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Agent-Based Modeling for Effective Innovation Ecosystem Management

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Abstract

Innovation ecosystems are complex systems involving diverse stakeholders with varying interests, focused on fostering innovative outputs. These environments enable large corporations, entrepreneurs, investors, and government institutions to connect, share knowledge, and combine their contributions to generate value through networking. They encourage partnerships and interactions that support co-creation. This paper investigates the innovation ecosystem as a network of interacting agents. While much research has emphasized qualitative analyses of orchestration, we use agent-based modeling (ABM) to explore both individual agents and their aggregated behaviors. Our model serves as a decision-making tool to evaluate the effectiveness of orchestration strategies on both individual agents and overall ecosystem performance.

Keywords
Innovation Ecosystem, Orchestration, Agent-based Modeling, Value Co-creation, Netlogo.

1.Introduction

For a long time, economies worldwide have aimed to secure stability by encouraging various national sectors to contribute to their growth. In this context, the development of an innovation ecosystem has emerged as a promising approach to strengthen economic foundations with new trends beyond reliance on just a few industrial sectors. The diversity of contributions fostered by such collaborative environments ensures a greater overall impact than what individual actors could achieve on their own.

The innovation ecosystem is a network of entities that collaborate to create and capture value through shared innovation efforts (Ritala et al. 2013). It comprises various entities that leverage both external and internal innovation practices to boost their profitability (Fosfuri and Rønde 2004). This economic environment promotes high productivity and business diversity by integrating various outputs from participating organizations (Garibay et al. 2015). However, these ecosystems are characterized by dynamic flows, non-linearity, and unpredictable patterns of interdependencies arising from engagement in open innovation activities. Additionally, members of an innovation ecosystem typically exhibit an accelerated learning curve, significantly enhanced by their interconnections (Ferasso et al. 2018). Likewise, an innovation ecosystem is described as a network where the flow of knowledge occurs (Tejero et al. 2016). This economic structure often extends its boundaries to include entities with diverse backgrounds and strategies, integrating their essential roles in creating and capturing value (Weil et al. 2014). Moreover, the potential contributions of players within the innovation ecosystem are influenced by the prevailing economic conditions (Saguy and Sirotinskaya 2014). The versatile environment in which entities interact is influenced by political, technological, and economic factors (Engler and Kusiak 2011). The innovation ecosystem is a multifaceted metaphor that encompasses a wide range of definitions. However, research consistently highlights the importance of establishing such a collaborative framework. The overarching goal of an innovation ecosystem is to create a solution-oriented network where innovative outputs arise from the sharing of knowledge, technologies, and expertise, regardless of the members' differences. Ensuring the harmonization of these systems can lead to significant benefits, particularly in contributing to the development of national economies. This paper is organized as follows: first, it addresses the nature of innovation ecosystem based on past theories; highlighting the complexity of such systems and the challenges that arise during the orchestration process. Following that, it explains and illustrates the attempt to simulate an innovation ecosystem. Finally, potential future work is discussed in the last section.

1.2 The Concept of Innovation Ecosystem

As competition intensifies in today's market, businesses of all sizes must strategize on how to navigate this economic landscape while enhancing their adaptability and resilience. One prominent trend is the formation of partnerships, which leverage shared resources and expertise to help organizations thrive. This collaboration gives rise to what is known as an innovation ecosystem—a network of diverse entities working together to produce innovative outcomes.

In this ecosystem, participants contribute goods, services, information, or resources in a mutually beneficial manner. The concept of reciprocal co-valuation underpins this collaboration, emphasizing that all members share responsibility for the overall success of the ecosystem. Large corporations, small and medium-sized enterprises, investors, researchers, and government agencies all play a role in the innovation process, cooperating across disciplines to achieve common goals. This dynamic interaction thrives on heterogeneity, incorporating a wide range of businesses and academic institutions, as well as elements from both the private and public sectors. Government-funded innovation infrastructures further enhance the ecosystem by accelerating idea development and reducing the time needed to launch new ventures.

