspiring to become what are termed as "smart" or "intelligent" regions.

Essentially, the intelligent region is an open social system that must interconnect with various networks of knowledge, skills, resources and other types of networks (Samara et al., 2024). Networking with the environment is one of the important conditions for a region to be competitive and have specific resources for development. Although the very concept of innovation and the factors influencing innovation seems difficult to analyze in general, the situation becomes much more complicated when the regional dimension is involved in the analysis. The innovation system involves the relationships and interactions between organizations and is defined as consisting of organizations that, through resources and activities, influence the speed and direction of innovation (Lundvall, 2002).

System dynamics traces its origins to the nonlinear dynamics' theory, originally developed in physics, mathematics, and engineering. It is applied to both to human systems, as in the case of cognitive and social psychology and economics as well as natural and technological systems (Bayer, 2004). Innovation systems are social systems since they essentially consist of social actors—institutions and organizations (Edquist, 2013), and this makes them suitable to analyze using the approach of system dynamics.

In addition, social systems are by nature open and dynamic to external interactions (Lundvall, 2002). This means that they are susceptible to irreversible changes and modifications from the environment in which they operate. To keep social systems coherent, they must possess a certain level of internal coherence, which must be greater than the level of coherence that exists with respect to the external world. The development, diffusion and exploitation of new information has been included in Schienstock and Hämäläinen's (2001) definition of innovation systems. It is related, in other words, to the path that knowledge follows (Carayannis & Campbell, 2010). In addition, Carayannis and Campbell (2012) contend that it is necessary to demonstrate the compatibility of a system model with several other notions, such as innovation networks and knowledge clusters, to fully grasp the significance of systems and, consequently, systems theory.

System dynamics was chosen as an approach because it can handle both qualitative and quantitative factors (Samara et al., 2024). Since this methodology has its roots in engineering (Beach, 1955; Forrester, 1997), such as the field of mechanical control systems, many computer simulation software programs exist today that can implement it. Despite the methodology's theoretical origins, it is commonly used in fields such as industrial management and public policy analysis (Pidd, 1998). System dynamics is the study of how the various components interact and how the whole system behaves (Roberts et al., 1997). How and in what direction policies for change are designed to achieve set goals depends on feedback patterns and the short- or long-term response of the system (Pidd, 1998).

A mathematical model serves as a mock-up of the system that allows us to experiment with the system's architecture and operating principles (Georgiadis et al., 2002). However, to create the system template, all data related to the installation and operation of the system must be recorded. System configuration in system dynamics is done in two steps: (a) creating the system impact diagram and (b) creating the system flow diagram.

Figure 1 illustrates the process of creating the mathematical model with the methodological approach of Coyle's system dynamics (Coyle, 1997). The whole process is analyzed in two phases: a qualitative study of the system and the quantitative analysis of the system. In the first phase, an influence diagram is created and then converted into a flow diagram. The flowchart is converted into a simulation program during the second phase, which is followed by verification and validation. Alternative scenarios are run through the program and the results are examined.

In particular, the first phase begins with the determination of the system's goal. Both the definition of the system and the identification of its components are influenced by the purpose of the system. The creation of the flowchart marks the completion of the qualitative study. The system variables make up the flowchart, which is a pictorial representation of the model's mathematical structure. The creation of the dynamic simulation model using a specific programming language for the simulation marks the beginning of the quantitative analysis phase. The simulated model is then checked for correctness and some changes can be made to its mathematical structure to better reproduce the real system. The mathematical model is simulated,

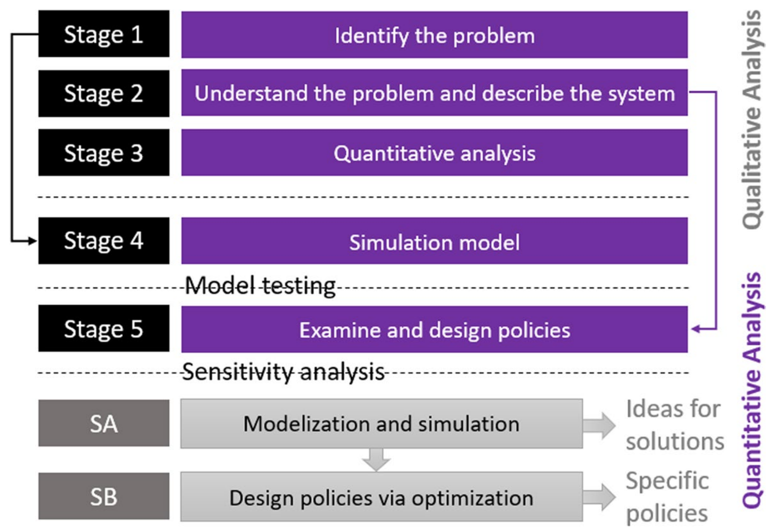

Fig. 1 Stages of the system dynamics model according to Coyle (1997)

and the behavior of the variables is examined. Finally, the simulation program is run for other scenarios, and their effectiveness is evaluated.

Presentation of the RIS model

The model focuses on the functional structure of the RIS, separating it in six diverse, interacting subsystems consisting of different components, captured by a total of 38 different factors which can be quantitatively assessed. They include (i) a Subsystem of Competence in Information and Communication Technologies; (ii) a Subsystem of Innovation and Regional Development; (iii) a Subsystem of Institutional Framework; (iv) a Subsystem of Knowledge Implementation/Capitalization; (v) a Subsystem of Knowledge Networking; and (vi) a Subsystem of Knowledge Production/Dissemination. In the model being developed, the rates of change of the statutory variables are not derived by an endogenous process, but rather through the consideration of alternative scenarios (what-if analyses). The six subsystems comprising the model are briefly described in turn below. The following diagram provides a concise depiction of the RIS's structure:

Figure 2 illustrates how the state variable RIS, which represents the RIS, is influenced by the RIS growth rate (Rin RIS) and the RIS depreciation over time (Rout RIS). Rin RIS rate is calculated by taking the mean of the rates of change of the individual subsystems comprising the RIS, as explained analytically in the "A subsystem of competence in Information and Communication Technologies (ICT subsystem)" and "The subsystem of Knowledge Production and Dissemination (universities and research centers), KPD subsystem" section below. Conversely, the Rout RIS rate of decline pertains to the gradual obsolescence of all the content within the subsystems comprising the RIS, as time passes. In the following sections, we describe the operation of each subsystem and provide its influence diagram.

