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Unpacking the Multilayered Nature of Entrepreneurial Ecosystems: A Conceptual Complex Adaptive System Model

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Abstract

The concept of entrepreneurial ecosystems (EE) is gaining increasing attention from academics, professionals, and policymakers because of its potential as a policy tool for promoting economic growth. However, the theoretical foundation for analyzing EE needs further development to comprehensively capture its systemic, complex, and adaptive nature. Although recent studies have made progress in this area by incorporating complexity theory into this field of literature, the multilayer characteristics of an EE have been overlooked in those conceptualizations. We therefore build upon those papers by introducing an understanding of EE as a multilayer network from the perspective of complexity theory. Building upon this understanding, we provide a representative example to illustrate the practical application of our conceptual model via agent-based modeling while outlining a research agenda that suggests new directions for future studies in this field.

Keywords: Entrepreneurial ecosystem, Complex adaptive systems, Multilayer-network, Evolution

1. Introduction

Entrepreneurial ecosystems (EEs) are as complex and interconnected systems in which different actors and factors are coordinated to foster productivity, growth, and employment (Spigel and Stam, 2018; Stam and van de Ven, 2019). This concept has gained interest during the last decade among academics, policymakers, and practitioners (Autio et al., 2018; Wurth et al., 2023) because of the new venture's ability to drive regional development (Stam and Van de Ven, 2021). Despite this growing interest and recent theoretical and empirical advances, research on the concept is mainly driven by policy (Candeias and Sarkar, 2023; Stam and Spigel, 2018; Wurth et al., 2023), resulting in somewhat undertheorized, conceptually fragmented literature (Cantner, 2020; Cao and Shi, 2021; O'Connor and Audretsch, 2022; Shi et al., 2023) that is not clearly linked to other theories and similar concepts in the field of innovation and entrepreneurship (Wurth et al., 2023). In particular, the mechanisms that govern an EE's evolution, that is, the causal mechanisms that link an entrepreneur's agency with an EE's structure and resources and the interdependencies between them, are poorly understood (Cho et al., 2022; Mack and Mayer, 2016; Wurth et al., 2021; Wurth et al., 2023;).

The importance of such understanding cannot be overstated, as those two elements—the entrepreneur's agency and the interdependencies of its constituting parts—are what differentiates EE from prior concepts such as clusters or regional innovation systems (Wurth et al., 2023). One promising avenue to advance research in this direction is to approach the EE concept from the perspective of complexity theory (Fredin, 2020; Roundy et al., 2018; Wurth et al., 2023). System theory, complexity theory, and particularly complex adaptive systems (CAS) have already been named at the 2017

Academy of Management as the most promising theoretical avenue to advance the EE research agenda (Ritala and Gustafsson, 2018), a path that has been picked up by recent research (Theodoraki et al., 2022).

Entrepreneurial ecosystems are, as the name indicates, ‘systems’ and thus should be studied as such (Roundy et al., 2018; Phillips and Ritala, 2019). They are ‘complex systems’, as they consist of numerous parts that interact with each other (Simon, 1962): entrepreneurs interact with incumbents, incubators, governments, service providers, and so on. Moreover, the interdependency of key elements such as formal institutions, infrastructure, culture, and leadership is crucial for the success of any EE (Stam and Van de Ven, 2019). Roundy et al. (2018) show that EEs are ‘complex adaptive systems’ as they are characterized by their constituting properties. Phillips and Ritala (2019) propose this conceptualization and highlight that EE consists of subsystems (e.g., Theodoraki and Messeghem, 2017), which are often related to hierarchies of power and legitimacy (Vargo et al., 2015), thus calling for the need to consider the consequences of multi-level relationships and processes to better understand the fundamental mechanisms of causation and organization in ecosystems. Similarly, Han et al. (2021) provide not only empirical qualitative evidence that Zhongguancun’s EE is characterized by the six properties of CAS but also, most importantly, that resources such as talent and finance connect EE agents in different ways, leading to the emergence of several sub-ecosystems. Moreover, Xu et al. (2023) contribute to this perspective by integrating a network-based approach with structural embeddedness (economic connections between actors) and cultural embeddedness (sociocognitive forces and social interactions) to elucidate their dual impact on venture creation dynamics in the EE. We build on this line of reasoning and argue that to further advance the understanding of an EE’s evolution, the multilayered network nature of

CAS needs to be taken into consideration; thus, in this article, we propose a conceptualization of an EE as a multilayered complex adaptive network.

Complex systems are commonly understood as nested hierarchies of subsystems that evolve themselves (Simon, 1962). However, while hierarchy is a well-established element of complex systems, so far, it has not been explicitly taken into consideration in the EE literature to understand EE as a complex system. Despite the argument that complex systems are self-organized without any central control—an argument that seemingly resists the notion of hierarchy and has been highlighted in EE research—Cilliers (2001) calls for a more nuanced view where the working of hierarchies within complex systems should not be equated with the classical understanding of hierarchies. Instead, with complex systems being structured entities, asymmetrical hierarchies exist that organize the working of subsections, each having unique functions (Cilliers, 1998). These hierarchies, a means of sense-making within the network, are thus not nested but rather interpenetrated, leading to "relationships that cut across hierarchies" (Cilliers, 2001, p.7). This cross-communication is, according to this author, part of the adaptability of the system, as such communication transforms hierarchies; that is, the way that the subsystems relate to each other. We argue that this notion should be linked to Boulding's (1956) understanding of social systems; in such a system, actors share a common social order to organize information received from the environment into many schemata that compete with each other (Gell-Mann and Mermin, 1994), and they struggle for the control of such shared interpretations. While EEs have been conceptualized as complex social systems consisting of different social clusters (Neumeyer et al., 2018), the multilayered structure of EE and the resulting social organization have been scarcely explored (Neumeyer and Corbett 2017; Neumeyer et al., 2018; Xu et al., 2023).

We contribute to EE research by combining the conceptualization of EE as CAS, thus allowing for insights into its dynamic evolution, what that as a multilayered network, thus enabling the disentanglement of its hierarchical (social) order. By providing a conceptual model and theoretical propositions, we show future research avenues to overcome the limitations of empirical research with respect to lacking tools for capturing networks on a larger scale and throughout time (Neumeyer et al., 2018) while leveraging the advantages of complexity theory. Additionally, we also advance the research stream that views EE as CAS by introducing the multilayered structure and thus enabling a better understanding of co-evolutionary process among an EE's subsystems and how this process influences its evolution. By providing an illustrative simple example relying on agent-based modeling, we show how such a conceptualization can be methodologically explored and thus provide avenues for future research.

2. Theoretical Background

2.1. Entrepreneurial Ecosystem

The concept of EE has gained increasing importance among academics and public policy. The first component of the word is 'entrepreneurial', which refers to the process of discovering, evaluating, and exploiting opportunities to create goods and services (Shane and Venkataraman, 2000). The second component, 'ecosystem', originates in ecology and represents a system of organisms and physical factors that interact shaping the environment (Tansley, 1935). Therefore, the concept of ecosystem applied to entrepreneurship suggests a community of interdependent agents that support entrepreneurial activity (Stam, 2015).