From the perspective of the innovation ecosystem, open innovation is essential and should not be overlooked. This approach supports the notion that merging research with commercial efforts is crucial for transforming innovative technologies from theoretical concepts into practical applications. A creative innovation ecosystem focuses on extracting and contextualizing knowledge to benefit stakeholders, emphasizing the need for entities to manage both incremental and radical innovations. To foster innovations at the system level, businesses are encouraged to network and strengthen their connections within both physical and digital environments to discover new information sources. Such systems provide significant experiences for all participants, even amid various interactions and partnerships that require different governance mechanisms. For example, while contractual agreements may outline member interactions, innovation ecosystems are often better coordinated through co-alignment strategies and the clarification of roles, which may not always be formally defined. The interdependencies created through co-specialization lead to cohesive co-creation. Consequently, participants of innovation ecosystem gain confidence as they recognize the compatibility of their contributions and engage in a process of mutual evaluation. Ultimately, the success of innovation ecosystem hinges on its ability to cultivate an environment of collaboration, openness, and shared responsibility. By embracing partnerships and leveraging diverse resources, organizations can navigate the complexities of the modern market, driving innovation that benefits not only themselves but the broader community as well. This holistic approach ensures that all participants are engaged in a continuous cycle of learning, adaptation, and co-creation, making the innovation ecosystem a powerful catalyst for growth and transformation.

2. Related work

Despite the growing interest in studying complex systems, innovation ecosystems have rarely been explored through simulation modeling, in which qualitative and observational approaches are being more common. However, Hirata and Ulanowicz (1984) and Hannon (1973) introduced an agent-based approach to modeling economic structures as ecosystems, treating agents as elements of an ecological network, afterwards, Bandini et al. (2001) and Chopard et al. (2002) attempted to model complex systems using the concept of cellular automata, demonstrating comprehensive agent-based modeling. Similarly, Tesfatsion (2003) developed an agent-based model for complex economic conditions, while Albino et al. (2006) addressed industrial innovators' interdependencies using a similar approach. Ma and Nakamori (2005) proposed an agent-based simulation model for evolutionary innovation frameworks. Luke et al. (2005) created an agent-based model of innovation ecosystems using MASON to explore microeconomic behaviors' impact on macroeconomic phenomena. Finally, Engler and Kusiak (2011) presented an agent-based model of innovation in the global economy, revealing the dynamics of innovation within this context.

2.1 The Complex characteristic of Innovation Ecosystem

The innovation ecosystem is classified as a complex system due to its interaction with a diverse range of entities, each with unique characteristics. These differences can lead to significant advantages, such as a wealth of knowledge and a variety of resources that can be shared and exchanged among participants. However, they can also pose challenges in aligning individual interests and promoting mutual benefits. Consequently, managing these networks requires considerable effort from the central entities responsible for overseeing and coordinating the structure of the innovation ecosystem. The ecosystem's effectiveness hinges on a continuous flow of resources among its members, which includes both physical and intangible assets. To sustain these flows, participants need to employ effective orchestration techniques and procedures. Furthermore, it is crucial for participants to communicate effectively across organizational boundaries to enhance collaboration and innovation. Therefore, the establishment of these interdependencies inherently carries risks that must be mitigated to foster an environment conducive to smoother networking among participants.

According to Adner (2006), when resource allocation occurs to partners outside of the firm's premises, it dramatically raises a red flag when evaluating the linked risk. In addition, regrettably, some organizations have a tendency to ignore the shared objectives that should be reached collectively and act selfishly in the name of their own self-worth rather than completing the tasks that have been delegated to them. Despite the fact that the business market's dynamism may cause unexpected changes, which in turn have an influence on flow, the innovation ecosystem is nevertheless subject to these alterations. Especially in cases where small and medium enterprises (SMEs) are engaged in the innovation ecosystem. According to Gawer (2014), SME's participation in an innovation ecosystem is only partially advantageous because of the limitations associated with their early development stage maturity in the market. In other instances, large firms tend to refuse to work with SMEs because they view them as inexperienced parties. This type of collaborative setting has some ambiguity when it comes to the strategic positioning of each entity; certain members have indirect contributions to the innovation ecosystem that cannot be explicitly classified. The strategic positioning of entities within an ecosystem tends to be more emergent than predetermined, as mentioned in (Mintzberg and Waters 1985). The innovation ecosystem presents a challenge in maintaining harmony, therefore getting all the players to cooperate for the greater benefit is not a simple task. The process of controlling such structure is known as orchestrating. And instead of being a precise and rigid approach, the term refers to resilient management practices in this context. As previously indicated, coping with a changing economic environment necessitates a hybrid blend of informal and formal management systems. Due to the dynamic nature of the market's constant evolution, this poses difficulties for those in charge of orchestrating innovation ecosystems. They must choose the best mix of management mechanisms based on a variety of economic factors. With the unstable state of the market which is brought by the quick adoption of new technology and variable economic needs, the business market's inherent stochasticity creates obstacles that prevent the free exchange of ideas and interactions among participants in innovation ecosystems and encourages their opportunistic behavior.

