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REGULAR ARTICLE

A conceptual framework for modeling heterogeneous actors' behavior in national innovation systems

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Abstract

Various analytical frameworks, such as the National Innovation System (NISs) and N-tuple innovation helices, have been developed to address technological change at a spatial or sectoral-technological level. Several quantitative methodological approaches have been used to capture the effectiveness, efficiency, and overall performance of innovation at the national level. Reviewing these approaches, we highlight important aspects of the innovation process, such as actor heterogeneity, the intensity of interactions, and evolutionary dynamics within and between innovation subsystems that are often underestimated. We conceive NISs consisting of five interacting helices: government, academia, industry, society, and finance. Actors belonging to these helices develop their behavior – in terms of resource commitment/allocation – in the context of interdependencies and interactions that condition the effectiveness and efficiency of their actions. As a result, their expectations are formed from their perception of how other actors and the system behave. We develop a conceptual framework that goes beyond the static illustration of 'innovation scoreboards' and linear models. It illustrates how individual parameter changes – in one helix of the system – may generate non-linear effects throughout. We use a causal loop diagram (CLD) to depict the intricacies of the interactions amongst various elements in NISs, and a stock-and-flow diagram (SFD), which forces more detailed specification of causal mechanisms. Our framework facilitates helix-based actor heterogeneity and highlights the key causal mechanisms and feedback loops – set in motion from actor interactions – that govern NIS's evolution and performance without losing oneself in immense detailed complexity.

Keywords National innovation system (NIS),·Innovation helices · System dynamics (SD) · Heterogeneity

JEL Classification C63 · O30

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1 Introduction

The concepts of Innovation Systems (ISs) and N-tuple innovation helices emerged in the 1980s and 1990s to respond to the criticism of linear thinking of innovation and of efforts to link demand-pull and technological advances in a holistic framework. Both approaches consider the innovation process as a complex set of interactions across many parts of the system.

The NISs concept was developed initially by Freeman (1987), Lundvall (1992), and Nelson (1993), emphasizing the social, institutional, and evolutionary character of innovation. The Triple Helix model (later developed in 'N-tuple innovation helices') was originated by Leydesdorff and Etzkowitz (1996), arguing that interactions among academia, industry, and government are crucial factors determining conditions for the innovation process (Etzkowitz and Leydesdorff 2000). Both approaches (ISs and N-tuple innovation helices) are conceptual frameworks that conceive innovation as activities and interdependencies and interactions between heterogeneous actors that co-operate and co-evolve.

During the last two decades, increasing interest in the quantitative measurement of innovation at the macro level has been explored through a variety of instruments (benchmarking analysis/scoreboards) and empirical methods such as cluster analysis, econometric analysis and modeling, data envelopment analysis (DEA), and system dynamics (SD) (Chaminade et al. 2018). Although these methods have been employed to capture the effectiveness, efficiency, and overall performance of NISs in a broad range of countries (developed, developing, emerging, in transition), critical issues and questions remain, including:

- How can the evolutionary path of NISs be captured in dynamic models that examine the specificities, behavior, and interactions of their constituents/components?
- Through which indicators can the dynamic patterns of change and the evolution of NISs over time be captured?
- What are the drivers of change and points of leverage within NISs for policy effectiveness?
- What are the coordination mechanisms amongst the multitude of heterogeneous actors (co-opetitive dynamics, feedback mechanisms, etc.)?

Considering these questions, we conceive NISs consisting of five interacting helices: government, academia, industry, society, and finance. We consider the helices as interacting 'subsystems-actors' and define the NIS as a system of interacting helices. These intrinsically heterogeneous actors (heterogeneity in terms of goals, intentionality, and original endowments such as learning capabilities, size, location, experiences, etc.) develop their behavior – in terms of resource commitment/allocation – in the context of interdependencies and interactions that condition the effectiveness and efficiency of their actions (Stamboulis 2007; Muñoz and Encinar 2014).

We develop a conceptual framework for modeling actors' behavior in NISs. It enables helix-based actor heterogeneity and highlights the key causal mechanisms and feedback loops that govern the evolution and performance of NISs, all without getting overwhelmed by excessive complexity. We use a CLD to depict the intricacies of the interactions amongst various elements in NISs, and a SFD that forces more detailed specification of causal mechanisms. We adopt a broad NIS concept embracing not only institutions that are directly and explicitly involved in research and development (R&D) but also the social, economic, and political arenas of innovation (Fagerberg 2003).

Our main contribution is twofold. First, we provide a comprehensive overview of policy instruments and empirical methods for the quantitative measurement of NISs. To the best of our knowledge, no previous study makes a critical review of the diverse quantitative methods for the analysis of NISs. Second, we propose a relatively novel method for assessing NISs, which could lead to better policymaking in the science, technology, and innovation domain and help countries better design their innovation policies. The mainstream approaches lack a 'system view' of the NIS and cannot model how the strategy of NIS emerges dynamically in a complex social system from the decisions made by the agents involved in them (Dawid 2015). We contribute to the modeling of NISs by developing a conceptual framework, which constitutes a more holistic approach in comparison to relative studies (e.g., Grobbelaar and Buys 2005; Samara et al. 2012; Castellacci and Dizyee 2019). It incorporates neglected elements in existing modeling such as innovative mindset and strategic behavior of main actors, institutional and regulatory framework, financial support, and interactive learning (user–producer, inter-firm collaboration, etc.).

Section 2 provides a review of the instruments and empirical methods used hitherto for the quantitative study and assessment of innovation performance at the national level, highlighting their main strengths and weaknesses. Section 3 describes the role of helices in the context of NISs and how SD modeling facilitates the depiction of interaction and evolution. Section 4 presents the proposed conceptual framework using a CLD and a SFD. Section 5 concludes with a summary and the main expected results from the developed framework.

2 Quantitative measurement of innovation performance at the national level: A review of instruments and empirical methods

Measuring innovation is paramount for action by managers and policymakers, but the development information and indicators will always reflect the prevailing conceptualization of reality (Chaminade et al. 2018).