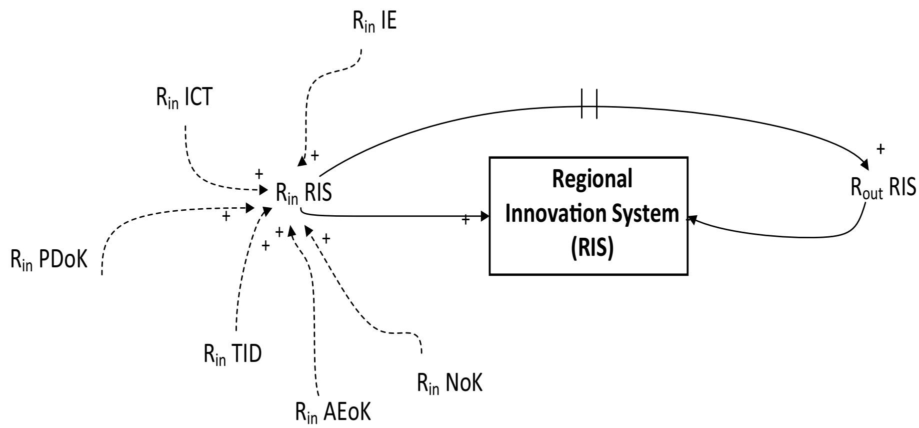

Fig. 2 RIS's structure

A subsystem of competence in Information and Communication Technologies (ICT subsystem)

The ICT capability subsystem refers to the features of a Regional Innovation System (RIS) related to modern Information Technology (IT), its use and people's skills related to it. ICT enables the dissemination of information by connecting people with common interests, promoting collaborative knowledge development and the development of smart learning ecosystems (Gunawardena et al., 2009).

While digital technologies play a crucial role in fostering innovation, not all individuals possess the requisite knowledge and abilities to effectively utilize them. A crucial aspect of digital transformation is the acquisition of fresh competencies and skills by the workforce, the cultivation of new capabilities within enterprises (Kilintzis et al., 2020), and the fostering of new attitudes and know-how among the general populace (Samara et al., 2021). The above should be supported by changes in the organizational and institutional support infrastructure of RISs. The development of new digital products and services requires changes in industrial proficiency and user behavior and attitudes (Isaksen et al., 2020).

According to Fan et al. (2019), some important features for RISs, in the field of ICT, are the existence of many ICT companies, the involvement of prestigious university institutions in the training of human capital and the support of local government to SMEs and ICT clusters, as strategy to promote future growth. Also, the use of ICT for communication can contribute to the creation and strengthening of networks at regional level.

The use of ICT brings about qualitative changes in governance mechanisms, such as greater transparency and legitimacy of public policy planning and decision-making, providing strong conditions for achieving consensus. Finally, according to Santinha and De Castro (2010), it is worth noting that to fully realize the importance of ICTs, changes are required in the conventional understanding of ICT policy makers, policy design, decision making and policy implementation. Figure 3 shows the influence diagram of the ICT capacity subsystem, where only the key variables are depicted.

The ICT competence subsystem score scale is 1 = subsystem is incomplete, 7 = outstanding subsystem level. The ICT state variable determines the subsystem performance grade and is boosted by Rin ICT growth and decreased by Rout ICT depreciation.

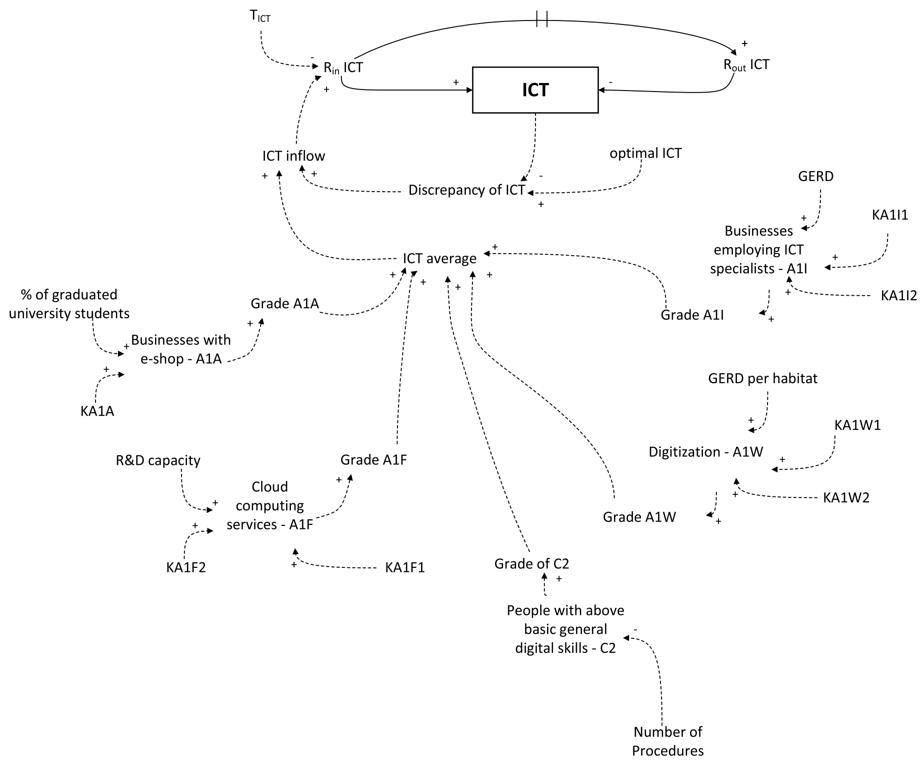

Fig. 3 Influence diagram of the ICT capability subsystem

ICT inflow divided by TTID, the time interval that elapses and affects the subsystem image, increases Rin ICT. ICT inflow takes the minimum value between the subsystem's actual state and its targeted value (7 = maximum) and the average value of the factors affecting it. Factors affecting it include

- Businesses employing ICT specialists (A1I). Government Expenditure on Research and Development (GERD) directly affects this aspect.
- Individuals with above basic digital skills (C2) decline as central management processes increase and increase when they decrease.
- A1W digitization. Digitalization measures the level of digital technologies and includes two indicators, Broadband penetration among enterprises and (the supply) of digital skills above the basic skills' level. The GERD/per capita ratio affects this factor.
- The percentage of businesses having e-shop sales (A1A) is proportionate to the population aged 25–34 who have completed tertiary education.
- Cloud computing services—A1F. This factor is proportional to the number of researchers employed in research and development (R&D capacity).
- Indicators Kxxx (KA1F1, KA1F2, KA1A, KA1I1, KA1I2, KA1W1, KA1W2) are constant variables which are used to calculate the value of each xxx factor. The values of these indicators are obtained after calculating the dependence of the under calculation factors with relative variables. For instance, indicators KA1F1

and KA1F2 are used to calculate the factor A1F, and their values capture the dependence of A1F to R&D capacity.

