SUSTAINABLE REGIONAL DEVELOPMENT AND COMPLEX ADAPTIVE SYSTEMS: A METHODOLOGICAL PROPOSAL THROUGH SOCIAL NETWORK ANALYSIS

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Abstract

The evolution of the main theories that have shaped Sustainable Regional Development (SRD) is traced in this paper, with the progressive incorporation of economic, social, environmental, and institutional dimensions showing how it is configured as a complex phenomenon. Based on this conceptual foundation, the study links the analysis of SRD to the Complex Adaptive Systems (CAS) framework and, within this approach, to Social Network Analysis (SNA) as a tool for modelling interactions among regional stakeholders. Finally, it introduces a correlation between the resulting regional network metrics and the Departmental Innovation Index (IDIC) indicators for Colombia's regions, offering an alternative perspective for analysing regional disparities.

Keywords: Sustainable Regional Development; Divergence, Complex Adaptive Systems, Social Network Analysis

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1. Introduction

The analysis of Sustainable Regional Development (SRD) represents one of the main challenges for the social, economic, and territorial sciences in the current context. The profound transformations of global capitalism, the growing pressure on ecosystems, and the persistent socioeconomic inequalities across regions within countries have created a scenario in which traditional theoretical frameworks have proven insufficient to understand and manage the complexities of regional development divergences (Pike et al., 2017; Rodríguez-Pose, 2013; Toro, 2007).

Over the past fifty years, theories of SRD have evolved from perspectives focused exclusively on economic growth towards multidimensional approaches that integrate social, environmental, spatial and institutional aspects (Bedrunka 2020; Sen 1990). This shift towards complexity has increased attention on the potential relationship between regional actors and SRD performance. This relationship highlights the necessity for tools that are capable of capturing non-linear, interdependent dynamics and the adaptive processes that occur within regions (Levin et al. 2013; Neely 2015).

It is evident that phenomena such as globalization, the adoption of neoliberal free-market policies, and a marked trend towards reducing the role of the state (Useche Arévalo 2002), have shaped a complex economic, political, and social scenario in Colombia. Regional development gaps highlight socioeconomic and environmental disparities. This divergence, initially measured through Gross Domestic Product (GDP), reveals that over the past forty years, three regions namely—Bogotá Region, Antioquia, and Valle del Cauca—out of Colombia's thirty-two regions, have concentrated on average 50% of the national GDP (DANE 2024).

These regional disparities, or divergences, are also reflected in social indicators. According to data from the 2024 National Quality of Life Survey (DANE 2024), the mean years of

schooling in Caribbean and Pacific municipal centers was recorded as 8.4, in comparison to 10.5 in the Bogotá Region. Coccia (2018) posits that such regional disparities can engender poverty, unemployment, social problems, income inequality, violence, and underdevelopment. These data confirm not only the persistence of economic divergences but also the economic and social polarization in Colombia over the past four decades.

It is evident that reducing divergences between regions can lead to more just and prosperous societies (Polyzos and Tsiotas 2025). The present study aims to deepen the understanding of this divergent phenomenon, as such understanding could contribute to the design of more precise and effective public policies to promote balanced and convergent regional development (Alexiadis, 2020; Mnatsakanyan et al., 2021).

In view of this economic and social scenario of divergence, an alternative approach through Complex Adaptive Systems (CAS) provides a distinctive theoretical framework to facilitate a more profound understanding of the possible causes of regional divergences in SRD. The CAS framework conceptualizes regions as open, dynamic, and relational systems, wherein interactions among agents or actors give rise to emergent and adaptive patterns (Naudé 2012). In the context of the analytical tools associated with this perspective, Social Network Analysis (SNA) is distinguished by its capacity to identify, represent, and measure relationships among actors. It has also been demonstrated that this method can be utilized to identify key structures and assess how these configurations influence regional performance (Holgado Ramos, 2016; Zhou et al., 2022).

Despite its analytical potential, the integration of SNA into the study of SRD has not received sufficient attention, and only a limited number of works can be found. For instance, within the domain of regional innovation analysis, studies have been conducted that examine the evolution of inventor networks within a German region (Cantner and Graf 2006), compare German territories to assess the role of universities and public research centers (Graf and Henning 2009), and measure scientific collaboration across European regions to determine its relationship with SRD (Hoekman et al., 2010). In the Latin American context, there are only two cases: one studying patent networks across cities or regions in Chile (Pinto et al., 2019) and another in Brazil (Mejdalani et al., 2021).