Several instruments using benchmarking analysis rank and compare NISs in scoreboards. Well-known examples are the European Innovation Scoreboard, the Global Innovation Index, the Global Competitiveness Index, the EBRD Knowledge Economy Index, and the Global Knowledge Index (Monteiro and Carayannis 2017; Chaminade et al. 2018). Scoreboards or 'league-tables' consist of dimensions-pillars and indicators contributing to measuring and evaluating technological capabilities and innovation at the macro level. Through their annual reports, scoreboards suggest policies that depend on the performance of countries both on individual and composite (weighted) indicators. The indicators examined are based on various statistical sources to capture the multidimensional nature of technological change (Archibugi et al. 2009). However, there is a lack of both a theoretical model ('measurement without theory') and relationships between the indicators of the pillars-dimensions (Cirillo et al. 2019). In addition, the selection criteria for indicators have even been called 'eclectic, even somewhat arbitrary' (Schibany and Streicher 2008; Adam 2014). The indicators used are technology-based (or science-based), cannot capture tacit knowledge, and underestimate the DUI mode;[1] the rankings tend to focus on science-based learning rather than on learning by doing, using and interacting (Chaminade et al. 2018). Composite indicators, which present a typical problem of 'aggregation between apples and oranges' (e.g., inputs and outputs), are characterized as biased and practically useless for policy. A low rank does not identify the area(s) necessitating the most urgent policy actions, and a high rank does not necessarily reflect a satisfactory performance (Archibugi et al. 2009; Adam 2014; Grupp and Schubert 2010).

A slightly more sophisticated analysis than benchmarking of individual countries is the one performed by some innovation scholars who attempt to group or cluster countries; a priori (by specific common characteristics) or a posteriori (similar levels of technological capacity or performance around technology clubs) (Chaminade et al. 2018). Cluster analysis studies (e.g., Radosevic 2004; Balzat and Pyka 2006; Filippetti and Peyrache 2011; Pinto and Santos Pereira 2013; Mahroum and Al-Saleh 2013; Alnafrah and Zeno 2020) use a wide range of indicators, covering a significant number of countries and present the importance of some aspects of NISs for growth and development. However, the studies use short periods of analysis, and the results (rankings) are similar to scoreboards (i.e., expected cluster groups). Another significant ascertainment is the absence of mechanisms linking the different elements of the system (Chaminade et al. 2018).

Econometric analysis and modeling are also used to shed more light on the relationship between different dimensions of NISs and growth in a global comparative perspective (e.g., Furman et al. 2002; Fagerberg and Srholec 2008; Krammer 2009; Filippetti and Archibugi 2011; Kravtsova and Radosevic 2012; Bartels et al. 2012; Castellacci and Natera 2013; Duarte and Carvalho 2020). Advanced econometric methods such as structural equation modeling (SEM), cointegration analysis, error correction models (ECMs), and causality tests are employed to investigate the main determinants of innovation performance at the national level. However, panel data analysis (group of countries with different characteristics) neglects the matters of 'path dependence' and 'historical context' (Chang 2011). Further, literature studies usually focus on developed countries and do not consider the DUI mode and the heterogeneity of actors (e.g., financial system, civil society, academia). Also, mainstream statistical and econometric approaches often reduce the complexity of NISs by not decomposing them into subsystems (Paredes-Frigolett et al. 2021).

DEA has been widely used in different cross-country studies on measuring the efficiency of NISs (Chaminade et al. 2018). Models such as constant returns to scale

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[1] The DUI mode is an experienced-based mode of learning based on Doing, Using and Interacting, and refers to know-how and know-who, which is tacit and often highly localized (Jensen et al. 2007).

(CRS) or/and variable returns to scale (VRS) are used to measure the efficiency of NISs and rank them due to their performance (e.g., Nasierowski and Arcelus 2003; Guan and Chen 2012; Kou et al. 2016; Carayannis et al. 2016; Edquist et al. 2018; Dobrzanski 2020; Barbero et al. 2021). These studies span a variety of countries using a broad set of technology-based indicators. Indicators are categorized into inputs (e.g., R&D expenditure, number of researchers, and population with tertiary education) and outputs (e.g., number of patents, number of scientific publications, medium-tech or high-tech exports, and GDP). DEA assumes the innovation process as linear and does not capture the actors' role and what happens inside the 'black box' of the innovation process. DEA studies neither employ 'soft' variables nor provide in-depth analysis of 'small' countries in the list of efficient.

Recent experience has highlighted the value of simulation to examine complex social and economic phenomena, such as innovation (Galanakis 2006; Malerba et al. 2008; Safarzyńska and van den Bergh 2010; Uriona and Grobbelaar 2019). A growing number of empirical studies employ SD modeling and simulation to explore NISs dynamics (e.g., Lee and von Tunzelmann 2005; Grobbelaar and Buys 2005; Samara et al. 2012; Castellacci and Dizyee 2019). CLDs are used to formulate dynamic hypotheses and SFDs to illustrate the behavior of ISs at the national level (Uriona and Grobbelaar 2019). SD method can capture dynamic complexity (interactions amongst the actors over time), feedback loops, and time delays (Santos et al. 2018). However, SD models concentrate on specific parts of an IS, losing sight of its big picture and underestimating the DUI mode (Uriona and Grobbelaar 2019). In addition, existing studies focus on peripheral countries (e.g., Taiwan, South Africa, Brazil, and Cuba) without providing country comparisons.

The instruments and quantitative methods mentioned above capture specific innovation matters (e.g., efficiency, efficacy, time lags) and provide some insightful findings for innovation policies at the national level. However, the methodologies used to model ISs are still dominated by mainstream statistical analyses, which have focused on the performance rather than the strategy of NISs (Paredes-Frigolett et al. 2021). Too much of the policy focus has been on optimal performance, where there is great variety in both system characteristics and the 'wider setting' in which the system is operating (Ricard 2015). Research issues such as path dependencies, DUI mode, actor heterogeneity, the intensity of interactions, and evolutionary dynamics within and between innovation subsystems should be examined to capture the evolutionary patterns of NISs' change.