Despite the lack of commonly agreed-upon definitions, the various definitions of an EE in the academic literature (Table 1) share commonalities. One is the emphasis on the (non-linear and complex) interconnectedness of elements (Audretsch and Belitski, 2017; Cohen, 2006; Isenberg, 2010; Mason and Brown, 2014; Neck et al., 2004; Roundy et al., 2018; Sheriff and Muffatto, 2018; Spigel, 2017). Most definitions also recognize the importance of co-evolutionary processes that derive from these interconnections, clearly indicating that they are not static but rather evolve continuously. Additionally, the self-organized, complex and adaptive nature of the entrepreneurial ecosystem is generally recognized (Roundy et al., 2018; Sheriff and Muffatto, 2018).

Table 1. Definitions of the entrepreneurial ecosystem

Contribution	Definition
Neck et al. (2004)	"incubator organizations, spin-offs, informal and formal networks, the physical infrastructure, and the culture of the region are related uniquely and interact to form a system conducive to dense high-technology entrepreneurial activity". (p.190)
Cohen (2006)	"sustainable entrepreneurial ecosystems are defined as interconnected groups of actors in a local geographic community committed to sustainable development through the support and facilitation of new sustainable ventures". (p.3)
Isenberg (2010)	"The entrepreneurship ecosystem consists of a set of individual elements—such as leadership, culture, capital markets, and open-minded customers—that combine in complex ways". (p.3)
Mason and Brown, (2014)	"a set of interconnected entrepreneurial actors (both potential and existing), entrepreneurial organizations (e.g. firms, venture capitalists, business angels, banks), institutions (universities, public sector agencies, financial bodies), and entrepreneurial processes (e.g. the business birth rate, numbers of high growth firms, levels of 'blockbuster entrepreneurship', number of serial entrepreneurs, degree of sell-out mentality within firms and levels of entrepreneurial ambition) which formally and informally coalesce to connect, mediate and govern the performance within the local entrepreneurial environment." (p.5)
Stam (2015)	"A definition that nevertheless seems widely applicable is that of the entrepreneurial ecosystem as a set of interdependent actors and factors coordinated in such a way that they enable productive entrepreneurship." (p.1765)
Audretsch and Belitski (2017)	"We define systems of entrepreneurship (further ecosystem) as institutional and organizational as well as other systemic factors that interact and influence the identification and commercialization of entrepreneurial opportunities." (p.1031)
Ben Spigel (2017)	"Entrepreneurial ecosystems are combinations of social, political, economic, and cultural elements within a region that support the development and growth of innovative startups and encourage nascent entrepreneurs and other actors to take the risks of starting, funding, and otherwise assisting high-risk ventures."(p.2)
Roundy et al., (2018)	"An entrepreneurial ecosystem is a self-organized, adaptive, and geographically bounded community of complex agents operating at multiple, aggregated levels, whose non-linear interactions result in the patterns of activities through which new ventures form and dissolve over time." (p.5)

Sheriff and Muffatto (2018)	"High-tech entrepreneurial ecosystems are open complex adaptive systems made up of a variety of agents that interact formally and informally in specific locations. The interactions among agents enhance self-organization and the emergence of loosely coupled connections that facilitates the establishment of high-tech ventures with potentially high growth. The selection of agents and their strategies influences the functioning, performance, and evolution of the ecosystem."(p.621)

While these elements are certainly not the only common ones, they point out that these definitions share a common recognition of an EE's complex, dynamic, adaptive and interconnected nature. However, clear differences in what the specific components or elements are and how one can classify them according to their role, function, or characteristics within an EE, i.e., whether they are agents, resources, products, or contextual factors, emerge. However, despite a clear focus on identifying the elements that constitute an EE (Mack and Mayer, 2018), Table 2 highlights the lack of a "universal list" of EE components based on these clear differences. In Section 3, we propose a categorization relying on complexity theory.

Table 2. Key elements of an entrepreneurial ecosystem as identified in the literature

Neck et al. (2004)	**Isenberg (2011)**	**Feld (2012)**	**Spigel (2017)**	**Stam and van de Ven, (2019)**	**Sheriff and Muffatto (2018)**
Components	**Factors**	**Participants**	**Attributes**	**Elements**	**Agents**
Incubator organizations	**Policy:**	**Leaders:**	**Cultural attributes:**	**Resource endowments:**	New and existing ventures
New ventures	Government	Entrepreneurs	Supportive culture	Physical infrastructure	Incubators/Accelerators
Informal network:	Leadership	**Feeders:**	History of entrepreneurship	Demand	Large firms
Friends, families, informal relations	**Finance:**	Government	**Social attributes:**	Intermediaries	Support firms
Formal network:	Financial Capital	Universities	Worker talent	Talent	Universities
University	**Culture:**	Investors	Investment capital	Knowledge	Local Governments
Government	Success stories	Mentors	Networks	Leadership	Investors
Support Services	Societal norms	Service providers	Mentors and role models	Finance	
Capital Sources	**Supports:**	Large companies	**Material attributes:**	**Institutional arrangements:**	
Talent Pool	Nongovernment institutions		Policy and governance	Formal institutions	
Large Corporations	Support professions		Universities	Culture	
Physical	Infrastructure		Support services	Networks	

Infrastructure		
Culture	**Human capital:**	Physical infrastructure
	Work	Open markets
	Educational institutions	**Outputs**
	Markets:	New firms
	Networks	
	Early customers	

Given the numerous systematic literature reviews and critical evaluations of entrepreneurial ecosystems that have already been conducted (e.g., Alvedalen and Boschma, 2017; Brown and Mason, 2017; Cao and Shi, 2020; Cho, Ryan, and Buciuni, 2022; Cavallo et al., 2019; de Brito and Leitao, 2020; Diaz Gonzalez and Dentchev, 2021; Fernandes and Ferreira, 2021; Garavan et al., 2019; Hakala et al., 2020; Maroufkhani et al., 2018; Nicotra et al., 2018; Wurth et al., 2022, 2023), our research does not aim to replicate these efforts. Instead, we focus on identifying the elements that are relevant to our specific research context. Particularly, the missing focus on the inherent evolutive nature of the EE has continuously been raised as a concern in the literature (e.g., Acs et al., 2016; Borissenko and Boschma, 2017; Mack and Mayer, 2016; Cavallo et al., 2018; Cao and Shi, 2020; Wuerth et al., 2022, 2023). Instead, most empirical research has restrained itself to the identification of successful EE components, thus implicitly designing static frameworks (Cao and Shi, 2020). However, what sets EE's theorizing apart from other – older – conceptualizations of regional economic development is its focus on the entrepreneur's agency and the explicit zooming in on the interdependencies of the various components that constitute an EE (Wurth et al., 2023). The latter is rooted in both evolutionary economic geography (Schmutzler et al., 2022) and CAS (Auerswald and Dani, 2017; 2022; Carayannis et al., 2022; Han et al., 2021; Haarhaus et al., 2020; Roundy et al., 2018).

When, however, a large part of the empirical literature merely uses the concept of EE as a metaphor to refer to geographical contexts or boundaries of entrepreneurship or those interdependencies are not carefully considered, as the focus is only on one of the many components or actors and a static nature is imposed (Wurth et al., 2022, 2023), then this differentiation remains theoretical at best. Thus, it is hardly surprising that the call to look into the evolutionary processes that arise from the non-linear and complex interactions has been constant throughout the past years (e.g., Cho et al., 2022; Mack and Mayer, 2016; Wurth et al., 2021; Wurth et al., 2023).