The ICT average, which represents the average value of the factors influencing this subsystem, is determined by assigning a value to each element on a scale ranging from 1 to 7. The operation is executed using variables referred to as 'Grade <variable name>'.

The subsystem of Innovation and Regional Development (IRG subsystem)

The innovation process is typically characterized by many ideas (programs ή projects) in the initial phases, and combined with various development mechanisms, evaluates, and selects the most promising ideas following the next steps. Typically, the innovation process approaches describe a sequence of approximately four phases (e.g., Idea Generation, Idea Formulation, Problem Solving and Exploitation) (Samara et al., 2012, 2020).

According to Komninos et al. (2006), the results of innovation are one of the features that can describe RISs. The innovation processes identified in a system can change the architecture of knowledge networks. Such processes include cooperative R&D, strategic intelligence, product innovation, process innovation, the creation of spin-offs, the opening of new markets and the attraction of knowledge intensive industries. Different kinds of innovation require different partners and alliances.

Two of the types that constitute the innovation process are product innovation and process innovation, the relationship of which is also a challenge. Changes in product production systems significantly affect the manufacturing system, as well as technical and administrative processes. Furthermore, before introducing a new product into production, process changes are required (Carayannis et al., 2015; Ettlie, 1995; Kim et al., 1992; Samara et al., 2020). Regional development grants, therefore, seem to help a significant proportion of establishments to introduce new processes under process innovation (Oakey et al., 1982).

On the other hand, since product innovation is mainly internal, confidential, and spatially based, its frequency of occurrence reflects more accurately the potential of a region's innovation performance. Policies that encourage the development of product innovation can also be implemented by identifying the local environmental factors that lead to better innovation performance. Access to private and public investment, formal or informal connections with government, private and academic research, and expertise in technical issues can also contribute to the development of innovation (Oakey et al., 1982).

Moreover, according to Landabaso (1997), the effective stimulation of regional innovation in less-developed regions cannot only rely on public financing of new inputs. Substantial structural changes and new relationships among key regional actors are required, so that the scientific and technological system acquires a new orientation. Increasing regional innovation capacity inevitably requires new forms of organization and institutional cooperation. Displayed in Fig. 4 is the influence diagram representing the subsystem.

Subsystem performance is determined by the state variable Total Innovation and Development (TID), which increases as Rin TID increases and decreases as Rout TID decreases due to time decay. TID inflow divided by TTID, the time interval between all

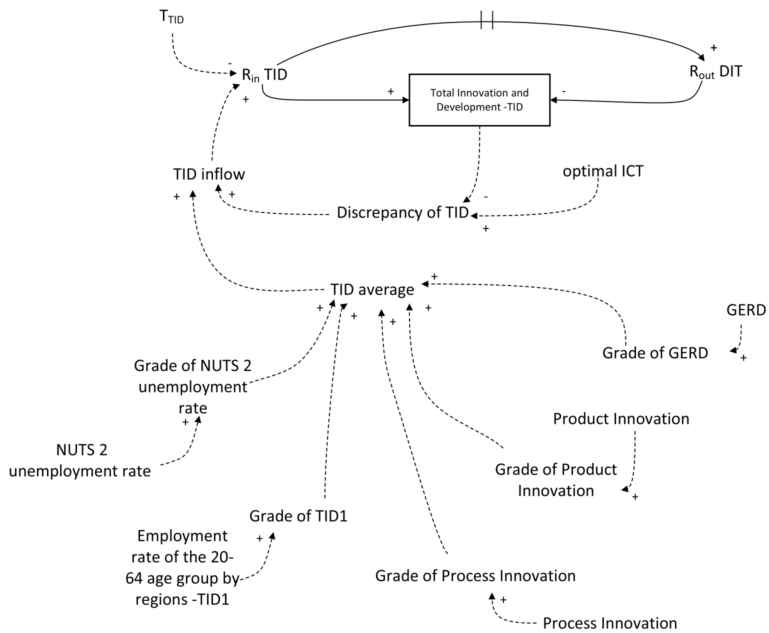

Fig. 4 Influence diagram of the Innovation and R&D subsystem

variables modifying the subsystem image, increases Rin TID. TID inflow take the minimum value between the innovation and regional development subsystem's actual state and its targeted value (7 = maximum) and the average value of the elements impacting it, which are

- Product Innovation (Prod.In.) rises with number of researchers, R&D contributions, and Prod.In. engagement (see Fig. 5).
- Process Innovation (Proc.In.) is influenced by Proc.In. growth rate according to a lag function, and researcher involvement in Process Innovation. Prod.In. and Proc.In. depreciate over time due to knowledge depreciation (Fig. 5).
- Public sector (GOV) research and development expenditure at NUTS 2 regional level (GERD).
- Employment rate for 20–64 age group by region (TID1).
- Unemployment rate in NUTS 2.

The subsystem of Institutional Framework (including regional governance)

The institutional framework subsystem focuses on the role of institutions. Various organizations, private and public, interact and cooperate within an institutional framework. Moreover, the creation, exploitation and dissemination of knowledge are enhanced by supporting the conduct of innovative activities (Asheim & Coenen, 2006; P. N. Cooke et al., 2004; Doloreux & Parto, 2004). The term 'Institutional framework' or 'Institutional environment' often refers to the patterns, habits, human value systems and social organization of a country (OECD, 2013). The institutional framework at the regional level includes national and global regulations as well as specific laws and standards (Asheim & Coenen, 2006). It is important to note that the institutional