Taken together, these studies highlight how the structure of relationships among different actors—identifying who collaborates with whom and how close certain actors are to others—reveals the coordinating potential of specific agents. In this sense, network structures may be linked to improved outcomes in economic development, technological advancement, scientific productivity, and regional innovation, while also integrating social and environmental results. However, it is important to note that none of these works has connected regional network metrics derived from SNA with composite socioeconomic indicators such as Colombia's Departmental Competitiveness Index (IDIC) (DNP, 2020). The integration proposed here, as a strategy for comparison and analysis of regional development divergences, identifies an alternative opportunity to advance an innovative methodological framework that systematically links and correlates SNA metrics (e.g., density, centrality, modularity) (Carrington et al., 2005) across regions with economic, sustainability, competitiveness, and social indicators such as the IDIC for the same territories.

Based on the above, this paper develops the proposed linkage and association of concepts in three stages. First, a historical and conceptual review of SRD is undertaken, tracing its foundations after World War II up to its interpretation as a complex and multidimensional framework. Second, a bibliographic review examines the main tools derived from CAS applied to the analysis of SRD, including neural networks, fuzzy logic, agent-based simulation, system dynamics, and SNA. Finally, the third stage presents a methodological proposal to correlate SNA metrics—obtained from modeling the networks of different regions—with SRD performance, using economic, innovation, social, and environmental indicators. The idea behind this methodological proposal is that it is based on solid theory, can be repeated and used in other situations with little alteration, and provides a different way of looking at the reasons for differences in SRD between regions.

2. Theoretical Framework

One of the objectives of tracing the origins and main theoretical advances in regional economic science—without attempting to encompass all currents and schools of thought—is

to understand the most relevant principles that have contributed to the theoretical and conceptual evolution of Sustainable Regional Development (SRD) and that have enabled it to be regarded as a complex and multidimensional phenomenon. This review outlines how different theoretical, conceptual, and methodological approaches have shaped the foundations of this field while simultaneously identifying the factors that have led SRD to be conceived as a complex phenomenon. The inclusion of variables beyond Gross Domestic Product (GDP) over time serves to further illustrate the inherent complexity of the phenomenon under investigation. The addition of social, environmental, institutional and governance indicators has resulted in a more comprehensive understanding of regional development, thereby reflecting its complex and interdependent nature.

2.1. Origins and Foundations of Regional Thought (1950–1970)

According to Polese (1999), modern regional development reached a turning point after World War II, when economic reconstruction and the consolidation of global capitalism gave rise to analytical frameworks still dominated by neoclassical theory—the basis of the growth and economic development propositions advanced by Perroux (1950) and Boudeville (1965). This convergent neoclassical influence led many authors to assert, a priori, that inequality between regions was transitory and would be corrected by market forces. However, this assumption was later challenged by the persistence and widening of inequalities in development levels, not only across countries but also among regions (Moncayo Jiménez 2003; Capello 2006).

In this context, (Knox and Myrdal (1960) introduced the theory of uneven development, which posited that growth is naturally divergent (Dhimitri et al., 2015). In Latin America, Carrillo Arronte (1978) warned against importing foreign models that disregarded the Latin American context—characterized by "caciquismo" (concentration of power) and social heterogeneity—arguing that such models were both risky and insufficient for understanding these realities. From its origins, therefore, regional thought has combined theoretical tensions and contextual diversity, elements that later opened the door to more flexible and adaptable approaches. The body of the text consists of different sections which describe the content of the article (for example: Method, Findings, Analysis, Discussion, etc.).

2.2. From Endogenous Growth to the Territorial Dimension (1980–1990)

During the 1980s, theories of endogenous growth and "bottom-up" development gained prominence. These approaches emphasized the internal potential of regions to generate employment and productivity through the strategic use of their own resources (Bogdański 2012). In this regard, Romer (1986) and Lucas (1988) refined theoretical advances in economic development, orienting them toward endogenous aspects and consolidating the idea that technological change and investment in human capital are key factors for development.

Porter (1990) formulated the theory of regional competitive advantage, highlighting the role of clusters and innovation as pillars of territorial competitiveness. Meanwhile, Krugman (1991) introduced a renewed spatial perspective with the New Economic Geography, and Stiglitz (2002) contributed insights into how information asymmetries affect regional opportunities. This shift toward endogenous and territorial perspectives paved the way for understanding regions as interconnected systems, emphasizing the role of social capital in regional development (Papadaskalopoulos and Nikolopoulos 2018). In doing so, it anticipated, perhaps, the integration into the language of CAS, which would later become central to the analysis of SRD.

2.3. The Emergence of the Sustainability and Institutional Approach (1987–2010)

The publication of the Brundtland Report (1987) marked the formal introduction of sustainability into the regional development agenda, defining Sustainable Development as the ability to meet present needs without compromising those of future generations. This perspective integrated economic, social, and environmental dimensions into a unified analytical framework (Moncayo Jiménez 2003). Complementarily, Ostrom (1990) demonstrated that local communities can manage natural resources more efficiently than the

state, while Acemoglu and Robinson (2012) emphasized the importance of inclusive institutions in preventing the concentration of power. Meadowcroft (2007) stressed that SRD requires not only economic performance but also strong institutional frameworks, participatory processes, and constant social engagement. Meanwhile, Piketty (2015) warned of the tendency for divergences to persist in the absence of redistributive mechanisms guided by the state.