Recent research has focused on the conceptualization of EE as CAS (Theodoraki et al., 2022). Roundy et al. (2018) conceptualize EEs as CASs by showing how an EE is characterized by the latter's specific properties. Phillips and Ritala (2019) extend this idea, highlighting that EEs consist of subsystems (e.g., Theodoraki and Messeghem, 2017) that are often linked to hierarchies of power and legitimacy (Vargo et al., 2015). They emphasize the importance of understanding multilevel relationships and processes to grasp the fundamental mechanisms of causation and organization in ecosystems. In this sense, they go alongside the argumentation of Aeeni et al. (2019), who define – similar to Roundy et al. (2018) – EE as complex systems by relying on the main characteristics of complexity theory. While non-linearity, self-organization, emergence and co-evolutionary order creation are mirrored by both conceptual frameworks, Aeeni et al. (2019) add the hierarchical nature of complex systems as an important element. They argue that, according to Simon (1962), complexity is reflected in hierarchical order. That is, complex systems are "being composed of subsystems that, in turn, have their own subsystems, and so on" (Simon, 1962: 468).

Those initial – conceptual – papers are increasingly complemented by empirical research. Han et al. (2021) show – based on qualitative work in Zhongguancun–how an EE exhibits the six properties of CAS, as suggested by Roundy et al. (2018). However, they also show how resources such as talent and finance connect EE agents in various ways, leading to the emergence of several sub-ecosystems. Building on this reasoning, we argue that understanding an EE's evolution requires considering its multilayered network nature. Thus, this article proposes conceptualizing an EE as a multilayered CAS, extending the conceptual work of Roundy et al. (2018).

In addition, networks and connectedness are major research topics within the EE literature (Wurth et al., 2021, 2023; Fernandes and Ferreira, 2021). This is understandable; social networks are intrinsic to EE, as they are complex interdependencies and relationships that generate system-level outcomes (Acs et al. 2017; Fernandes and Ferreira, 2021; Spigel, 2017; Spigel and Harrison, 2018; Stam, 2015; Xu et al., 2023). Adner (2017) defines EE as structure. Network theory enables a detailed understanding of the multiple and complex interactions among the multiple actors that make up networks (Carter et al., 2015). However, while work on EE and networks is increasing (Fernandes and Ferreira, 2022), so far the multilayered structure has not been taken into consideration. In fact, Wurth et al. (2022) propose one exemplary research question: "How can we model EEs as multilayer networks and what are the relevant layers?" (p. 755). Several empirical examples show potential subb-systems within an established EE that can be understood as multilayer networks whose interaction generates co-evolutionary processes of the entire EE: we already mentioned Han et al. (2021), who show how the circulation of different resources within an EE generate distinguishable networks among EE's actors. Similarly, Hong and Spigel (2024) demonstrate how the role(s) of agents define different EE configurations. We thus combine these insights on a multilayer network structure with the conceptualization of an EE as a CAS and propose an extension of the latter, including the multilayer structure. However, before doing so, we provide an overview of CAS and multilayer networks.

2.2. Properties of Complex Adaptive Systems and application to Entrepreneurial Ecosystems

The study of complex systems is strongly rooted in advances in other areas of science, ranging from physics to anthropology (Bar-Yam, 1997; Thurner et al., 2018). Complex systems allow the study of interconnected agents (Bar-Yam, 1997), where the interaction among them and with their environment creates and strengthens a behavioral pattern to which agents must adapt or react (Carmichael et al., 2019). This process of adjustment and change varies over time and is iterative: agents' reactions lead to pattern changes; pattern changes initiate new agents' reactions, which lead to new pattern changes. Unless an asymptotic state or equilibrium is reached, complex systems evolve and develop constantly over time (Arthur, 2015). Particularly, a subset of non-equilibrium systems in which macro-level behavior emerges as a result and influences micro-level interactions exists: CAS (Levin, 2022). Thus, to understand the evolution of a complex system, it is necessary to understand the individual behavior of its agents and, most importantly, how they interact and function as a system (Carmichael and Hadzikadic, 2019).

This understanding makes it so attractive to conceptualize EE as CAS, as it allows to capture and analyze their dynamic, evolutive and interconnected nature (Han et al., 2021; Phillips and Ritala, 2019; Roundy et al., 2018). According to Roundy et al. (2018), any CAS is characterized by the following six properties: self-organization, open-but-distinct boundaries, complex components, non-linear dynamics, adaptability through dynamic interactions and sensitivity to initial conditions. EEs exhibit *self-organization* with activities and ventures emerging from diverse interactions without centralized control (Knox and Arshed, 2022; Lichtenstein, 2016). EEs arguably emerge without top-down control (Nicolis and Priggine, 1977); no single actor exerts sufficient agency or control over the other actors of the EE to direct their actions (Lichtenstein, 2016; Roundy et al., 2018).

EEs operate within *open-but-distinct boundaries*, integrating external resources while maintaining an internal identity (Phillips and Ritala, 2024; Roundy, 2018). These boundaries facilitate the exchange of resources such as technology, financing, and talent while maintaining a competitive edge, although excessive permeability can dilute advantages, and rigidity can isolate the ecosystem (Han et al., 2021; Phillips and Ritala, 2024). Both geography and EE are generally conceptualized as "an interconnected group of actors in a local *geographic* community" (Cohen, 2006, p.3) – as well as socio-cultural elements (O'Connor and Audretsch, 2022; Scheidgen and Brattstroem, 2022) define boundaries of an EE that may help differentiate insiders from outsiders. However, these boundaries are sufficiently permeable to allow the influx of external resources into them (Roundy et al. 2018).

The element of *complex components* is arguably the most direct connection between complexity theory and the EE literature. We have already noted above that one essential component of an EE is its agents; these agents are heterogeneous and diverse (Thai et al., 2023), and they interact with each and with their environment (Stam and Van de Ven, 2021). These agents exhibit heterogeneity in their attributes, such as opportunity recognition and resource availability, as well as in their interactions (Phillips and Ritala, 2019; Roundy et al., 2018; Thai et al., 2023). Despite this diversity, there are similarities that allow for the classification of agents into specific roles, such as entrepreneurs, investors, emerging and established enterprises, educational institutions, and knowledge generators (Roundy et al., 2018).

Research on entrepreneurial ecosystems highlights the importance of *non-linear* dynamics inherent in the complex interactions among ecosystem components (Brown and Mason, 2017; Hant et al. 2021, Kauffman, 1996; Roundy et al., 2018). Nonlinearity means that small changes can lead to disproportionate outcomes due to the diversity and interconnectedness of agents (Carter and Pezeshkan, 2023; Hant et al., 2019; Roundy et al., 2018). EE performance involves positive and negative feedback loops among components (McKelvey, 2004). Feedback loops contribute to self-reinforcing behaviors; particularly positive feedbacks amplify and lead to indefinite increases or decreases in system behaviors (Cilliers, 1998; Roundy et al., 2018).

These non-linear interactions not only generate complexity but also *adaptability*, that is, the system's ability to adjust to internal and external changes through continuous interactions among agents (Han et al., 2021; Roundy et al., 2018). When agents respond to disturbances or injections of new resources (Han et al., 2021) or small changes of behavior or interactions among actors (Arthur, 2015), the network evolves autonomously (Arthur, 2015; Han et al., 2021; Roundy et al., 2018). System-level adaptability is generated at a lower level (Seo and Creed, 2002).