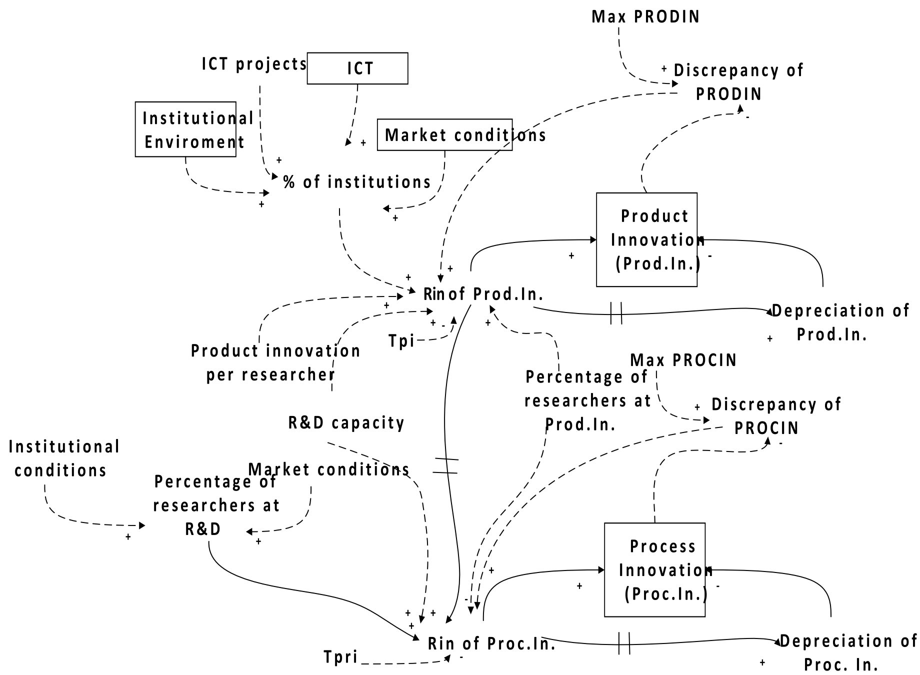

Fig. 5 Product and Process Innovation influence diagram

framework of an RIS can be very complex and lead to various correlations and interactions between different kinds of institutions. This is because regions are embedded in national and global environments, which host various industries and a multitude of heterogeneous businesses and organizations (Zukauskaite, 2018).

According to Komninos et al. (2006), institutions are placed at the top of knowledge networks and can describe an RIS. Their role in knowledge networks is that of enabling or disabling funding and making positive or negative decisions about the innovation process (Lundvall et al., 2002). Approaching innovation systems from the perspective of institutions, it is observed that the existence and operation of markets are not possible without the existence of rules and institutions, which establish them (Pavitt, 1995). Institutions and economic development co-evolve, with changes in capacity building and improvements in governance contributing to the growth and shaping of economic and innovative activity and vice versa (Farole et al., 2011; Zukauskaite, 2018).

According to Doloreux and Parto (2004), the institutional environment is a cornerstone for the creation and diffusion of knowledge through knowledge networks in an RIS aiming at strengthening and conquering existing regional capabilities (Dahesh et al., 2020; Doloreux & Parto, 2004; Hervás-Oliver et al., 2021). An appropriate regulatory and legal framework that promotes knowledge transfer, development and creation it creates ideal conditions for businesses that wish to innovate (Rahm et al., 2013).

In addition, the institutional structure of society and the economy provides incentives and sets constrains, which determine the interests of actors and shape their behaviors (Zysman, 1994). Within a market, however, the institutional framework can create barriers and operate competitively. New businesses may face bureaucratic hurdles when starting out.

A sound institutional framework underpinned by good governance implies adequate planning and avoidance of government failures. When the institutional framework is solid and effective, it can promote innovation by providing a guarantee for the approval of new investments (Peiró-Palomino & Perugini, 2022). Displayed in Fig. 6 is the influence diagram representing the subsystem.

The Institutional Environment (IE) state variable changes subsystem performance as Rin IE increases and Rout IE decreases owing to depreciation. For all factors that change the subsystem image, the variable IE formation divided by the time TIE determines the rate of rise Rin IE. IE formation takes the minimum value between the difference between the subsystem's actual state and its desired value (7 = maximum) and the average value of the institutional framework's variables. Its influences are

- Tax policy quantified using three indicators: Tax effect, Indicator B, and Total tax rate. Higher variable values mean better tax policies.
- The regulatory framework is based on the number of procedures and government barriers. The subsystem's overall picture worsens as the variable increases.
- Quality of regulatory legislation: Considers the government's capacity to create and enforce effective policies and regulations that encourage private sector growth.
- Government efficiency: Public service quality, public administration independence from political influences, policy creation and implementation, and the government's commitment to those policies are all considered.

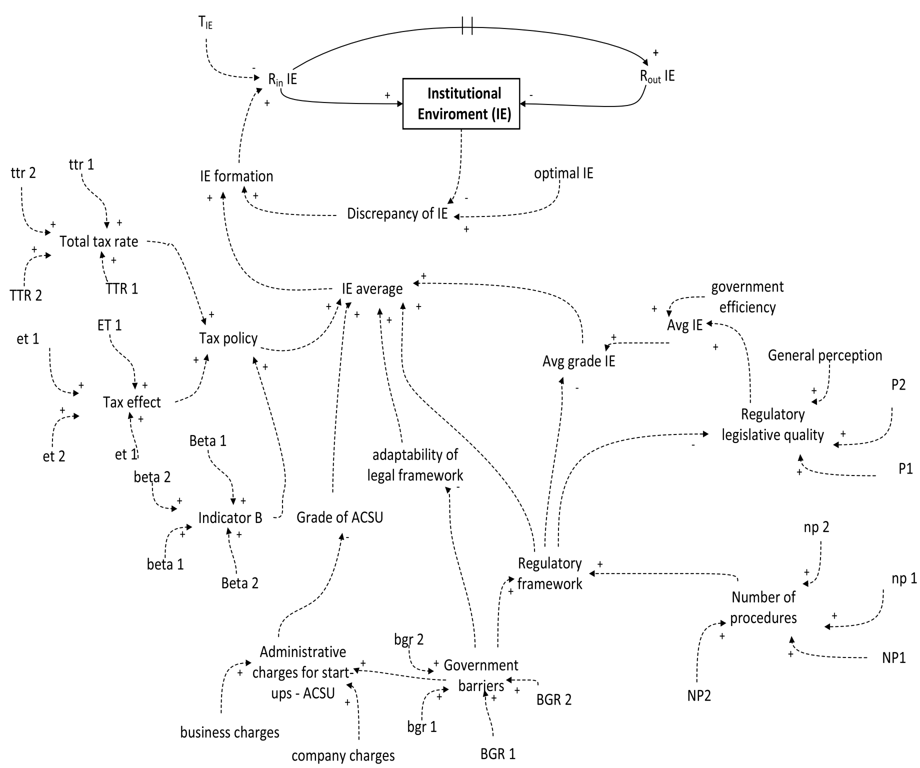

Fig. 6 Influence diagram of the Institutional Framework subsystem

- The adaptability of legal framework to smart digital business models. This variable is inversely affected by government regulation barriers.
- Administrator fees for start-ups (ACSU): The value of the ACSU is determined by three factors: company charges, business charges, and government barriers.