NIS actors constitute enablers of structural change, and this requires addressing their decisions, activities, and behaviors (in terms of resource commitment, collaboration, and competitive responses). A plethora of feedback loops emerge through the interactions of modular subsystems affecting the overall system performance and its success (Freeman 2002). More sophisticated conceptual frameworks considering the commitment of resources, the innovative mindset of heterogeneous actors (e.g., firms, universities, society, financial system, public authorities), and their mutual interactions can contribute to our understanding about diverse trajectories of NISs. In the following sections, we conceive and elaborate on the evolution of NISs as a process involving both the allocation of actors' resources and the cognitive and institutional endowment of the IS (Stamboulis 2007).

3 Innovation helices as 'interacting actors' and the SD approach

We combine the NISs and 'N-tuple innovation helices' frameworks and employ SD to illustrate and examine the interdependencies and interactions between intrinsically heterogeneous subsystems. In Section 3.1, we analyze how the various innovation actors interact in the context of NISs, affecting the process of technological change. Section 3.2 provides a brief presentation of SD and its central concepts, ideas, and building blocks.

3.1 Heterogeneous innovation actors within a NIS

NISs are ensembles of organizations and institutions operating at the national level, which jointly contribute to the development and diffusion of innovations (Adamides 2018). NISs rest on complementarities and synergies operating between different subsystems, notably (firms, universities, industrial institutes, infrastructure, finance, vocational training, etc.) (Radosevic 2022). The systemic approach to innovation addresses the non-linear and heterogeneous nature of innovation processes. Instead of focusing solely on the number of new product and process innovations, it also encloses R&D efforts by business firms and public actors as well as the determinants of innovation such as learning processes, incentive mechanisms, or the availability of skilled labor, as well as the interplay between organizations and institutions (Balzat and Hanusch 2004).

Amongst the actors involved in the innovation process, the industry is the most important, as it is the main field of innovation realization (Chung 2002; Freeman and Soete 1997). Firms play the most crucial role in NISs innovating in interaction with other firms and knowledge infrastructure (Lundvall 2016). As repositories of knowledge, firms are the main engines for technological development and wealth creation (Ranga and Etzkowitz 2013).

National governments affect the innovation process, by strengthening the science and technology infrastructure (Teubal et al. 1996), via procurement and policy initiatives (Mazzucato 2016), and by improving the regulatory framework for innovation and reduced market uncertainty (Freeman and Soete 1997). Governments establish, maintain, and adjust institutions such as the legal system, patent system, and tax system (Liu and White 2001). Their role is affected by the economy's position in the world technological frontier (Mahmood and Ruffin 2005).

In a knowledge-based economy, universities – academia in general – are a strategic actor as a human capital provider, knowledge creators, and seed-bed of new firms (Etzkowitz et al. 2000; Deiaco et al. 2012). Besides teaching (1st mission) and research (2nd mission), the 'entrepreneurial university' encompasses a 'third-mission' of economic development by fostering links with knowledge users and facilitating technology transfer (Perkmann et al. 2013; Feola et al. 2021; Compagnucci and Spigarelli 2020). The modern university is not only the cradle of talent cultivation but also the laboratory of scientific research, especially basic research, and the birthplace of significant scientific and technological achievements. Universities, like all organizations, are products of their history and can act as catalysts – through their three core missions – in NISs (Deiaco et al. 2012).

In the existing Quintuple Helix Innovation Model, the civil society is associated with 'media', 'creative industries', 'culture', 'values', 'art', 'creative class', and bottom-up actions while the natural environment has been added as environmental and ecological issues affect the direction of knowledge production and innovation (Carayannis et al. 2012; Park 2014). Nevertheless, environmental factors are not under any in-system control and should not be mistaken as system components. Because they do not interact with the system, environmental factors dependent on the system should not be considered as part of it (Hughes 1987). In contrast, the financial system constitutes a significant individual structural element of NISs due to the varying degrees of appropriability and uncertainty of innovative efforts (Christensen 2010; Wonglimpiyarat 2011).

A financial system function is necessary to support innovative entrepreneurs from the early stages of their start-up process with different forms of financing. Established innovative firms should have efficient access to equity and credit markets (Tylecote 2007). The foundation and survival of vigorous new firms depend on a sophisticated private financial system that can support new firms during their infancy (Mowery and Rosenberg 1993). Different financing forms are required for every stage of the innovation process; venture capital (VC) is proposed for the R&D process, stock markets for financing the business development phase, while banking and bond debts seem appropriate for the period of innovation dissemination in the form of gross fixed capital formation (Guilhon and Montchaud 2006). Although the financial sector is represented as a subsystem of NISs in several studies (Lee and von Tunzelmann 2005; Lee 2006; Samara et al. 2012) is not included in the Quintuple Helix Innovation Model, as a distinct helix. In our approach, the financial subsystem is conceived as a fifth helix instead of 'natural environment'.

These subsystems helices are relatively autonomous, and catching up, forging ahead, or falling behind can be understood through the interactions amongst these subsystems (Radosevic 2022).

3.2 System dynamics (SD) method

SD is a computer simulation modeling technique used to holistically analyze complex dynamic feedback systems to generate insight for the emergence of nonlinear behavior and design policies that will improve system performance. SD facilitates the depiction of emergent behavior[2] and system evolution and the examination of structural differences and changes in a quantifiable manner. Complex systems are composed of boundedly rational agents, feedback loops, and time delays (Sterman 2000; Uriona and Grobbelaar 2019).