Sensitivity to initial conditions in entrepreneurial ecosystems means that minor changes at the beginning can lead to significant, unexpected effects later (Han et al., 2021; Roundy et al., 2018). This can create path dependency, where historical experiences shape future trajectories, as seen in Silicon Valley (Kenney and von Burg, 1999). Initial conditions related to the diversity of initial components influence the diversity and future state of the ecosystem (Han et al., 2021). This sensitivity to initial conditions can engender substantial disparities in outcomes across regions, particularly when amplified by positive feedback loops within initially small, competitive market conditions (Akioide, 2023).

2.3. Complex Adaptive Systems as Multilayer Networks

Although conceptualizations of EE as CAS have not included a multilayer characteristic, we have pointed out earlier that for complexity theory, this is not new (Thurner et al., 2018). A multilayer network is a structure composed of several layers of interactions between nodes or agents (Bocalletti et al., 2014). Agents' properties, specified by state variables such as financial capital in the case of a firm, vary over time (Thurner et al., 2018). Each layer represents a specific set of interactions among the same nodes in the network (Bocalletti et al., 2014), which can be individuals or institutions (Thurner et al., 2018). These interactions are dynamic and shaped by ongoing exchanges between agents, with their intensity being influenced by the quantity of exchanged objects (Boccaletti et al., 2014; Thurner et al., 2018). Coevolution refers to the simultaneous interaction of the different layers in the network (Boccaletti et al., 2014; Thurner et al., 2018) (as illustrated in Fig. 1).

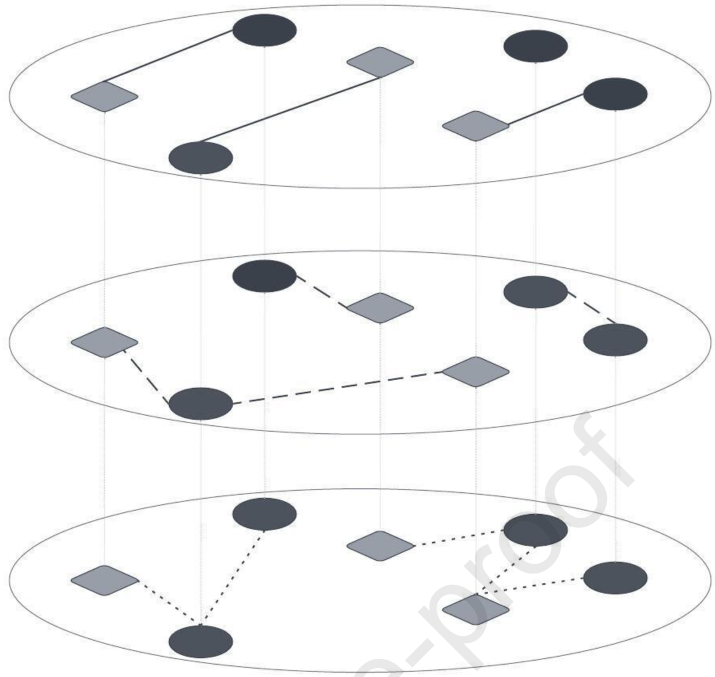

Fig. 1 Coevolution

Thurner et al. (2018) define an agent's local environment as the set of neighbors who interact with her in the network, typically determining the future value of that agent's state variable. In addition, the state variable of each agent (partially) determines the existence and intensity of future interactions. Taking these elements into account, co-evolution can be expressed by the following statements:

- The topology and intensity of multilayer network interactions determine the future value of each agent's state variable.
- Agent state variables determine the future topology value and intensity of each multilayer network interaction.

Therefore, studying a particularly complex system involves identifying and describing the coevolution between its agents and interactions, based on which the evolution of the system can be represented. In particular, co-evolution generates behavioral patterns that can be understood by employing metrics of multilayer networks. These metrics allow, for example, the classification of agents according to their centrality, the identification of a correlation between layers, and the evaluation of the clustering level between agents (Bianconi, 2018; Boccaletti et al., 2014; De Domenico et al., 2015). Table 3 presents some of these metrics that are promising to describe the structural changes of a multilayer network such as an entrepreneurial ecosystem.

Table 3. Metrics of multilayer networks

Metrics	Definition	Contribution
Average Degree	Refers to the mean number of connections per node across multiple layers of the network.	Bianconi (2018)
Mediation	Indicates the mediating role of interactions that an agent has on a layer α, between two layers β and γ.	Donges et al. (2011)
Eigenvector	Captures the centrality of the agents, taking into account the influence of the centrality they have in other layers.	Bianconi (2018)
Global Clustering Coefficient	Represents the average proportion of possible triangles that exist among nodes, considering all layers of the network. Measures how cohesive the network structure is across its various layers.	Battiston et al. (2014)
Modularity	Measures the density of edges within network communities compared to a random distribution, identifying cohesive groups more connected internally than with the rest of the network.	Boccaletti et al. (2014)
Average shortest-path length	Represents the minimum average distance between all pairs of nodes, considering all types of interactions present, and reflects the global connectivity efficiency of the network	Bianconi (2018)
Pearson Correlation	Evaluates the degree correlations between two layers.	Boccaletti et al. (2014)

While CAS can be represented as multilayer networks, addressing their dynamics necessitates combining this approach with other methods capable of capturing the emergent and nonlinear nature of these systems (Najmaei, 2016; Roundy et al., 2018). In this context, agent-based models (ABMs) (Bonabeau, 2002; Burk et al., 2007; Snijders et al., 2010) and exponential random graph models (ERGMs) (Lusher et al., 2012; Wang et al., 2013) are two complementary methodologies for studying multilayer networks (Bianconi, 2018; Snijders and Bosker, 1999; Wang et al., 2013).

ABMs simulate the behavior of autonomous individuals, known as agents, who interact within a defined environment (Bonabeau, 2002). Each agent follows a set of simple rules, and through these local interactions, emergent macro-level behaviors can be observed (Bonabeau, 2002). Additionally, ABMs facilitate the modeling of dynamic networks, where nodes represent social agents and connections represent relationships (Snijders et al., 2010). These models assume that the network evolves as an agent-driven process, considering both the effects on the current network structure and the characteristics of the agents (Burk et al., 2007; Snijders et al., 2010).

Conversely, ERGMs provide a statistical framework for analyzing social networks, allowing the modeling of various interaction structures among system components (Lusher et al., 2012; Wang et al., 2013). These models are useful for examining how different types of networks interact and how these interactions influence the structure of each network (Lusher et al., 2012). The primary difference lies in the fact that ABMs focus more on individual agent behavior, whereas ERGMs emphasize network dynamics as a whole (Lusher et al., 2012).

Combining these methodologies with the multilayer network approach p.e. (Snijders and Bosker, 1999; Wang et al., 2013) is valuable for studying complex social systems, such as entrepreneurial ecosystems, as it enables the analysis of both individual behavior dynamics and network structures with various types of interactions.

3. Entrepreneurial Ecosystem as a Multilayer Network

3.1. Structure of the Entrepreneurial Ecosystem

As it is essential for this paper to characterize the relationships between the components of an EE and thus to classify them, we propose conceptualizing them into three categories: agents, resources and contextual factors (Table 4).

Agents in an EE manage a spectrum of resources (Han et al., 2021; Shi and Shi, 2022), including financial assets, human capital, knowledge, and business assistance (Feld, 2012; Spigel and Harrison, 2018). Their primary objective is to leverage these resources effectively, ultimately contributing to the development of services and products (Romer, 1990; Stam and van de Ven, 2019). These resources, services, and products flow among agents within the EE (Han et al., 2021; Spigel and Harrison, 2018). In complex systems, most interactions are established by a process between agents (Thurner et al., 2018). In this context, the flows of resources, services, and products are considered interactions among EE agents, and the strength of these interactions correlates with the quantity exchanged. The specific nature of these interactions within an EE is determined by the availability of these resources or other relevant types.