2.2 Orchestrating Innovation Ecosystem

To facilitate interactions within the innovation ecosystems, various coordination strategies have been developed. Some scholars argue that formal controls are essential for managing the relationships and connections between entities to ensure economic alignment. Conversely, other academic perspectives recommend approaching these alliances with caution. Hybrid combinations of formal and informal regulating mechanisms have been proposed in certain publications. Cobben and Roijakkers (2019) assert that an evaluation of the degree of partnership alignment would be a necessary step in determining the correct orchestration methods by the hub organization. To preserve discipline within the innovation ecosystem, for instance, the focal entity would be compelled to take strict measures in situations where entities disobey orders and tend to resist harmonization. Through the employment of explicit rules and regulations, control-based methods are utilized to bring entities into alignment. whereas in certain circumstances, the focal entity might have a tendency to loosen the regulating mechanisms toward the participants in the innovation ecosystem. In this case, building trust became the hub firm's primary concern. Dhanarai and Parkhe (2006) identify three orchestration aspects that a focal entity might use to direct the innovation ecosystem. These factors primarily focus on controlling innovation appropriability, promoting network stability, and facilitating knowledge mobility. The hub business makes sure that all entities are demonstrating a high degree of information absorption, application, and rationing throughout the initial step. The allocation of value among the stakeholders is of interest to the focal entity. Likewise, in the context of innovation ecosystem, the focal entity is in charge of bringing the participants to a consensus on how to jointly capture value. The authors also place a strong emphasis on the hub firm's capacity to mobilize and maintain participant commitment in order to foster value generation and accelerate ecosystem growth. However, Adner (2012) proposes five potential ways to reconfigure the innovation ecosystem: relocation, separation, combination, addition, and subtraction. The author suggests that the members' roles can be divided and assigned to them separately, or they can merge their work. Additionally, he noted, current players may be removed if they are no longer contributing value to the ecosystem and new actors can be considered anytime new specialized activities are involved in the innovation ecosystem. Three sorts of network strategies—keystone, dominator, or niche—that an entity may employ in an innovation ecosystem depending on its strategic position within the ecosystem and the need for a specific authority structure that establishes the functional hierarchy in such ecosystems (Iansiti and Levien 2004) were mentioned. In a similar manner, Muegge (2011) has identified four distinct roles that are particularly prevalent in innovation ecosystems where intensive technology business enterprises are active participants. They are described by the author as promoters, guardians, adopters, and users of open platforms.

3.The Objective of Orchestrating Innovation Ecosystem

The formation of innovation ecosystem requires the clustering of companies with diverse competencies and sizes. However, these differences can lead to unmet expectations, particularly among small and medium-sized enterprises (SMEs). Larger corporations may underestimate the capabilities of SMEs, resulting in a reluctance to engage with them, neglecting the fact that collaboration could be mutually beneficial. Additionally, competition for control within the ecosystem often creates a blurred picture of authority distribution. One major challenge in coordinating the behaviors of these varied-sized businesses is the difficulty of aligning them under a single set of management practices and norms. Consequently, the innovation ecosystem often lacks clarity on effective techniques that would allow for flexible engagement while maintaining cohesion. Ultimately, achieving a balance between shared objectives and individual interests is key to creating a win-win situation. Moreover, some organizations tend to prioritize their own survival over the overall sustainability of the innovation ecosystem. The uncertainties associated with managing such a system stem from the emergent nature of cooperation strategies among its entities. This complexity presents challenges for orchestrators, whether they are central components of the ecosystem or external organizations responsible for monitoring coordination. Traditionally, the role of directing the innovation ecosystem has been viewed as one that can only be filled by a single individual. This leader must possess expertise in various areas, including advocating for SMEs and ensuring the effective mobilization of resources to achieve the ecosystem's shared goals. It is important to recognize that the dynamic nature of the co-evolving market influences the characteristics of ecosystems throughout their life cycles. This means that during the value creation process, the strategic positioning of entities can change. Consequently, all players in the innovation ecosystem, regardless of their size or structure, influence one another and are affected by the strategic positions of surrounding entities. The primary success of such a kind of ecosystem hinges on the collective achievement of value-capturing activities. This leads us to question the earlier assumption that effective harmonization can be achieved if a single hub entity manages coordination. What if a fair orchestration process requires the active participation of nearly all entities involved in the innovation ecosystem?