SD assumes that system models are structural accounts of the real-world system and aims to create endogenous explanations of (non-linear) system behavior and the challenges that they face (Richardson 2011). The link between system structure and dynamic behavior is one of the defining elements of SD. In a sense, a

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[2] 'Emergence' is a term of scale (Cohen and Harel 2007) and expresses the appearance of novelty or something previously absent or unprecedented (Lawson 2015). Behavior emerges – in a transcendental mode (Lawson 1997) – from the interaction of the elements of the system.

simulation model can be viewed as an explicit and consistent theory of the behavior it exhibits (Kampmann and Oliva 2009). SD is established as an appropriate method for developing dynamic models to deal with the structural and functional complexity of the innovation processes at a national level, as it provides policy-makers with powerful tools for sense-making, forecasting, and decision-making (Ricciardi et al. 2020; Allen 2014).

In SD, systems are represented in three ways: (i) CLDs, which highlight the feedback structure of the system; (ii) SFDs, which serve to understand the dynamic behavior of the system through computer simulations; and (iii) the mathematical notation underlying the SFDs, which are partial differential equations (Sterman 2000).

From a SD perspective, a system's structure consists of stocks, flows, and feedback loops (reinforcing and balancing). Stock variables (levels) are the accumulations within the system, while the flow variables (rates) represent the activities in the system, which result from the decision-making process. Feedback (interaction) is what makes systems dynamic; without such feedback, systems are static.

Nowadays, several schools of heterodox economics (e.g., evolutionary, institutional, behavioral, post-Keynesian) utilize SD models to explain systemic and emergent phenomena in complex systems (Radzicki 2020).

The combination of N-tuple innovation helices and SD facilitates a meaningful way to explore and understand the functional dynamics that emerge amongst heterogeneous actors, meeting the need for a representation of real-world dynamics that appropriately describes NIS trajectories so that future trends can be estimated (Phillips and Linstone 2016).

4 A helix-based framework for modeling the dynamics of NISs

Although most countries are striving to develop a more holistic innovation policy, linearity still prevails due to the emphasis on the 'commercialization of science' through a simplistic technology-push model (Edquist 2014; Diercks et al. 2019). Linear approaches and 'innovation scoreboards' dominate the discourse, underplaying the endogenous and evolutionary dynamics of NISs.

We develop a conceptual framework for modeling heterogeneous actors' behavior in NISs. The framework goes beyond the static illustration of scoreboards and linear models and illustrates how individual parameter changes – in one helix of the system – may generate non-linear effects throughout. Thus, we build a helix-based framework of NISs representing interacting helices and their corresponding structure and interactions. We expect to identify the *salients* (the most efficient or effective components of the system) and the *reverse salients* (components out of phase or falling behind in terms of efficiency) that emerge through the evolution of NISs.

In Section 4.1, we classify an indicative set of innovation-related indicators that contribute to the construction of our conceptual framework. In Section 4.2, we develop our dynamic hypothesis using a CLD that illustrates the reinforcing and balancing loops of interaction, cooperation, and coordination amongst and within the five subsystems helices. In Section 4.3, we present a SFD that depicts the mutual interactions between the various subsystems.

4.1 Classification of innovation-related indicators into five helices

Recent studies have introduced preliminary taxonomies of innovation-related indicators in helices to examine the role and performance of subjects within NISs (Cirillo et al. 2019; Maruccia et al. 2020; Barcellos-Paula et al. 2021; Paredes-Frigolett et al. 2021; Vetsikas 2023).

Similarly, we classify a broad range of indicators from various databases (World Bank, OECD, Eurostat, etc.) into helices to develop a concise and complete dashboard of innovation system behavior and performance. These indicators cover the key dimensions of various subsystems' resources, activities, framework conditions, institutions, and outcomes.

In Table 1, we highlight the most important indicators of the parameters used in the analysis that follows in Section 4.2 and 4.3. Indicators capturing interactions between different actors (e.g., university–industry collaborations, tertiary education attainment, government expenditure on tertiary education) are also classified along the five helices.

Next, we develop a CLD to depict the interactions and interdependencies amongst various elements in NISs and a SFD to offer a slightly sounder basis for inference of behavior.

4.2 Dynamic hypothesis

CLDs capture the structure of a system in SD methodology. A CLD[3] represents the key feedback mechanisms. These mechanisms are either negative feedback (balancing) loops or positive feedback (reinforcing) loops.[4]

Figure 1 illustrates our dynamic hypothesis of the mechanics of NISs in the form of a CLD that illustrates the interactions within and amongst the helices of industry, academia, government, society, and finance. We notice the most important reinforcing and balancing feedback loops.

The first reinforcing loop (R1) shows that more *investment in business R&D (BER&D)* attracts *personnel in R&D activities* that enhance *accumulated knowledge in firms*. Increased knowledge leads to more *innovation outcomes* (new products and/or processes), which lead to *returns on innovation* activities (e.g., revenues and business profits) which, eventually, confirm the behavior of resource commitment to innovation, leading to further *business R&D investments* (Galanakis 2006; Lee and von Tunzelmann 2005; Lee 2006; Samara et al. 2012; Choi et al. 2016).

Furthermore, *returns on innovation* can lead to an increase in the *flow of VC* that amplifies the growth of *new innovative firms* (e.g., startups). The higher number of firms engaged in innovation increases business R&D investments, creating a second reinforcing loop (R2) besides the first one (R1).

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[3] CLDs allow to map systems, identify loops, determine their polarity (+ and R or – and B for reinforcing and balancing loops respectively), trace them, and communicate about specific loops or sets of loops (Sterman 2000; Pruyt 2013).

[4] Reinforcing or positive feedback loops may be perceived as a trend reinforcing mechanism which may lead to escalation and eventually loss of control, while a balancing or negative feedback loop should be understood as counterbalancing one, often interpreted as a force pulling towards a target (Pruyt 2013).