Additionally, both the characteristics of agents and interactions are influenced by contextual factors present in the EE location, which represent a structure of incentives or obstacles that can either favor or hinder the development of entrepreneurship (Audretsch et al., 2014; North, 1994; Stam, 2015). These contextual factors encompass formal and informal institutions, along with physical infrastructure (Stam and Van Ven, 2019). Institutions are constraints designed by human beings to structure human interaction

(North, 1994). In turn, physical infrastructures are the fundamental facilities, structures, and systems in a region that facilitate its economy (Bennett, 2019).

Table 4. Elements of the entrepreneurial ecosystem

Agents	**Description**
New and existing ventures	It refers to the businesses of entrepreneurs, and it covers start-ups and growing companies. They are the source of the generation of new products and services. They are considered a fundamental piece of the ecosystem (Bengtsson and Edquist, 2022; Brown and Mason, 2017; Feld, 2012; Stam, 2015).
Incumbent Firms	They significantly contribute to job creation (Kuratko and Audretsch, 2022), acting as attractors of talent, provide technical and managerial training to employees, and are a source of new ventures since many employees leave to start their businesses (Mason and Brown, 2014). They are key for knowledge spillover in the region (Bhawe and Zahra, 2019), contribute resources for new companies, and create programs to encourage the creation and growth of entrepreneurial enterprises (Brown et al., 2019; Mason and Brown, 2014).
Investors	It refers to organizations or undertakings with investment capital. The offer and accessibility of financing for new and young firms are key conditions for their growth and survival (Haider Alvi and Ulrich, 2023; Stam and van de Ven, 2021). In addition, they support ventures with advice and mentoring (Feld, 2012).
Universities	They attract human capital (researchers and students) and research projects, commercialize know-how, create talents, generate spillovers of knowledge, and transfer technology to other agents (Erina et al., 2017; Feld, 2012; Gachanja, 2023; Spigel, 2017; Stam, 2015).
Incubators/accelerator s	They involve programs that help entrepreneurs incubate their business idea or accelerate their entry into the market. They attract founders to develop their ideas over some time. Incubators facilitate technical skills, market, and product knowledge, and develop an understanding of structures, strategies, and organizational systems appropriate for companies (Sheriff and Muffatto, 2018). Accelerators act as investment facilitators, interacting as intermediaries between ventures and investors. They also help in the creation of work teams, the development of ideas, and the orientation of new ventures, from the idea to the launch of the product (Mason and Brown, 2014; Sheriff and Muffatto, 2018).
Support firms	They include companies and organizations that offer supplementary assistance to ventures in various domains, including legal, accounting, marketing, management consulting, and personal recruitment (Mason and Brown, 2014; Sheriff and Muffatto, 2018; Spigel, 2017,). Their provision and availability play a crucial role in lowering entry barriers and expediting the creation of new value (Stam and van de Ven, 2019).
Resources, Products, and Services	**Description**
Financial Capital	Retained earnings are generated by agents or funds provided by investors to EE agents, which are used for the purchase of resources and products (Nicotra et al., 2018; Stam and van de Ven, 2019).
Human Capital	This includes intangibles such as education and experience (Spigel, 2017; Stam and van de Ven, 2019).
Knowledge Capital	Refers to the specific knowledge available from agents (e.g. scientific and technological

	knowledge, market knowledge, products and services, investment knowledge, management, and administration) (Feld, 2012; Mason and Brown, 2014; Stam, 2015).
Social Capital	It indicates the behavioral assets of relationships and the extent to which members consider the needs and goals of others, including aspects such as members' trust, norms, obligations, and expectations (Theodoraki et al., 2018).
Business Assistance	Refer to the assistence that support firms provide to other agents within the EE (Mason and Brown, 2014;Stam and van de Ven, 2019).
Products and Services	It concerns the creation and introduction of new products and services to the market (Romer, 1990; Stam and van de Ven, 2019), developed by both ventures and incumbent firms. These products and services can be either final (targeting end consumers) or intermediate (utilized by other agents of the EE as supplies for their own products and services).

Contextual Factors	**Description**
Formal institutions	They represent the regulatory framework of the region which encourages entrepreneurship, either through direct funds or the elimination of barriers to the creation of new companies (North, 1994; Spigel, 2017; Stam and van de Ven, 2019).
Informal institutions	It refers to the culture of entrepreneurship and reflects the degree to which entrepreneurship is valued in society (Fritsch and Wyrwich, 2014; North, 1994; Stam, 2015). It includes cultural attitudes that support and normalize risk-taking, innovation, sharing experiences, and knowledge (Feld, 2012; Mason and Brown, 2014; Spigel, 2017).
Physical infrastructure	Availability of office space, telecommunications facilities, and transport infrastructure that favor interaction between agents, the creation and growth of firms (Neck et al., 2004; Spigel, 2017; Stam and van de Ven, 2019).

The author's own elaboration is based on literature on EE. Consequently, the structure of the EE can be depicted as a multilayer network framework, resulting in the following proposition.

Proposition 4.1. *The structure of the entrepreneurial ecosystem as a multilayer network consists of the following:*

a) Agents such as ventures, investors, universities, established firms, incubators, accelerators, and governmental institutions, each with their distinct characteristics.

b) These agents interact across different layers, with each layer representing a type of resource, product, or service exchanged among them. This conceptualization identifies six types: financial, human capital, social capital, knowledge, services, and products.

c) The characteristics of agents and interactions are influenced by contextual factors present in the ecosystem.

Fig. 2 presents a schematic representation of the entrepreneurial ecosystem at a given moment in time.

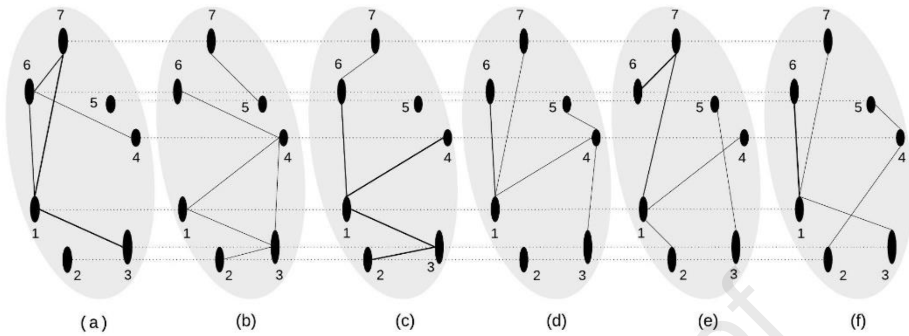

Fig. 2 Entrepreneurial ecosystem

3.2. Coevolution in the Entrepreneurial Ecosystem

Coevolution in complex adaptive systems involves an interactive dynamic between network interactions and individual agent characteristics, where both elements undergo constant changes and mutually influence each other (Arthur, 2015; Bonabeau, 2002; Miller and Page, 2007; Snijders et al., 2010; Thurner et al., 2018). On the one hand, modifications in the network, such as the creation or removal of connections between agents, can impact the individual characteristics of agents (Bonabeau, 2002; Snijders et al., 2010). On the other hand, variations in agent characteristics can influence the dynamics of interactions within the network (Bonabeau, 2002; Snijders et al., 2010). For instance, the emergence of a startup with an innovative product stimulates the formation of new interactions with investors and supports companies, universities, and other agents within the entrepreneurial ecosystem. Simultaneously, the termination of financial interactions between investors and other startups may result in the bankruptcy of the latter. This alteration in the startups' characteristics likely leads to the cessation of all interactions these startups had with other agents in the entrepreneurial ecosystem.