The average value of the elements impacting this subsystem (IE average) is calculated by comparing their values on a scale of 1 to 7. This method uses ”Grade ” variables. Furthermore, the variable Avg grade IE is added which generates all the conversions in the scores, so that a high score describes the tendency toward excellence and not the opposite, as for example in the buffer.

The subsystem of Knowledge Implementation and Capitalization (enterprises and clusters), KIC subsystem

According to Autio (1998), the application and exploitation of knowledge is a major area of the commercial activity of RISs. The key features of this subsystem are customers, contractors, collaborators, and competitors. At the heart of a dynamic RIS are innovative firms and clusters with strong learning capabilities that can transform their existing knowledge into commercial success (Trippl, 2010).

In the knowledge implementation and capitalization subsystem there are two types of networking, the horizontal, between partners and competitors, and the vertical, between customers and contractors. Vertical networking has a greater correlation with firm growth, while horizontal networking has a positive impact on profitability (Autio, 1998). Company-based ecosystems seem to be a future orientation (Longi & Niemelä, 2023).

According to Foray (2014), regional industrial development begins with an entrepreneurial discovery, which is the first step in the development and reorganization of the regional economy (Deegan et al., 2022). Their industrial structure separates RISs into specialized and diversified ones. In specialized RISs the industrial structure is dominated by one or a few industries and the knowledge infrastructure is based on the specialized industrial base of the region. In this case, the powerful networks of the specific few actors hinder various alternative ideas and skills. In diversified RISs, on the other hand, the industrial structure consists of many and large sectors, which have knowledge exploitation and support mechanisms, thus promoting innovative activity in the economic and technological sector. The challenge lies, in this case, in the fact that this great fragmentation of the RIS can ultimately hinder the exchange of knowledge (Deegan et al., 2022; Isaksen & Trippl, 2016).

According to Cruz-Castro et al. (2018), increases in regional R&D budgets are effective in improving R&D resilience only if they occur in regions where knowledge exploiting RISs exist. One of the purposes of business clusters is to ensure the development of research-based innovation through their collaborations with universities and research centers. In fact, many HEIs are members of business clusters (Njøs et al., 2016).

From a supply perspective, industrial structure upgrading is more complex and focuses on factors such as environmental regulations, technological processes, capital market and Foreign Direct Investments (FDI). Environmental regulations can encourage technological progress, which has a positive effect on upgrading the industrial structure

(Acemoglu et al., 2012; Cheng et al., 2022; Jiang et al., 2020; Wang et al., 2019; Yu & Wang, 2021).

According to Sisti and Goena (2020) the economic development of a region and the interaction between various networks must be understood through mechanisms implemented by Knowledge Intensity Business Services. These types of services are considered highly desirable, yet they are crowded out by other, less risky ventures. There is a positive correlation between the strengthening of RISs and the creation of new Knowledge-Intensive Business Services, which are an important source of knowledge-based regional development (Sisti & Goena, 2020; Wyrwich et al., 2019). Figure 7 presents the influence diagram.

Subsystem performance is regulated by the state variable (AEoK), which increases as Rin AEoK increases and decreases as Rout AEoK decreases (due to depreciation). Rin AEoK increases at the rate of AEoK inflow divided by the period T_{AEoK}, the time between all subsystem changes. AEoK inflow takes the minimum value between the difference of the subsystem's actual state (AEoK) and its desired value (7 = maximum) and the average score of the factors affecting it. The following elements impact the subsystem:

- C21: Employment in intensive-knowledge activities. This is the number of persons employed in knowledge-intensive activities in business sectors. C21 adversely affects 'Cloud computing services—A1F'.