4. Methodology of Simulating the Innovation Ecosystem

As has been mentioned, innovation ecosystems are complex systems, and developing a simulation model is a key adaptive strategy for managing them. The primary aim of modeling such a system is to reduce uncertainties and simplify its complexity. In agent-based modeling, for example, entities such as large corporations, SMEs, government agencies, and academic institutions are represented as agents, each following specific rules and interactions within the simulated environment that reflects the ecosystem of collaborative contributors where value is created.

4.1 Conceptual data of Innovation Ecosystem

Through research and literature review, a conceptual model of an innovation ecosystem is developed to illustrate the various interconnections among these agents. As depicted in Figure 1, actors seek to establish multiple connections with others, particularly those that are well-established. These interdependencies involve sharing cognitive and physical resources between parties. The model highlights the importance of focal agents—such as orchestrators, incubators, and accelerators—who maintain the integrity of the ecosystem by connecting with multiple players. These focal entities are essential for fostering networking practices within the ecosystem. However, the model also reveals the inherent complexity of these networks. The nature of partnerships can vary due to differing strategic positions among entities, leading to fluctuations between control-based and trust-based relationships. Such dynamics can give rise to opportunistic behaviors, complicating the functioning of the innovation ecosystem. Therefore, the ABM aims to identify what influences the ecosystem's harmony and explore various orchestrating policies to maintain alignment among agents. The dynamic environment consists of innovation agents, each contributing with resources and expertise relevant to the value proposition at any given time. Agents interact to exchange information or resources in response to demand, resulting in the formation of diverse alliances. Each agent possesses unique characteristics—such as market share and degree of interaction—that distinguish them. For example, a minimum market share may be required to initiate interactions, although other financial metrics like revenue can also be considered. Since actors may not focus solely on one metric, a weighted score of financial indicators is often used to reflect a comprehensive range of selection criteria relevant in a dynamic market context.

4.2 The ABM of Innovation Ecosystem

Building on the previous conceptualization, an agent-based simulation of the innovation ecosystem has been developed. This model employs a bottom-up approach, where individual agent behaviors are generated and subsequently aggregated to represent the macro-level dynamics of the innovation ecosystem. These behaviors are defined through a combination of conditional statements and characteristic variables, which are utilized in governing the interactions among agents. In this agent-based model, interactions between agents are determined by fulfilling specific conditional statements. Each agent category is assigned characteristic variables, such as market share and interaction history, which help distinguish them from others. These variables are used to decide if interactions can occur, requiring the introduction of threshold values that represent the minimum criteria for forming partnerships. Each agent has a weighted score based on the summation of these variables, reflecting the diverse perspectives of real agents in an innovation ecosystem when choosing partners. The model aggregates micro-level key performance indicators to derive macro-level indicators, such as the growth rate of the innovation ecosystem and the number of new startups. Policymakers can use the model's outputs to assess their policies, but they must carefully select input parameters, like the weights of importance, as these significantly impact the results. The simulation model evaluates the performance of the innovation ecosystem on a dual scale basis, introducing relevant key performance indicators to measure its effectiveness. The model (Figure 1) provides key performance indicators (KPIs) for the innovation ecosystem, enabling policymakers to analyze the effects of proposed strategies and policy adjustments. These KPIs are derived from the aggregation of the defining characteristics of the system's agents, such as the ecosystem's growth rate and the number of new startups. It is important to note that some KPIs may not directly correlate with the performance of orchestrators, so policymakers must carefully select them.

4.3 Policy-maker Interface with Innovation Ecosystem

Figure 2 illustrates a simulation of a hypothetical innovation ecosystem using NetLogo software. The simulation model's interface includes three primary components: input parameters, the interaction environment (IE) where agents interact, and output monitors. Plots and monitors visualize how different contributing elements of the simulation affect the outcomes. Users can adjust input parameters using sliding buttons on the left side of the interface to create various scenarios and analyze potential results. After setting the parameters, users press the setup button, modify the inputs as needed, and then click the go button to observe agent behaviors and evaluate the consequences displayed in the plots and monitors. The complex system addressed by this simulation involves multiple agents and interactions, as detailed in Table 1, which outlines the various input variables considered.