This bidirectional interaction drives a continuous process of adaptation and evolution within the ecosystem (Han et al., 2021; Roundy et al., 2018), where both the network and the agents transform in response to themselves and those of the other component (Nowak et al., 2017; Snijders et al., 2010; Thurner et al., 2018). Therefore, the co-evolutionary process is expressed through the following proposition.

Proposition 4.2. *Coevolution of Agent Characteristics and Interactions:*

1) The characteristics of agents at future time (t+1) are determined as a function of the characteristics of agents and their interactions at the current time.

$$Y_i(t+1) \sim F\left(R_{ij}^{\alpha}(t), Y_i(t)\right) \quad (1)$$

2) The interactions of resources, products, and services at future time (t+1) are defined as a function of the characteristics of agents and their interactions at the current time.

$$R_{ij}^{\alpha}(t+1) \sim G\left(R_{ij}^{\alpha}(t), Y_i(t)\right) \quad (2)$$

The first equation signifies that the characteristics of agent (i) at time (t+1) are modeled as a function F dependent on the current characteristics of (i) and the state of its present network, $R_{ij}^{\alpha}(t)$, (Thurner et al., 2018). The second equation illustrates how the multiple interactions, $R_{ij}^{\alpha}(t+1)$, of agent (i) with other agents (j) evolve over time as a function G dependent on the same inputs, the agent's characteristics, and its present network (Thurner et al., 2018).

These functions (F) and (G) can be deterministic or stochastic (Thurner et al., 2018), serving as the evolutionary rules of the ecosystem. They can be determined analytically or algorithmically, implying that they can be expressed as mathematical equations or as update rules (Thurner et al., 2018). The definition of functions (F) and (G)

depends on the specific study undertaken on the entrepreneurial ecosystem, and these can be derived from previous research or new studies. In the following section, we illustrate coevolution with a specific example.

Consequently, the evolution of the entrepreneurial ecosystem (EE) can be understood by mapping the coevolution of agents (through their characteristic *Y*) and multiple interactions (*R*), which reflects the evolution of the network's structure. This concept is articulated in a third proposition:

Proposition 4.3. *The coevolution of agents and their interactions, or the progression of the multilayer network, signifies the evolution of the EE.*

Through metrics of the multilayer network, patterns can be identified within an entrepreneurial ecosystem. Visualization and analysis of these metrics reveal behaviors associated with the development of entrepreneurial activities, extending from the birth and growth of new firms to the emergence of a collaborative culture. Fig. 3 summarizes the propositions presented in this analysis.

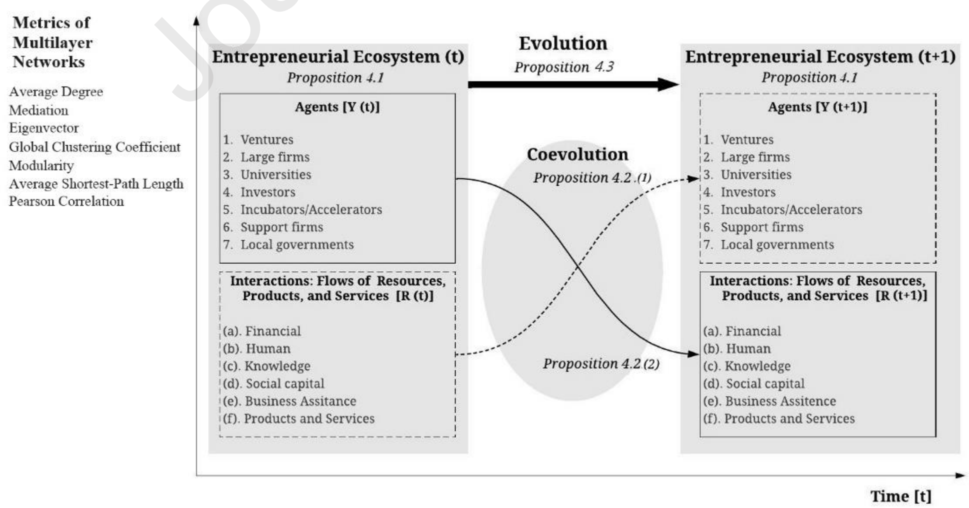

Fig. 3 The propositions

3.3. Illustrating the Conceptual Model in the Financial Support Network

In the following, we illustrate - based on one specific example - how our conceptual model enables a better understanding of the EE's co-evolution. Van Rijnsoever (2020) has argued that an EE consists of different subsystems or networks. This author – based on the prior work by Clarysse et al. (2014) – states three of them: knowledge, the business, and the financial support network (FSN). In this example, we focus on the latter, as FSNs are argued to bridge the other two networks (Clarysse et al., 2014; Powell et al., 2012). The FSN is a network of startups, venture capitalists, banks, public funders, and business angels who provide access not only to much-needed financial funds (Van Rijnsoever, 2020) but also to business knowledge (i.e., intellectual capital) and social capital through market connections for each actor (Clarysse et al., 2014; van Rijnsoever, 2020). However, if the FSN remains underdeveloped, it acts as a barrier to the development of an EE, as the financial funds necessary to bring innovation to the market will not flow (Nelson, 2014). Thus, understanding the emergence of this network is vital not only to better understand the evolution of an EE but also because such knowledge enables public and private agents to foster its effective development.

We analyzed the evolution of the FSN by constructing an artificial FSN as a multilayer network (Fig. 4) implementing it in an agent-based model using the NetLogo software (Wilensky, 1999), following the recommendations of Bonabeau (2002), Snijders et al., (2010) and Wilensky (1999). The structure of our FSN comprises 100 startups and one VC, where these agents interact across two layers: a social layer and a financial layer. In this multilayer network, circular nodes represent startups, with their characteristic (*Y*) indicating their financing status, either 'funded' -meaning they have received financial resources from the VC, denoted by circular nodes in green- or 'unfunded', indicated by circular nodes in black. The hexagonal green node represents the venture capitalist. Black links denote social interactions among startups, indicating a flow of knowledge about venture capital funds or effective business models, all framed within the social layer(s). Conversely, green links represent financial interactions, showing the flow of funds from the VC to some startups located within the financial layer (f). The significance of the social layer lies in its potential as an intermediary; that is, access to financing for startups can be facilitated through other startups that are already backed by the VC (van Rijnsoever, 2020).