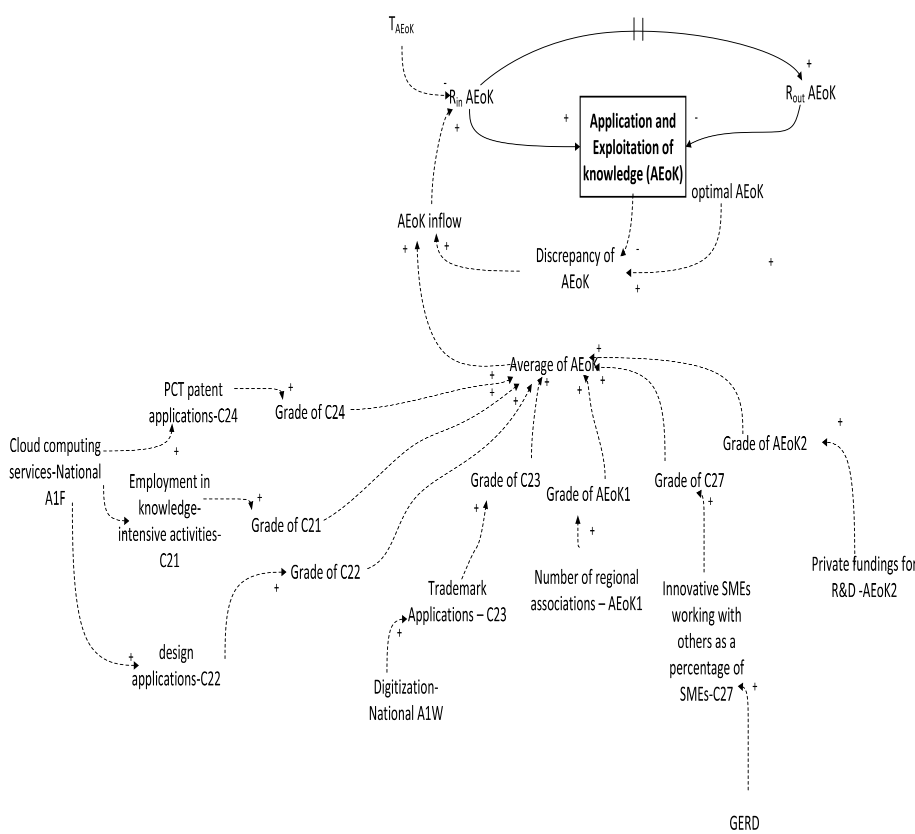

Fig. 7 Influence diagram of KIC subsystem

- C22: Design applications. This variable is also influenced by the variable 'Cloud computing services—National A1F', except that they are proportionally correlated.
- C24: PCT patent applications. The variable 'Cloud computing services–National A1F' has a similar correlation to the number of EPO patents submitted by year.
- AEoK1: The number of clusters. Greece has 18, Western Macedonia 3, and Central Macedonia 4.
- Private fundings for R&D. It depends on the number of enterprises in a region and R&D spending. The latter depends on regional innovation culture.
- C27: Innovative SMEs collaborate with others as a percentage of SMEs. The number of SMEs cooperating on innovation. Variable C27 is proportional to the GERD indicator.
- C23: Trademark Applications. Digitization—AW1 positively affects this variable.

The subsystem of Knowledge Networking

According to Komninos (2008), knowledge can be categorized into explicit and tacit forms. The term "explicit knowledge" refers to information that is conveyed in formal languages, documented, and stored in libraries, archives, and databases. On the other hand, "tacit" knowledge is characterized by its personal nature, making it challenging to formalize and communicate through other forms of human communication. Spatially based tacit knowledge facilitates the accumulation of inventive activity.

Lundvall and Johnson (1994) extended this division into four categories.

1. "Know—What": Refers to broad knowledge about facts, which is similar to information.
2. "Know—Why": It concerns the understanding of scientific principles.
3. "Know—How": Refers to specific skills that range from manual skills to the ability of people in the business world.
4. "Know—Who": It refers to the density and power of social networks.

Regions are an important factor in the knowledge production process because they include firms, supply chain relationships, and networks of practices that can create new knowledge through interaction. However, not all regions have similar resources and the ability to create new knowledge is highly dependent on industrial and institutional structures (Storper, 1997). Firms in regions with a dense concentration of related firms' benefit both from tacit knowledge, which is acquired through the market and informal interactions with suppliers and competitors, as well as from financiers and direct observation of competitors' strategies and fortunes without express partnership or relationship. Furthermore, the process of creating regional knowledge is not exclusive and regions in which firms can acquire tacit knowledge from multiple sources are more likely to be more dynamic and successful (Zook, 2004).

Technological parks are also an important "tool" of regional development policy through the transfer of knowledge produced by universities, through the development of products in regional contexts (Theeranattapong et al., 2021). Also, clustering seems to have a positive effect on companies, industry and regional performance and contributes to reducing production input costs (Bathelt & Cohendet, 2014; Tallman et al., 2004; Williams & Pouder, 2020).

According to Krätke (2010), the innovative capacity of regional economies can be strengthened by the formation of inter-organizational networks, which foster the interactive production and diffusion of knowledge. The interconnection of knowledge sources is done at two different scales. The first concerns geographic clustering and intra-firm networking within a region, which can promote inter-organizational knowledge flows. The second scale concerns supra-regional and global connections, which are equally important for access to external sources of knowledge. Innovation success may therefore depend on the appropriate combination of knowledge inputs from local, regional, national, and global knowledge sources.

Knowledge networks are, consequently, a key pillar of an RIS. They connect actors through formal and informal relationships, which hold and channel knowledge flows between organizations at the regional level (Krätke, 2010). The influence diagram follows in Fig. 8.

The state variable (NoK) increases as Rin NoK increases and decreases as Rout NoK decreases (due to subsystem content depreciation). This determines the subsystem's performance score (from 1 to 7). Rin NoK increases at the rate of NoK inflow divided by TNoK, the period between all variables modifying the subsystem picture. NoK inflow takes the minimum value between the gap of the subsystem's actual state (PDoK) and its desired value (7 = maximum) and the average score of the elements affecting the Knowledge Networking subsystem. These elements affect it:

- Number of PhDs completed in the past 3 years (NoK1).

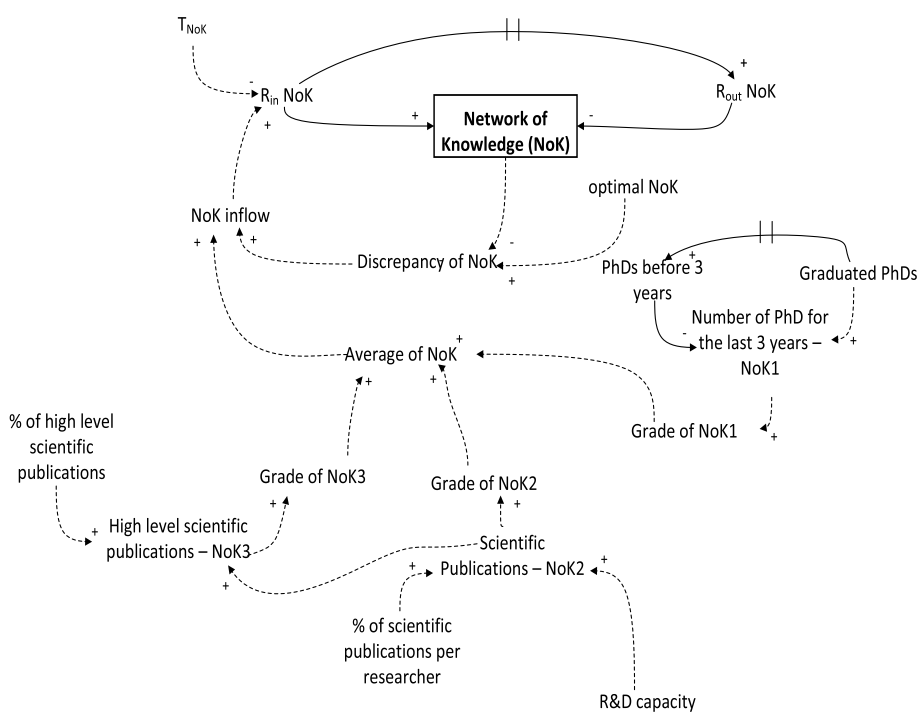

Fig. 8 Knowledge Networking subsystem influence diagram

- NoK2 refers to international scientific co-publications. The number of researchers and developers is directly proportional to this characteristic, and the larger the population, the more worldwide scientific publications.
- High-level scientific papers (NoK3) in the top 10% of citations.