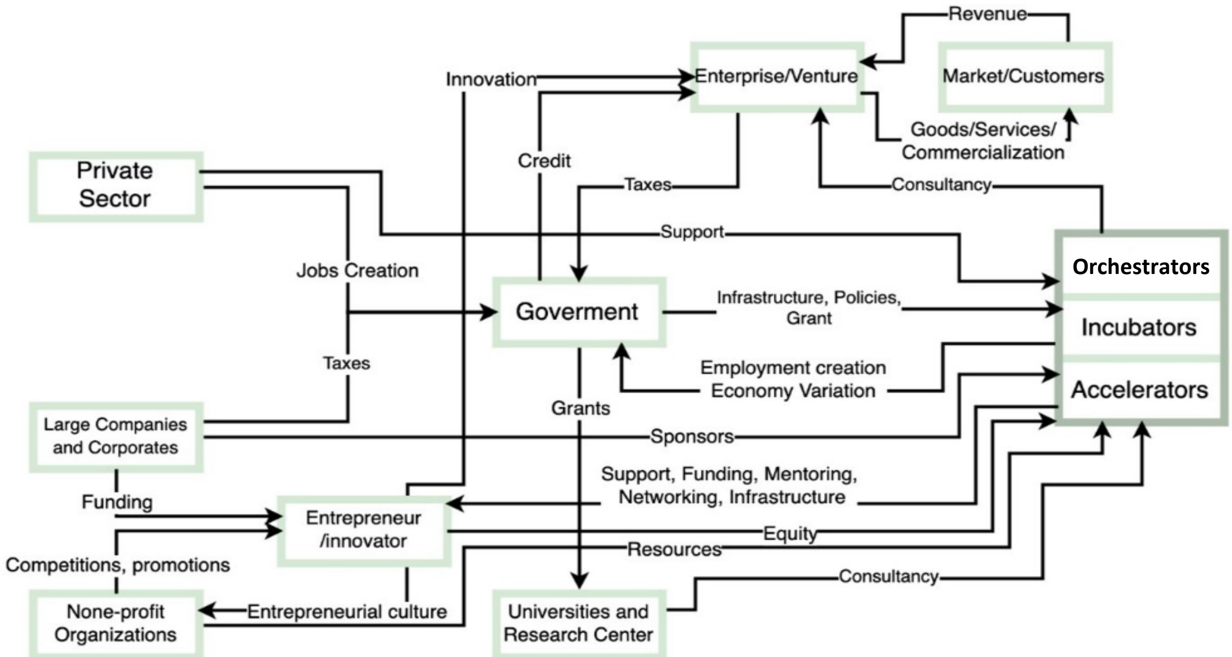

Figure 1. Conceptual Model of Innovation Ecosystem

Figure 2. Simulation Model of Innovation Ecosystem Using Netlogo

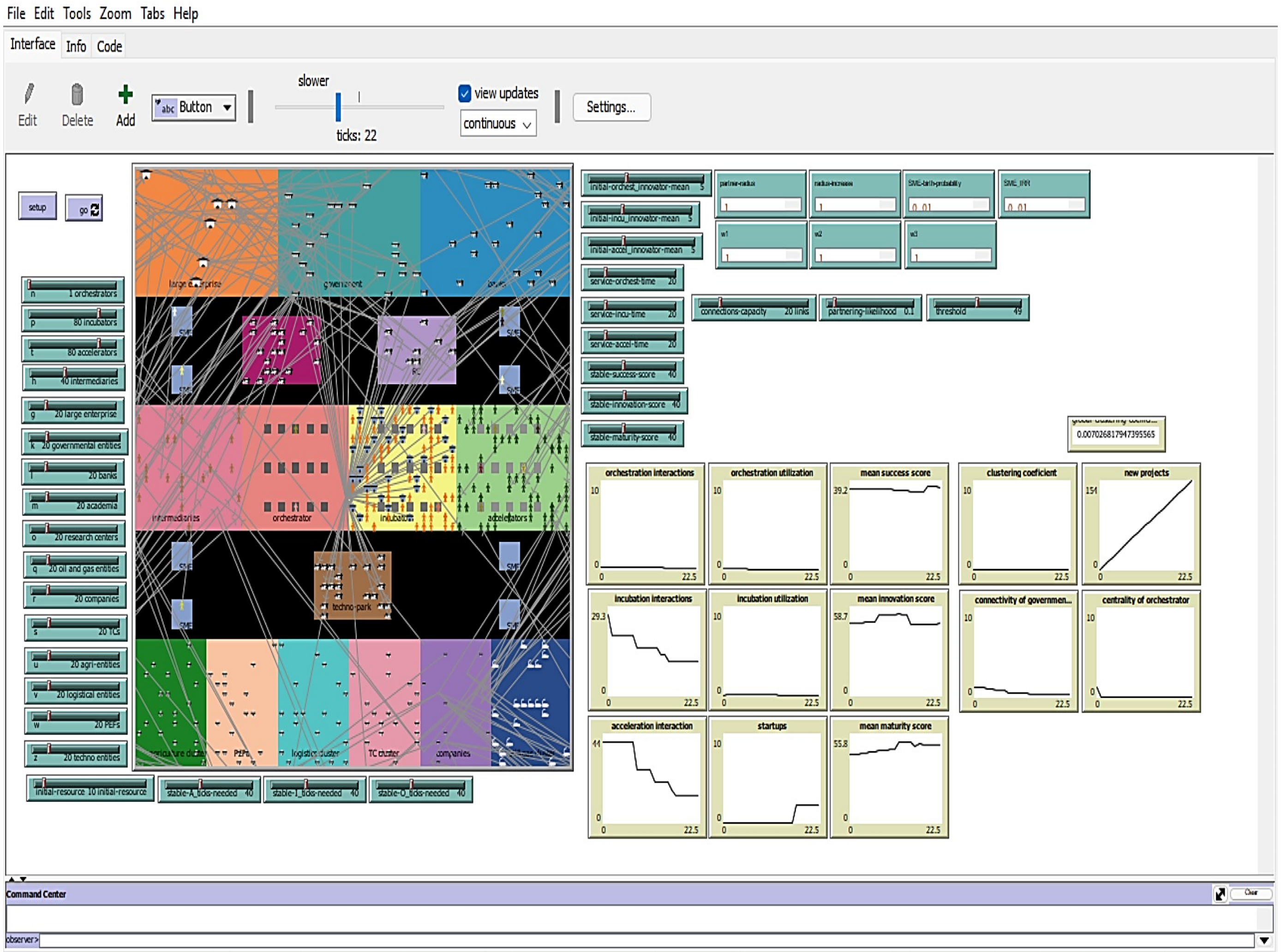

Table 1. Interpretations of the simulation model's input parameters

Factors/input parameters	**indication**
Number of orchestration entities	Indicates how many orchestrators are there in IE
Number of incubation entities	Indicates how many incubators are there in IE
Number of acceleration entities	Indicates how many accelerators are there in IE
Number of intermediaries	Indicates how many intermediate entities are there in IE
Number of large enterprises	Indicates how many large enterprises are there in IE
Number of governmental entities	Indicates how many governmental entities are there in IE
Number of banks	Indicates how many banks are there in IE
Number of academic entities	Indicates how many higher education entities are there in IE
Number of research centers	Indicates how many research centers are there in IE
Number of oil and gas entities	Indicates how many entities are specialized in oil and gas sector
Number of companies	Indicates how many companies are there in Oman IE
Number of telecommunication entities	Indicates How many entities in telecommunication sector in Oman IE

Number of agricultural entities	Indicates How many entities in agricultural sector in Oman IE
Number of logistical entities	Indicates How many entities that deal with logistics in Oman IE
Number of private equity firms	Indicates How many private equity firms are in Oman IE
Number of entities in Oman's technology park	Indicates how many entities in Oman technology park
agents' arrival to orchestration	Mean value of agents' arrival distribution to orchestration
agents' arrival to incubation	Mean value of agents' arrival distribution to incubation