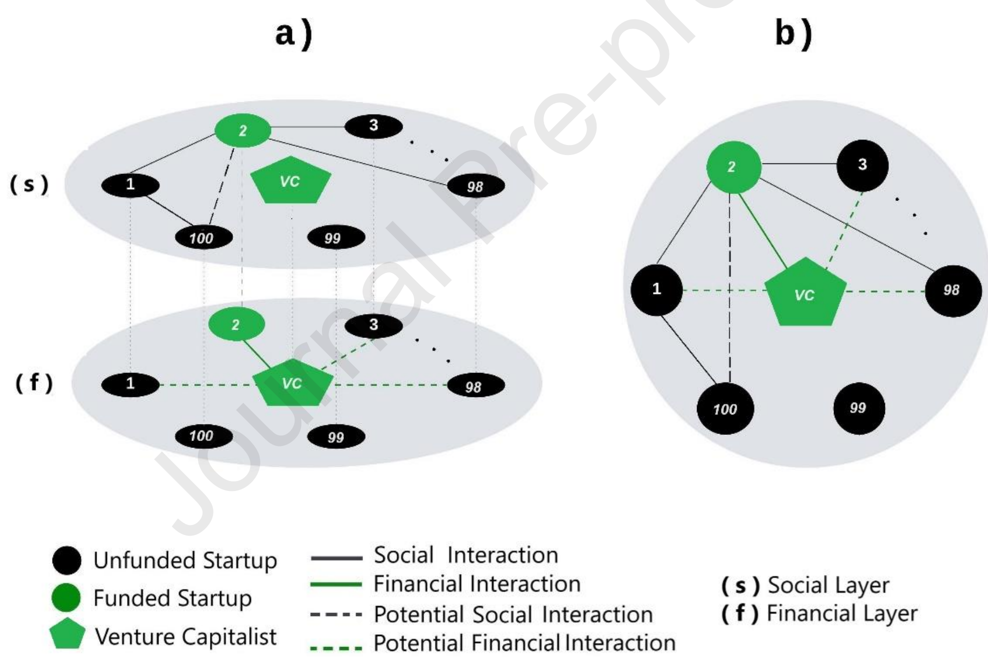

Fig.4 The evolution of the FSN

The interactions between startups and VC establish an interdependence between the two layers: social and financial. This interdependence can be described through the coevolution of the financing status of startups (whether funded or unfunded) and the social environment in which they operate. Clarifying this interdependence requires delineating how the financing status is influenced by the state of the network (denoted as function F in

Equation 1), as well as how the network itself is influenced by the financing status (denoted as function G in Equation 2):

a) The future state of startups is influenced by the social environment.

In this context, the social environment is defined as the interactions experienced by each startup in the social layer of the FSN. If a startup remains without financing but is connected to an intermediary (a startup that has already obtained financing) in the social environment, there is a higher chance of securing financial resources in the future (Clercq et al., 2006). The underlying reason is that the intermediary can serve as a bridge, facilitating the connection with the VC in the financial layer (Clercq et al., 2006). This effect is implemented as follows: If a startup is linked in the social layer to a funded startup, then with a probability of 0.1[1], it will connect to the VC in the financial layer and update its financing status to 'funded'.

b) The future state of links in the network is influenced by the state of startups.

After a startup has secured funding, its financing status is adjusted from "unfunded" to "funded". This alteration in the financial layer is not an isolated process; it has implications in the social layer, influencing the behavior of other startups. The funded startup shares insights into its funding experience within its social network, leading knowledge to spread to other startups connected to them, some of which may then connect with the funded startup to gain access to the VC. We implement this effect in the model as follows: A random startup located within two social links of the funded startup connects with a probability of 0.5[2].

This coevolution within the FSN influences its development and evolution. To analyze this dynamic in the FSN, we conducted simulations in our model over a period of

[1, 2] These probabilities serve solely as illustrative examples

10 years, where each time step corresponds to one week. Therefore, our model runs for 500 time steps. After each run, we record the following output indicators: the number of funded startups, the number of new interactions, the global clustering coefficient, the modularity coefficient, and the average shortest path. We run the model 100 times, and for our results, we present the mean values of these indicators.

In Figs. 5, 6, and 7, we outline the results. Fig. 5 presents the evolution of network modularity associated with funded and unfunded startups. Initially, modularity increases, reaching a peak, which suggests a low level of community structure among both funded and unfunded startup communities. However, as the network evolves, these communities become more interconnected, as indicated by the decrease in modularity. Moreover, this decrease in modularity is accompanied by an increase in the number of funded startups, suggesting that these funded entities contribute to the growth of the FSN network.

Fig. 6 illustrates the evolution of the global clustering coefficient. It is apparent that as the clustering coefficient increases, so does the number of funded startups, similar to the previous figure, suggesting that funded startups promote network growth by enhancing connections among startups and with venture capitalists. Fig. 7 indicates the evolution of the average shortest path within the FSN. As the network evolves, the average path length decreases (i.e., the distance between any two startups becomes shorter), accompanied by an increase in startup financing.

Altogether, these metrics reflect a network evolving toward a more cohesive and collaborative structure, facilitated by the injection of capital into certain startups and the emergence of new social and financial interactions.

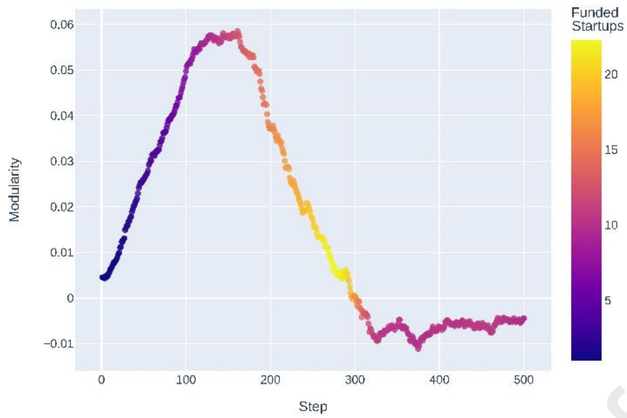

Fig. 5 The evolution of network modularity associated with funded and unfunded startups

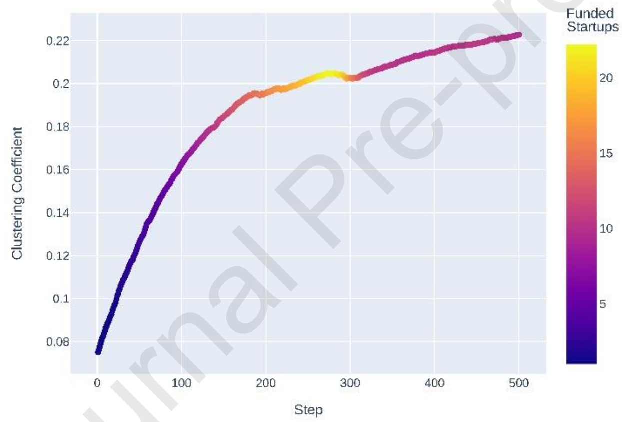

Fig. 6 The evolution of the global clustering coefficient

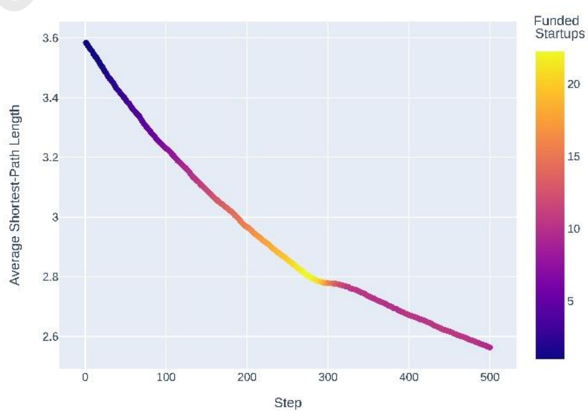

Fig. 7 The evolution of the average shortest path within the FSN

4. Discussion and Conclusion

Entrepreneurial ecosystems represent a valuable framework for analyzing entrepreneurial activity in a region and the economic growth associated with it. The current focus on the structure and evolution of an EE revolves around understanding how agents affect each other and stimulate the development of entrepreneurship and how the birth or extinction of firms drives or decreases the growth of EE. However, the entrepreneurial ecosystem concept does not have a solid theoretical foundation for these topics, which can be strengthened from the perspective of other areas of science. This article contributes to this literature by using complexity theory as the theoretical foundation. As such, we first present a theoretical basis consisting of concepts specific to EE (structure and co-evolution) and foundations of the theory of complex systems. Thus, the need to deepen the co-evolutionary behavior between the agents and interactions of the EE emerges, since it has not been specified in previous work, and its study is key to understanding the evolution of the ecosystem. Second, a conceptual model of EE based on complex systems has been introduced, where agents and interactions have been identified and specified from the previous literature, making it possible to explain the ecosystem as a multilayer network, where each layer represents a different type of interaction. The advantage of this representation is that it allows studying the co-evolution between agents and interactions, and therefore the evolution of the ecosystem, through the intrinsic properties of the network.