Table 1 Summary of indicators classified in helices

Helices	Indicators
Industry	Business R&D expenditure, Business R&D personnel, SMEs with product or process innovation, GDP per hour worked, Medium and high-tech exports, Sales of new-to-market/new-to-firm innovations, Global value chains, SMEs collaborating with others, Patents, Industrial designs, Charges for the use of intellectual property, University–industry collaboration in R&D, Intensity of competition, Distance from technology frontier, Birth rate of firms, Death rate of firms
Academia	Higher education R&D expenditure, New entrants (Bachelor, Master, PhD), Students enrolled in tertiary education (Bachelor, Master, PhD), Tertiary graduates (Bachelor, Master, PhD), Academic staff, Scientific articles, Citations, Number of projects, Quality of research institutions, Quality of the education system
Government	Government expenditure on tertiary education, Percentage of Business R&D expenditure financed by government, Government effectiveness, Rule of law, Regulatory quality, Political stability and absence of violence, Control of corruption, Protection of property rights, Government procurement of advanced tech products
Society	Employment with tertiary education, Unemployment with tertiary education, Immigration & Emigration (flows), Buyer sophistication, Lifelong learning, Population completed tertiary education, Individuals with above basic overall digital skills, Disposable income
Finance	Venture capital (seed, start-up, later stage)

Similar to R1 and R2 loops, a third reinforcing loop (R3) is identified through the causal links '*number of innovative firms-BER&D-Business R&D personnel-BERD activity-Accumulated knowledge in firms-innovation outcomes-returns on innovation-number of innovative firms*'. As the number of innovative firms increases, there is an expected increase of investment in (commitment to) R&D. An increase in business R&D investment leads to an increase in R&D personnel in firms. Increased personnel engaged in R&D activity enhances accumulated knowledge in firms, which further increases innovation outcomes. An increase in innovation results leads to an increase in returns on innovation (conditional to complementary investment). As these returns are increasing, there is a greater stimulus for innovative firms.

The fourth reinforcing loop (R4) illustrates that more investment in *higher education R&D (HER&D)* leads to an increase in *academic personnel (researchers)*, and their increased number enhances *research activity* (e.g., new scientific articles, participation in projects) that boosts new *research results*. Increased research results enhance the *quality of the academic sector*, which further attracts new *higher education investments for research* (Rodríguez and Navarro-Chávez 2015; Rad et al. 2015).

The fifth reinforcing loop (R5) shows that an increased level of tertiary education *(population with tertiary education)* attainment would lead to greater demand for a *better quality of institutions* (Marginson 2016; Botero et al. 2013). Improved *quality of institutions* decreases the trend of skilled workers (Ngoma and Ismail 2013; Cooray and Schneider 2016; Dimant et al. 2013) to migrate and thus reduces *'brain drain'* which – if unimpeded – dwindles the pool of the *population with tertiary education* (Tritah 2008).

A similar reinforcing loop (R6) describes the causal links between '*population with tertiary education-pressure for a better quality of institutions-quality of institutions-number of innovative firms- BER&D – business R&D*

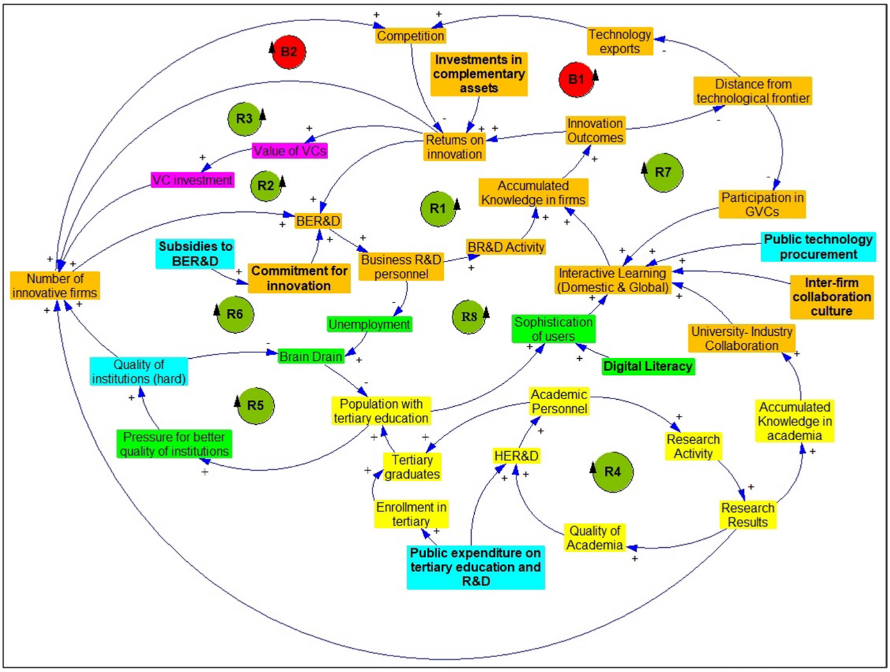

Fig. 1 Causal loop diagram (CLD) of the interactions between the helices of a NIS (*The CLD has been designed on the Vensim system dynamics software. We use different colors corresponding to the five helices to facilitate their distinction: orange for industry, yellow for academia, light blue for government, green for society, and purple for finance. Bold characters denote decision/policy variables (e.g., public expenditure on tertiary education and R&D, subsidies to BER&D).*)

personnel- unemployment-brain drain- population with tertiary education'. As the increasing education level of individuals leads to an increase in the quality of institutions, new firms are established in an environment with more favorable conditions (Cieślik and Goczek 2018; Farla et al. 2016; Alam et al. 2019). New and existing innovative firms would increase their investment in R&D – in terms of resource commitment – attracting new business R&D personnel. An increase in business R&D personnel in firms leads to a decrease in unemployment and a consequent decrease in the migration of high-skilled workers. Therefore, a decrease in 'brain drain' leads to an increase in the country's tertiary graduates (key knowledge stock).

The seventh reinforcing feedback loop (R7) explains that an increase in *innovation outcomes* leads to a decrease in the *distance of a country from the global technological frontier* and more developed NISs (i.e., successful catch-up). As this distance is increasing, a country presents fewer opportunities to *participate in global value chains* (GVCs) (Ye et al. 2020). However, intensive participation in international networks and value chains enhances collaborations and learning by interactions from abroad (external sources of knowledge) which further boosts the *stock of knowledge in firms* (Goñi and Maloney 2017; Tajoli and Felice 2018; Kergroach 2019). As aforementioned, increasing knowledge promotes *innovation outcomes*.