agents' arrival to acceleration	Mean value of agents' arrival distribution to acceleration
Orchestration process time	Time needed to accomplish orchestration service
Incubation process time	Time needed to accomplish incubation service
Acceleration process time	Time needed to accomplish acceleration service
Stable innovation score	Threshold weighted score indicates the fulfillment of orchestration process
Stable incubation score	Threshold weighted score indicates the fulfillment of incubation process
Stable acceleration score	Threshold weighted score indicates the fulfillment of acceleration process
Connection capacity	Maximum number of links an agent may have
Partnering likelihood	The probability of initiating a partnership
Threshold value	Weighted score that agents have to fulfill it to initiate partnerships
radius	The distance between two agents
Birth of SME	The probability of establishing new SMEs
SME IRR	The average value of SMEs IRR
W1	Amount of importance of IRR
W2	Amount of importance of age
W3	Amount of importance of Market share

5. Results and Discussion

This section presents the results of Netlogo's simulation runs with various input parameters to demonstrate how changes in system parameters affect the outputs, shown through counters and plots. This section presents the outcome of Netlogo's simulation run with various input parameters, showcasing how the system's parameters influence its performance, by means of counters and plots. The simulation model can explore different scenarios based on the interests of users or policymakers. However, the scenario of centralizing incubation/acceleration processes, which examines the effects of having fewer incubators and accelerators, while involving multiple orchestration agents, indicating decentralized orchestration, is addressed as shown in Figure 3.