The subsystem of Knowledge Production and Dissemination (universities and research centers), KPD subsystem

Knowledge is a key factor in highlighting competitiveness both at the national and regional level, and also at the business level. Huggins and Izushi (2007) argue that the knowledge base of an economy can be defined as the ability and potential to create and innovate new ideas, thoughts, processes and products, as well as their interpretation in economic development. The transfer of knowledge, according to Tallman et al. (2004), is considered the process of disseminating, sharing and transferring tacit and explicit knowledge through formal and informal practices and is obtained through an existing knowledge network, which is understood as a structure of ties between actors that enables learning between firms and organizations.

Universities and all institutions of higher education have come to be seen as key sources of knowledge that can be exploited in the pursuit of economic development, as knowledge and technology transfer acquires an increasingly important role in universities. As the role of HEIs and technology communities in shaping a culture of innovation is widely recognized, regional commitment and innovation capacity are key themes in institutional mission statements (Huggins et al., 2008; Smith, 2007).

Also, MacKinnon et al. (2002) argue that the focus on learning and innovation has drawn attention to numerous important aspects of the regional development process. These concern the mechanisms of knowledge and information production within regions, the concept of innovation as an interactive process, which leads to new questions about the learning capacity of disadvantaged regions, and the evolutionary emphasis on divergent paths of economic development (Samara et al., 2021).

According to Eberle et al. (2020), public research bodies play a key role in the innovation process and are related to regional development. Regarding the direct and indirect effects of public research on regional economic development, a primary factor is the abundance of research activities. This is expressed through scientific publications and funding of bodies such as universities, technical employment institutes and research institutes. The research area is even linked to economic factors such as the regional investment rate, human capital and indicators of innovation, employment, and economic growth.

Universities contribute to regional development through numerous channels. Examples include investments in physical capital stock and the human capital created through graduates. Universities create knowledge, transfer know-how to businesses and organizations, provide a basic structure to knowledge and establish a spirit of innovation in the regions. Technical employment institutions, then, focus mainly on applied and specialized research, having more frequent collaborations with businesses. In the end, research institutes act complementary to the basic research and knowledge transfer of universities to companies (Eberle et al., 2020).

The promotion of the interconnection between universities and businesses takes place mainly with the following two widespread practices. The establishment of technology transfer offices and the creation of science parks. The main function of technology transfer offices is to assist schools with the legal processes of pitching and patenting intellectual property, establishing new companies, and coordinating license sales (Huggins et al., 2008; Steffensen et al., 2000). In other words, regional knowledge networks as well as ways of interaction between HEIs and the business community are becoming more and more prevalent. Knowledge transfer and commercialization of research should benefit businesses and communities in the region (Thomas et al., 2023). Displayed in Fig. 9 is the influence diagram representing the subsystem.

The subsystem's performance (on a scale of 1 to 7) is defined by the state variable (PDoK), which increases as Rin PDoK increases and decreases when Rout PDoK decreases (due to subsystem content depreciation). Rin PDoK increases at the rate of the PDoK inflow variable divided by the TPDoK time, the period between all factors affecting the subsystem picture. The variable PDoK inflow takes the minimum value between the difference of the subsystem's actual state (PDoK) and its desired value (7 = maximum) and the average value of the associated factors' scores, which are shown below:

- R&D staff and researchers by performance area gender and NUTS 2 regions (R&D staff and researchers by performance area gender and NUTS 2 regions—PDoK1). This variable has a similar relationship to the Digitization—National AW1 variable as presented in paragraph 1.7.

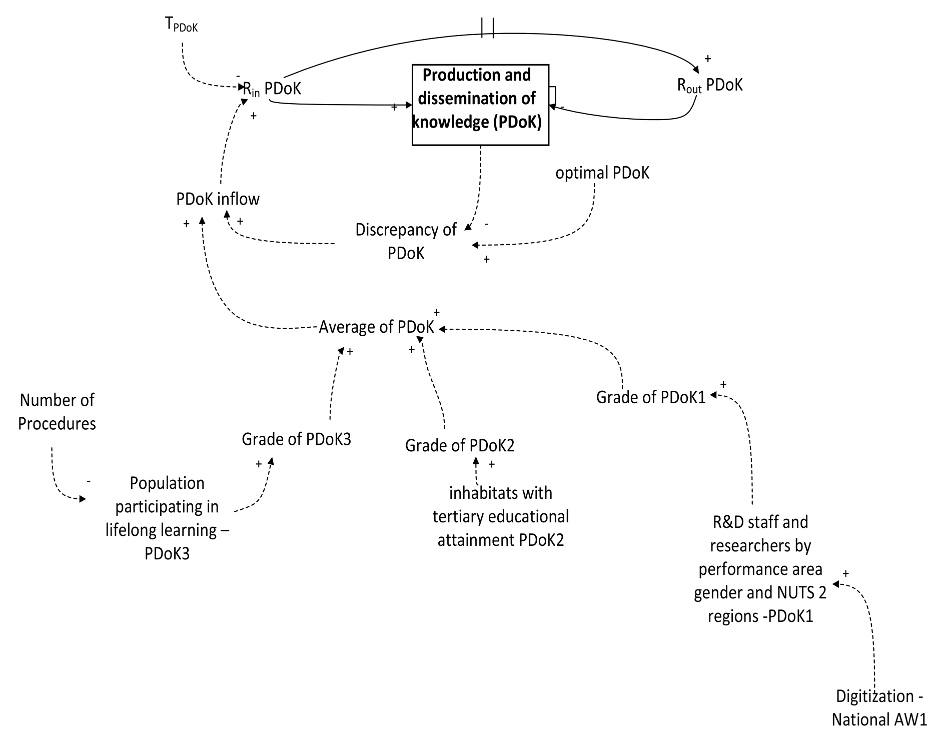

Fig. 9 Influence diagram of the KPD subsystem

- Inhabitants with tertiary educational attainment—PDoK2. This is a general indicator of the supply of advanced skills.
- Population participating in lifelong learning (PDoK3). The variable PDoK3 has an inverse relationship with the variable describing the Number of Procedures.