The eighth reinforcing feedback loop (R8) constitutes an extension of the first reinforcing loop (R1). It includes the connection of the *population with tertiary education* and the *sophistication of users*. In CLD, it is described by the following linkages '*population with tertiary education-sophistication of users-interactive learning-accumulated knowledge in firms-innovation outcomes-returns on innovation-BER&D-business R&D personnel-unemployment-brain drain-population with tertiary education*'.

We should emphasize that all the above reinforcing loops may work in both directions leading to an increase or decrease of the relevant behaviors and results.

Regarding the balancing feedback loops, the first one (B1) describes how more *innovation outcomes* decrease the *distance of a country from the global technological frontier* while an increased distance from the frontier would decrease the absorption of *technology and exports* (Özak 2018). Increased *medium and high technology exports* further enhance the exposure to more *intense competition*, and intensifying competition between firms decreases the *returns on innovation*.

A second balancing feedback loop (B2) is identified through the relationship of *intensive competition*, *returns on innovation*, and the *number of innovative firms*. An increase of the latter may consequently lead to increased *competition* (Amendola et al. 2000), and increased *competition* decreases *returns on innovation*. As aforementioned, increased *returns on innovation* (as 'windows of opportunity') boost the creation of *new innovative firms*.

In Section 4.3, we further develop our dynamic hypothesis using a SFD, as CLDs do not always explain well how flows influence stocks and how time delays may emerge. Furthermore, CLDs may lead to mislabeling of loops and do not provide a sound basis for the rigorous deduction of behavior (Lane 2000; Pruyt 2013).

4.3 Development of SFD for the interactions of heterogeneous actors

SFDs are used to illustrate the mathematical model and the differential equations (Olivares-Aguila and ElMaraghy 2021). In SFDs, stocks are symbolized by rectangles, flow variables by valves, converters (intermediate variables) by circles, and constants (model parameters) by rhombuses (Sterman 2000; Lane 2000). In Fig. 2, we present the SFD where the five subsystems-helices operate and interact within a NIS. We need to consider that each actor or subsystem is made up of diverse elements and that this micro-diversity changes over time because of successes and failures (Allen 2014).

Adopting the evolutionary logic of variation-selection-retention (VSR), we consider that actors decide each period on the allocation of resources (continuous trial-and-error learning) amongst a variety of choices (Safarzyńska and van den Bergh 2013). Innovation actors (much like biological organisms) try various choices (responses) in a competitive situation until the one found is sufficiently successful in achieving their goal. The commitment of resources and the corresponding choices may lead either to success (e.g., increasing returns on innovation, new products or processes, increasing research outcomes) or failure (e.g., increasing distance from world technological frontier, decreasing participation in projects and global value chains).

Within an IS, a percentage of firms engage in innovation activities and commit the required resources (financial and human). The R&D is the key activity that

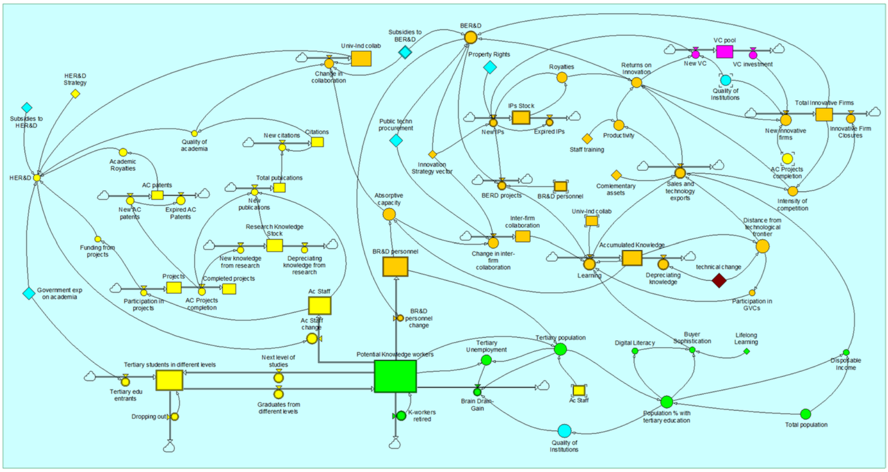

Fig. 2 Stock-and-flow diagram (SFD) of the interactions between the helices of a NIS (The SFD has been designed on the *Powersim* system dynamics simulation software. We use orange for industry, yellow for academia, light blue for government, green for society and purple for finance. Decision/policy variables (e.g., public expenditure on tertiary education, subsidies to BER&D) are represented by rhombuses. The Bordeaux-colored rhombus depicts the exogenous nature of technical change.)

creates know-how. An organization accumulates knowledge through R&D. Firms usually do not innovate in isolation but interact with other organizations through complex relations, often characterized by several loops of reciprocity and feedback mechanisms (Edquist 2011). Both product and process knowledge result from networking and interactive learning with other actors such as universities, government, firms, and end-users (Malerba 1992; Nooteboom 1999; Edquist 2011).

We illustrate accumulated knowledge (product and process related) as an array stock variable while learning is an array flow variable adding more knowledge to the stock (see Fig. 2). In order to access any kind of knowledge, firms should improve their ability to learn, often referred to as 'appropriability' (Cohen and Levinthal 1990). This ability is achieved by accumulating knowledge via different learning modes (Malerba 1992; Muscio 2007). We show that accumulated knowledge enhances the absorptive capacity of firms. The outflow of the array stock variable (accumulated knowledge) represents the accumulated knowledge depreciation because of exogenous technical change (Grobbelaar and Buys 2005). As firms increase their accumulated knowledge, they can reduce their distance from the global technological frontier and participate in GVCs increasing the rate of absorption of external knowledge and increasing their domestic sales and exports (medium and high tech).