This scenario is generated by running the simulation model for at least 22 hours. In the first scenario, the simulation model reduced the number of incubators and accelerators. As a result, both the average innovation score (46.9) and maturity score (41.9) were lower than their stable values of 50. Interactions between agents and incubators or accelerators were minimal, representing only 0.2% of all interactions within the innovation ecosystem. However, the presence of orchestrators helped mitigate the shortage of incubators and accelerators, as most agents maintain connections with focal entities in a decentralized approach. Due to the lack of incubators and accelerators, no significant clustering activities were observed, indicating that agents were not sufficiently mature in terms of acquired technology and networking. Consequently, the establishment of new mature startups was low, with almost no startups being formed due to the scarcity of mentoring and financial support typically provided by incubators and accelerators.

On the other hand, the level of governmental interactions was acceptable, as they tended to form links with other mature and well-established agents, such as large enterprises. The overall global clustering coefficient indicator was low at 0.008, highlighting the impact of insufficient incubators and accelerators. In the light of the simulated scenario, engaging agents in the central activities of the focal entity would be effective in providing both zoom in and zoom out view of the innovation ecosystem. Hence, providing wide and narrow lenses to coordinate the whole system would probably stand as a strong advantage for the sake of the ecosystem's health and sustaining its performance as well. As shown in Figure 4; establishing a focal entity within an innovation ecosystem involves including representatives from each participating agent. The agents must elect members who will represent their interests during the policy-making process, which takes place at the hub. Whether the innovation ecosystem is specialized in a particular industry or not, it is crucial for the hub firm to include these elected representatives to ensure a high level of consensus when establishing policies or making decisions. This approach reduces the likelihood of opportunistic behavior compared to scenarios where the focal entity operates independently. Furthermore, if the hub entity is responsible for providing platforms for connections, the presence of these representatives will facilitate the dynamics of interconnecting and clarify the interdependencies among the ecosystem's members. Engaging agents in the central activities of the focal entity is effective in offering both detailed and broad perspectives of the innovation ecosystem. This dual view helps coordinate the entire system, which is advantageous for maintaining the system's health and sustaining its performance.