Materials and methods

This paper outlines the methodology employed in developing and validating a mathematical model of Regional Innovation Systems, utilizing the system dynamics approach. To accomplish this objective, the model's structure is founded upon the widely acknowledged attributes of an RIS (Samara et al., 2024). The utilization of this mathematical model will facilitate the enhancement of our understanding of the dynamic characteristics of the components included in the RIS. To provide a demonstration of the aforementioned concept, the proposed model will then be implemented in the RIS of two specific regions in Greece, namely Western and Central Macedonia. Within this context, various policies will be formulated to modify the indicators of Smart Technology, with the objective of assessing their influence on the overall regional development of the aforementioned regions. The utilization of system dynamics for evaluating the effects of smart technology and innovation policies within the framework of the RIS results in the development of models that serve as indispensable instruments for policy makers.

Results/model validation

To validate the model, it is imperative to examine if the distinct interactions can coexist effectively inside the same model (Forrester, 1997). Furthermore, it is necessary to evaluate its parameters. The utilization of quantitative data regarding the connections between the regional innovation system, emerging technologies, and regional development is based on various indicators sourced from the following references: Eurostat, OECD (Organisation for Economic Cooperation and Development), the Observatory for Regional Policies (ORP), The Hellenic Statistical Authority (ELSTAT), The World Bank, the ESPON SDG localization tool: 'Localizing and maturing Sustainable Development Goals (SDGs)' in regions; and The National Documentation & Electronic Content Centre.

To assess the validity of the model, a set of tests were carried out in accordance with the recommendations put forward in the system dynamics literature (Barlas, 1996; Senge & Forrester, 1980; Sterman, 2002). Initially, the model's dimensional consistency was verified. Subsequently, a series of rigorous tests were conducted to assess the model's ability to accurately simulate real-world scenarios, including harsh conditions. Subsequently, integration error tests were conducted to assess alterations in behavior by the reduction of the simulation time step (dt).

Discussion

This paper has successfully demonstrated the development of a system dynamics model to investigate the intricacies of RISs. Our research underscores the pivotal role of systemic approaches in understanding and optimizing the innovation landscape of regions. By highlighting the critical factors that contribute to the success of RIS, including stakeholder collaboration, tailored innovation policies, and the leveraging of unique regional assets, we have offered a comprehensive framework for enhancing regional innovation capabilities.

More precisely, the research paper delves into the structural intricacies of RISs by examining six distinct but interconnected subsystems, which collectively frame the multifaceted dynamics of regional innovation and development. These subsystems encompass

- Competence in ICT: This subsystem underscores the pivotal role of ICT proficiency, including the utilization of digital technologies, in fostering innovation and connecting stakeholders within the region.
- Innovation and Regional Development: It highlights the processes and outcomes of innovation, including the development of new products and services, which are crucial for regional economic growth and competitiveness.
- Institutional Framework: This subsystem examines the influence of legal, regulatory, and policy environments on innovation activities, emphasizing the importance of a supportive institutional framework for innovation and entrepreneurship.
- Knowledge Implementation/Capitalization: This area focuses on the commercialization of knowledge, how regions transform research and development outputs into marketable products and services, and the role of firms and clusters in this process.
- Knowledge Networking: It covers the dynamics of knowledge exchange and collaboration among actors within the innovation system, including the importance of networks and partnerships for the diffusion of innovation.
- Knowledge Production/Dissemination: This subsystem is concerned with the generation and spread of knowledge, the role of universities and research institutions in producing new knowledge, and the mechanisms for disseminating this knowledge across the region.

Together, these subsystems form a comprehensive framework for understanding and enhancing regional innovation capabilities. By analyzing these components, the study provides insights into how regions can leverage their unique assets and collaborative networks to foster innovation, drive economic development, and position themselves competitively in the global marketplace.

The system dynamics approach has proven to be a powerful tool for analyzing and enhancing regional innovation systems. This study not only contributes to the theoretical understanding of RIS but also offers practical guidance for fostering innovation-driven development in the regional level. Moreover, it calls for a nuanced understanding of regional dynamics to tailor policies that bolster innovation ecosystems. The adoption of a system dynamics approach has not only facilitated a deeper understanding of the complexities inherent in RIS but also outlined a path forward for regions seeking to harness their innovation potential fully.

In conclusion, the findings of this research advocate for a strategic focus on smart technologies, collaborative networks, and innovation policies that are attuned to the unique contexts of regions. As we move forward, it is imperative that these insights inform the development of robust, adaptive, and inclusive innovation systems that can drive sustainable economic growth and regional competitiveness on the global stage.

Conclusions

Building on the approach outlined here, the next step for the research is to expand into the exploration of simulation scenarios designed to illustrate the impact of smart technologies on regional development. These simulations will serve as a critical next step in understanding the dynamics at play within the RISs' framework of two Greek regions mentioned above. By altering variables related to the adoption and integration of smart technology within the model, the research aims to project the potential effects of various scenarios on regional growth and innovation capacity.

These scenarios will specifically examine how advancements in ICT, along with strategic innovation policies, can significantly alter the innovation landscape of a region. Through these simulations the model will provide insights into the effectiveness of different policy interventions, the potential for fostering a more collaborative and interconnected innovation ecosystem, and the role of smart technologies in driving sustainable economic development. The ultimate goal of the line of research started in this paper is to offer a robust analytical tool for policymakers and regional planners to visualize the outcomes of their strategies and make informed decisions to enhance the competitiveness and innovation potential of their regions.

While our model offers valuable perspectives, it is not without limitations. The emphasis of the current model is on the impacts of smart technologies and regional innovation policies. We believe that these are critical aspects for a system, but we acknowledge that they are only a part of the entirety of factors involved. Future research should aim to incorporate a broader set of variables, such as environmental sustainability and social innovation, to provide a more comprehensive view of an RIS. In addition, the model should be applicable to every region in the world, as the aspects examined here are all common to all regional innovation systems. However, extending the experimental application of the model to other regions and contexts can validate its applicability and robustness, and demonstrate its universality and practical value.

Author contributions

Conceptualization, E.S. and P.K.; methodology, E.S., P.K. and E.K..; writing—original draft preparation, E.S. G.M. and P. Ko.; writing—review and editing, E.S., P.K., E.K. and G.M.; project administration, E.S.; funding acquisition, E.S. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. All data used were publicly available from open databases mentioned in "Results" section.

Declarations

Competing interests

The authors declare that they have no competing interests.

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