In the array flow variable 'BERD projects', the dimension of process knowledge affects new processes related to innovation (such as changes in techniques, equipment, and software). These processes are associated with increased productivity and lower production costs. Firms achieve efficiency of committed resources and increased returns that enhance further business R&D investment. Firms seek to minimize costs through process innovation to maximize the efficiency of resources employed in production (Choi et al. 2016). In contrast to process innovation, the dimension of product innovation – in BERD projects – breeds new differentiated products. New products with upgrading quality and brand name further increase the domestic sales and the medium and high technology exports. In both cases, new sales and technology exports are associated with BERD projects through accumulated knowledge and decreasing distance from the global technological frontier. The distinction (product and process innovation) is widely illustrated in several SD studies (Samara et al. 2012; Lee and von Tunzelmann 2005; Lee 2006; Choi et al. 2016).

Previous SD models do not include intellectual property (e.g., patents, industrial designs) of R&D activities in their analysis. As innovation activity (BERD projects) increases and depending on their strategy (e.g., offensive, defensive, opportunistic) firms have greater incentives to protect their innovation activity results. The stock of 'IPs' (array variable: patents and industrial designs) generates royalties that produce returns on innovation (Kondo 1999). Furthermore, as the firm generates and encloses more knowledge, it will be more attractive to VC (Niosi 2003).

As mentioned in the second balancing feedback loop (B2), increasing returns on innovation encourage the creation of innovative firms. In mathematical terms, the total number of active innovative firms (stock variable) is the integral of the birth rate of new innovative firms (inflow) and the death rate of existing ones (outflow). In a sense, we aspire to capture a part of the 'creative destruction' process employing these two flow variables. The average rate of firm creation and the rate of firm destruction is the most used measure in the literature on firm and employment dynamics (Aghion et al. 2021).

In the helix of academia, universities and research institutes are central actors in education, research, and 'third mission' (Sánchez-Barrioluengo 2014). The mission of teaching is associated with the development of human capital in the form of skilled labor (Bayuo et al. 2020). Increases in government expenditure on tertiary education stimulate the entrants of potential graduates from academia. In each stage, tertiary graduates leave the subsystem and constitute potential knowledge workers (in the helix of society). Many of them may continue their careers inside the academic sector and across different stages (postgraduate, PhD, and new academic staff) in a resource chain process (Frølich et al. 2010; Dangerfield 2014). The process of new entrants in different levels of tertiary education and new graduates (as potential knowledge workers) is represented by the connection of array flows (inflows and outflows) with the two array stock variables entitled 'tertiary students in different levels' and 'potential knowledge workers'.

Regarding the research mission, we consider research activity and experience (measured by the number of publications and research projects) as research outcomes. Increasing participation in international projects enhances the absorption of universities' external knowledge, contributing to new scientific publications and consequent citations. The increasing number of citations improves the quality and reputation of the academic sector (Bejan et al. 2020). Increasing research activity (e.g., participation in projects and knowledge networks, new publications) stimulates accumulated knowledge in academia and its quality, which further increases collaboration (usually in R&D) between firms and academia. These collaborations facilitate interactive learning, which, in turn, is the basis for innovation (Edquist 2011).

In recent years, universities have been urged to expand their scope from teaching and research to a 'third mission', described as 'contribution to society' (Compagnucci and Spigarelli 2020). Research outcomes usually a result of completed projects can spur – amongst others – the creation of new innovative firms (e.g., start-ups and spinoffs), accelerating the process of creative destruction. Furthermore, universities engaged in patenting activity may increase their revenues via royalties. This means that as the stock of academic patents increases, universities enhance their income from academic licensing, and then they may re-invest in basic research.

Regarding the role of government, its increasing ability to formulate and implement policies and regulations would increase the perception of the extent to which agents have confidence in and abide by the rules of society (Maruccia et al. 2020). An improvement in a country's institutional environment (e.g., control of corruption, bureaucratic quality, political stability) seems to impact positively both on the likelihood of establishing high tech firms (Pereira and Temouri 2018; Pereira et al. 2020) and on attractiveness to VC investment (Bustamante et al. 2021). Moreover, the higher quality of (hard) institutions would also reduce the drive for brain drain and lead to the retention of those with high levels of educational attainment (Cooray and Schneider 2016; Dimant et al. 2013). For instance, the high political corruption and instability, and the lack of transparency seem to act as catalysts for brain drain in several countries (Panagiotakopoulos 2020; Mlambo and Adetiba 2019).

Demand-side activities such as innovative public procurement can contribute to interactive learning, the formation of new product markets, and the articulation of quality requirements (Edquist 2011; Radicic 2019). From the supply side, 'traditional' innovation policy instruments such as fiscal incentives for R&D and direct subsidies to business R&D aim to the creation of new knowledge and innovation (Edler and Fagerberg 2017). In Fig. 2, we include these two sides of governments' innovation activities using the variable 'public technology procurement', as well the variable 'subsidies to BER&D'.

Regarding the society helix, tertiary education graduates constitute a central stock of knowledge (potential knowledge workers) in a NIS and one of the main mechanisms of knowledge spillovers from academia. Citizens with higher digital literacy seem to be more sophisticated users (rather than passive buyers) and develop their skills and capabilities via lifelong learning. In Fig. 2, we illustrate digital literacy and lifelong learning as factors influencing buyers' sophistication. We assume that persons with higher digital literacy and lifelong learning have higher capabilities to participate in interactive user–producer learning (depicted in the industry helix) (Von Hippel 1986; Lundvall 1992). In the SFD, we consider that higher sophistication of buyers amplifies DUI mode learning. Also, individuals with higher educational attainment are significantly more likely to lodge complaints against their government about general services, police abuse, and corruption. For instance, NISs with higher educational attainment (such as Australia, New Zealand, Norway, Finland, Denmark, etc.) have higher control of corruption, political stability, and government effectiveness than countries with low education level like Pakistan, Senegal, Sri Lanka, and Sudan (Botero et al. 2013). Hence, in our analysis, the variable of the population with tertiary education is associated with the variable of quality of institutions.