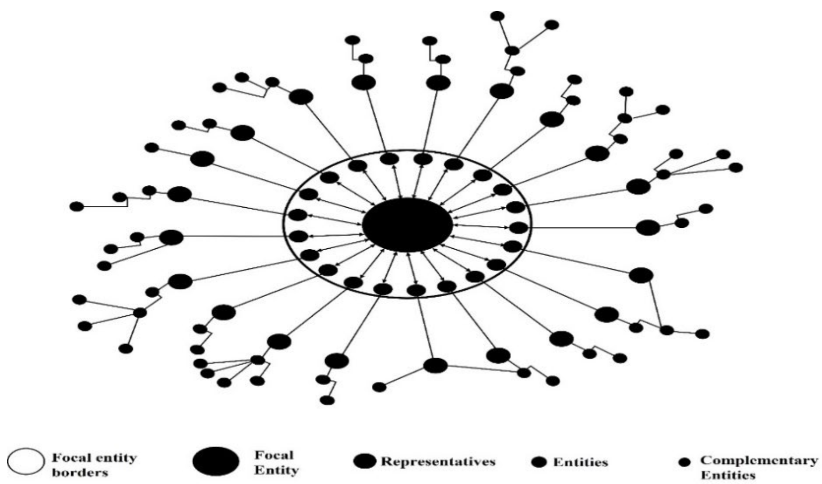

Figure 3. The Structure of the Hub Orchestrating the Innovation Ecosystem

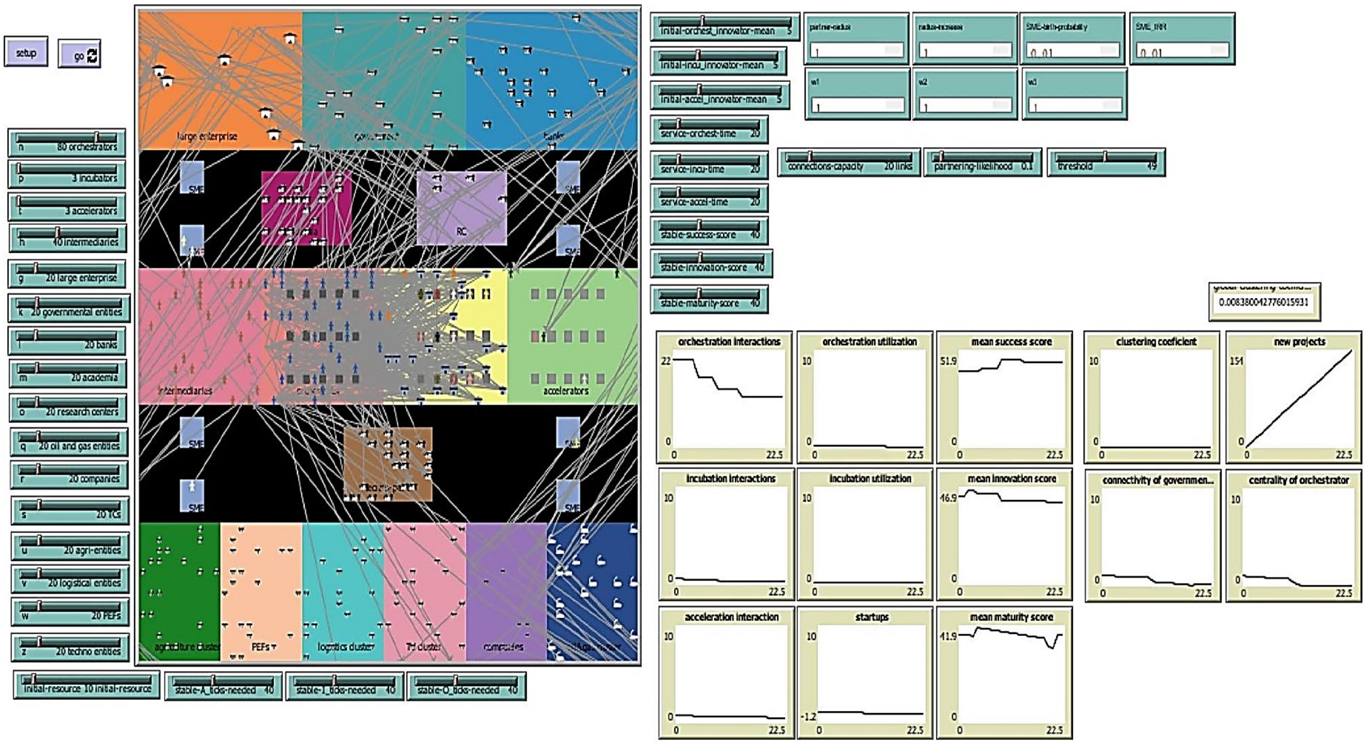

Figure 4. Netlogo Simulation of Decentralized Orchestratio

6. Conclusion

This paper aims to elucidate the phenomenon of establishing innovative ecosystems and proposes a novel approach to address the complexities associated with orchestrating these systems. To better understand the nature of innovative ecosystems, we developed an agent-based modeling simulation. This calibrated simulation model serves as a valuable what-if analysis tool, enabling policymakers to evaluate and validate their strategic recommendations without the need for real-world experiments, which can be resource-intensive and time-consuming. By allowing for the exploration of various scenarios and potential outcomes, the simulation offers insights into how different factors may influence the dynamics of the ecosystem. As such, it facilitates informed decision-making and strategic planning in the context of innovation. Looking ahead, our future work will prioritize the integration of real-world data into the model to enhance its calibration and operational effectiveness. This process will involve collecting empirical data from established innovative ecosystems, which will allow us to refine the model's parameters and improve its predictive capabilities. By utilizing actual data, we aim to make the simulation more representative of real-world dynamics, thereby increasing its accuracy and relevance. Gathering this data will entail collaborating with various stakeholders within innovative ecosystems, including businesses, research institutions, and government agencies. We will seek to understand the unique characteristics and performance metrics of different ecosystems, focusing on factors such as the types of collaborations, knowledge flows, and innovation outcomes that can impact the overall effectiveness of the ecosystem. Incorporating this empirical data will not only bolster the model's reliability but also enhance its utility for policymakers. By providing a data-driven basis for simulation, we can offer more precise insights into the potential impacts of different strategic decisions. This will empower policymakers to test various scenarios, evaluate the implications of their choices, and ultimately foster environments that promote innovation and economic development. Additionally, we envision that this iterative process of calibration will facilitate continuous improvement of the model. As new data becomes available and as innovative ecosystems evolve, we can update the model to reflect these changes, ensuring that it remains a relevant and powerful tool for analysis and decision-making. Ultimately, our goal is to create a robust framework that not only aids in understanding existing innovative ecosystems but also supports the development of new strategies for enhancing their effectiveness and impact.

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