The validity of any framework used for informing practice should be considered provisional until sufficient evidence exists to justify its use (Ifie et al., 2023). While our proposed conceptual model outlines several network properties that can be used to analyze the structure and evolution of EEs, it is essential to conduct empirical research to test the effectiveness of our framework and gain further insights into the antecedents and outcomes of the entrepreneurial ecosystem. In addition, researchers can employ our conceptual framework to construct artificial models of an EE and simulate its dynamics. Such simulations can help identify areas for potential improvements and offer a deeper understanding of the behavior of the EE. To apply the model effectively, it is crucial, in any scenario, to define the agents (and their characteristic or state variable to be studied), interactions (and their phases or dynamics), and contextual factors to be analyzed.

However, it is important to acknowledge several limitations in our model, as its intrinsic simplifications may limit its ability to fully represent the complexity and dynamics present in an entrepreneurial ecosystem. First, the classification of ecosystem components can vary from one context to another, making its applicability dependent on the region where the ecosystem is embedded. Second, by focusing on interactions such as exchanges of resources, services, or products, the model may overlook other important aspects, such as power structures, competition dynamics, and cooperation dynamics. Third, by focusing on coevolution, the dynamics associated with changes in agent characteristics and multiplex interactions are not deeply addressed, as they depend on the specific type of study being conducted. The construction, calibration, and validation of a multilayer network model for an entrepreneurial ecosystem requires a wide range of data on agents, resources, and contextual factors. This detailed data collection is challenging, especially due to the difficulty of accessing private or confidential information, as well as the availability of longitudinal data. Therefore, it is more practical to apply this method to a subsystem or specific study topic.

To further advance the field, we propose a comprehensive research agenda that identifies several theoretical and practical questions regarding EEs as multilayer networks, which merits future academic attention.

Explore the impact of contextual factors on EE interactions: Our model recognizes these influences but requires a detailed analysis. Future research could identify and quantify the effects of factors such as cultural norms, government policies, and physical infrastructure on agent behaviors and on the ecosystem. These factors can act as barriers or drivers for interactions and can be represented by parameters that moderate interactions. By varying these parameters, the impact on interactions within each layer of the EE can be studied. For example, understanding these effects can inform the development of public policies to boost entrepreneurship.

Analyze the impact of different types of resources and products on EE (or the EE subsystem): The proposed model identifies and characterizes six types of interactions that occur among agents in EE, defined as the flow of resources and products. Future research could focus on exploring the specific impact of each type of resource or product on EEs or how changes in the flow of one type of resource or product affect the flow of others, as well as how changes in the flow influence the production of agents (or other attributes of agents). In this case, the degree or strength of the agents in one of the layers can be taken as an input parameter, which implies that their values can be modified and how these changes affect the average degree or strength of the other layers, and the entire network can be observed.

Examine the influence of the role of agents on EE (or the EE subsystem): The model identifies several types of agents involved in EE, such as intermediaries and investors.

Future research could focus on exploring the specific roles and impacts of incubators and accelerators or other support organizations in the evolution of EEs, including how they facilitate the flow of resources and products between other agents. To assess the changes in the importance of an agent in the network or a specific layer, the evolution of the eigenvector centrality metric can be utilized. This metric captures the centrality of the agents, considering the influence they have on other layers.

Investigate the interdependence between layers in the EE (or EE subsystem): The model outlines the interdependence between layers and suggests that this process impacts the dynamics of the EE. Future research could focus on exploring how this interdependence between layers affects the development and sustainability of EEs. This interdependence can be determined by defining the degree of the agents in each layer and then calculating the Pearson correlation coefficient for each pair of layers (using the previously calculated degrees). A representative coefficient can subsequently be calculated for the case study, such as the average degree of the agents or the clustering coefficient of the entire network, to be compared with the correlation coefficient.

Exploring the Interaction Between Entrepreneurial Ecosystems. The identification of EE interconnectivity is currently needed (Xu et al., 2023). Expanding our conceptual model to represent a broader region containing two or more entrepreneurial ecosystems is essential. This approach allows for the examination of interactions both within individual ecosystems and between multiple ecosystems. By employing the modularity coefficient in this regional model, researchers can determine the level of connectivity between ecosystems and the interconnectivity within each ecosystem.

In creating a favorable environment for the development of entrepreneurial ecosystems, a systemic vision is required to recognize their complexity (Han et al., 2021;

Roundy et al., 2018). Our conceptualization, which uses complex systems viewed as multilayer networks, has significant implications for those seeking to understand the state and dynamics of EE. First, it is crucial to acknowledge the complex interactions involved in the formation, establishment, and termination of relationships between agents in the entrepreneurial ecosystem (Han et al., 2021; Wurth et al., 2021). These interactions play a fundamental role in shaping the individual characteristics of ecosystem members. Agents are not isolated within the ecosystem but are encapsulated in a social environment (Roundy et al., 2018; Wurth et al., 2021). Therefore, analyzing the state or evolution of the entrepreneurial ecosystem without considering these interactions fails to capture the systemic perspective. It is essential to adopt tools such as multilayer network theory to classify and measure the state and dynamics of interactions in entrepreneurial ecosystem research (Wurth et al., 2021).

Second, from a theoretical perspective, gaining a deeper understanding of the co-evolutionary behavior between agents and interactions (Snijders et al., 2010) within an entrepreneurial ecosystem is crucial. Policymakers and professionals should prioritize designing strategies that foster such interactions, thus supporting individual and collective development within the ecosystem. Our conceptual framework, combined with methodologies such as agent-based modeling (Bonabeau, 2002) or exponential random graph models (Wang et al., 2013), plays a crucial role in this regard by enabling simulations to explore various scenarios and identify effective approaches. For example, stakeholders involved in ecosystem development could assess the impact of a policy promoting the creation of new shared workspaces near the ecosystem on the emergence of new social relationships and resource exchanges among mentors, investors, and entrepreneurs.

Similarly, they could inquire whether reducing production tariffs for new businesses could enhance cohesion among ventures, accelerators, and investors.

Finally, this article responds to the call for a shift from the current static framework to a dynamic approach in studying EEs (Auerswald and Dani, 2017; Haarhaus et al., 2020; Roundy et al., 2018). Although complexity science theory and methodologies have been utilized to examine the dynamic patterns of EE (Carayannis et al. 2016; Han et al., 2021; Haarhaus et al., 2020; van Rijinsover, 2020), the potential of multilayer networks remains largely unexplored in this context (Wurth et al., 2021). In this context, our work represents one of the initial conceptualizations to leverage this theory to represent the complex phenomenon of EE.

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