Financial capital is indispensable in the early stages of business development, and the financial helix is essential for technology development and commercialization (Wonglimpiyarat 2011). We concentrate on VC and its contribution to the creation of new innovative firms. The VC pool (represented by a stock variable in Fig. 2) refers to available capital that may be invested in new innovative firms in exchange for equity. Increasing returns on innovation enhance venture capitalists' value and income and their 'appetite' for new investments.

At any moment in the system's evolution, some feedback loops may be highly influential, and others may be inactive. As the system enters new states (surpassing critical mass in accumulations),[5] latent loops with limited impact on the system's behavior until then may suddenly become dominant, causing qualitative structural changes in the mode of system behavior (Richardson 1995). This needs to be validated in future research, with the use of simulation analysis, which is above and beyond the scope of this paper. Simulation analysis can allow policymakers to better understand the results of various choices (via continuous experimentation), the selection amongst policy alternatives, and the retention of successful resource commitment strategies. For example, the exploration of various combinations of innovation subsidy policies for business and investment in HER&D will produce different results depending on the scenarios for 'external' – to the S&T system – conditions (e.g., distance from technological frontier, rate of technical change, sophistication of users) or actor behavior (e.g., the resources committed to R&D from business as a response to subsidies, competition, etc.).

In comparison to other SD studies, which focus on specific parts of ISs (such as R&D policies, innovation diffusion policies, and science and technology policies) (Uriona and Grobbelaar 2019), our approach offers a broader view of NISs incorporating important issues such as the 'creative destruction' process, different sources of learning (domestic and global) for firms, the 'openness' of a country and its participation in GVCs, the quality of institutions, the 'three missions' of academia, the active involvement of sophisticated users, and the VC role.

There are weak or lagged parts between and within helices that operate as obstacles for the virtuous cycle of knowledge affecting the evolutionary path of NISs. These parts may concern knowledge creation and exploitation, R&D activity, interactive learning, participation in GVCs, commercialization, regulation, financial support, sophisticated demand, etc. The crucial issue is to understand the whole system behavior through the dominant and weak feedback loops.

Thus, improvements in innovation policies based on identified weak/lagged parts and leverage points of the system may contribute substantially to the overall system performance. What-if analysis, through alternative scenarios, can lead to the shift from 'static innovation scoreboards' to 'dynamic innovation dashboards' for innovation policies and new tools for innovation management.

5 Conclusions

The quantitative analysis and measurement of innovation remain a crucial but highly arduous effort for researchers and scholars. In this paper, we reviewed the main approaches and empirical methods that examine the performance (effectiveness,

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[5] 'Critical mass' refers to a sufficient level (size of firms, number of scientists, number of R&D personnel, funding, etc.) that allows a NIS to be able to take up and effectively harness new technological knowledge (Archibugi et al. 1999).

efficiency, efficacy, etc.) of NISs, highlighting their main strengths and weaknesses. Despite the aspiration of holistic approaches, the dominant empirical methods fail to address crucial aspects of innovation such as actor heterogeneity, the intensity of interactions, complexity, time delays, and endogenous dynamics in NISs.

To overcome these shortcomings, we developed a generic conceptual framework for modeling heterogeneous actors' behavior in NISs. We considered five helices as 'aggregate actors-subsystems' that evolve and interact asymmetrically in a co-opetitive game, in the production, diffusion, and use of new knowledge. Different strategies and activities of actors take place based on the resources they have committed to them (Pisano 1997). Actors' resource commitment depends on expectations and previous experience, while strategy involves making choices on resource commitments (Stamboulis 2007).

Within a NIS, the absence of synergies between actors creates lagged or weak elements (areas) of the system affecting its overall performance and success. We consider that the intensity of spatio-temporal interactions within and between subsystems and the level of cooperation and coordination amongst them can explain the evolutionary trajectories of NISs.

Each NIS has its own history, path dependence, institutions, routines that determine its evolution. Mapping the dominant loops – in SD terminology – may contribute to understanding the varying evolutionary patterns of NISs' change. We expect to identify the leverage points and suggest system-oriented policies for overall system performance improvement through what-if analysis.

Our proposed conceptual framework allows us to develop concise models and understand the impact of policy choices and actor behaviors. We can identify system failures (e.g., infrastructural, institutional, interaction, and capabilities') and design policy measures accordingly (Woolthuis et al. 2005). In comparison to existing SD modeling attempts (either conceptual or with formal validation), our integrated framework introduces new modeling elements in NISs such as innovative mindset and strategic behavior in terms of resource commitment, institutional and regulatory framework (i.e., collaboration culture, quality of institutions, IPRs), financial support, policy effects, user-producer interaction, and interactive learning, exogenous factors, and global technical change. It enables quantification for comparative analysis, scenario (what-if) processes, and 'cost-benefit' calculations by investigating different possible impacts of specific interventions. Through scenario analysis, we may identify successful policy interventions (what works and what does not) in terms of resource commitment.

In further research, we aim to validate the structure of the model with historical data, examine diverse scenarios for selected NISs, and provide some comparative analysis (e.g., North vs. South, innovation leaders vs. emerging innovators). Moreover, we could examine the diversity[6] (considering the properties of variety, balance, and disparity) of structural elements (e.g., firms, and universities) within NISs for capturing the evolutionary patterns over time. The framework may also be enriched by detailing further the financial helix and incorporating factors related to

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[6] For instance, Stirling (2007; 2010) suggests a general quantitative non-parametric diversity heuristic that allows exploration of trade-offs between diversity and performance including consideration of system constraints and interactions.

the country's economic growth (GDP), complementary assets (e.g., consultancy and technical services – KIBS), demand-side activities (e.g., quality requirements, environmental-social awareness), and supporting functions for innovation and entrepreneurship (e.g., incubation activities, pattern formation). At a different level of analysis, depending on the availability of relevant data, the proposed framework may be adapted at the regional or sectoral level.

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Declarations The present paper did not require any interaction or experimentation that demands ethical compliance.

Conflict of interest The authors declare that they have no conflicts of interest.

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