In this sense, the incorporation of sustainability, institutional frameworks, and social dimensions broadened the scope of regional development analysis, introducing a complexity that demands methodologies capable of integrating multiple dimensions, variables, and actors.

2.4. Endogenous and Exogenous Factors: A Persistent Debate

According to Salguero Cubies (2006), the debate on SRD largely revolves around the weight of endogenous versus exogenous factors. The former—such as local resources, capacities, and institutions—fall under a degree of regional control (Millar 2014; Šabić and Vujadinović 2017). In contrast, exogenous factors depend on external forces such as global trends, national policies, or international investments (Merchand, 2007; Trippl et al., 2018).

Complementarily, Bogdański (2012) and Nijkamp and Abreu (2020) note that most contemporary studies recognize the interaction between these two dimensions. Additionally, Stimson et al. (2011) call for research that integrates these scales and approaches. Cooke et al. (1997) further argue that regional innovation systems serve as spaces where such interactions generate unique development trajectories, with public policies exerting a significant regulatory effect on regional divergences (Panjawa et al., 2018). This debate on internal and external factors reinforces the idea that regional development is neither linear nor predictable but rather an emergent process with multiple interdependencies.

2.5. Evolution in the Measurement of SRD

As early as the 1970s, Seers (1972) warned that GDP alone was insufficient to measure development, proposing instead the inclusion of variables such as poverty, unemployment, and inequality. Sen (1990) advanced this line of thought with the Human Development Index (HDI), which incorporated dimensions of health, education, and income. Boutros Boutros-Ghali (1995) identified five pillars for regional development: peace, economy, environment, justice, and democracy. Gualdrón Guerrero (2011) provided an insightful analysis for Colombia, comparing economic growth measured through departmental GDP with development measured by the HDI.

More recently, Bedrunka (2020) and Jackson et al. (2019) have proposed indicators integrating economic, environmental, spatial, and innovation dimensions. For example, Rodríguez Miranda et al. (2021) developed a system of 24 indicators distributed across eight dimensions, applicable to Latin American contexts. Regional indicators that go beyond GDP thus open new possibilities for understanding regions more comprehensively Tektas et al. (2016). Similarly, Ladias et al. (2023) emphasize that the adoption of regional economic indicators could help identify and address regional disparities; as well as guide public policy priorities (Fedotova, Zhiglyaeva, and Stolyarova 2018)—one of the main challenges facing developing countries Pourmohammadi et al. (2014). In this sense, Pike et al. (2017) synthesize this evolution, highlighting that regional development is an adaptive process, rooted in territory, and shaped by multiple interactions. This evolution in measurement reflects a growing recognition of the complexity of SRD, paving the way for analytical frameworks capable of identifying its nonlinear and interdependent dynamics.

2.6. Synthesis

The historical and conceptual trajectory of SRD demonstrates its transformation from an essentially economic framework to a multidimensional and dynamic vision, thereby becoming a complex phenomenon (Boschma and Martin 2010). This trajectory, marked by the interaction of endogenous and exogenous factors, the incorporation of economic, social, and environmental dimensions, and the adoption of comprehensive measurement systems, underscores the need for approaches capable of integrating these interdependencies and constant adaptations to new realities in order to understand divergences in regional

development (Martin and Sunley 2007). In this regard, the CAS paradigm and tools such as SNA emerge as suitable approaches to better comprehend and explain, from a different perspective, the persistence—or perhaps the overcoming—of divergences in regional development.

3. Analysis of Tools for the Study of SRD from the Perspective of Complex Adaptive Systems

This study adopts a qualitative and exploratory approach aimed at articulating the concepts of Sustainable Regional Development (SRD) with tools derived from Complex Adaptive Systems (CAS), among which the following stand out: Neural Networks, Fuzzy Logic, Agent-Based Simulation, System Dynamics, and Social Network Analysis. Based on the assumption that combining SRD concepts with these tools generates complex and multidimensional constructs, an inductive and interpretive approach was chosen, grounded in a review of academic literature and theoretical content analysis (Hernández Sampieri, Roberto; Baptista Lucio and Fernández Collado 2016). This approach is particularly useful for exploring fields that are either poorly systematized in combination or still emerging, with the aim of identifying initial patterns and building theoretical hypotheses.

The bibliographic search was carried out in databases such as Scopus, Web of Science, and Google Scholar, using the following search equations:

Sustainable regional development AND *Imbalances* OR *Disparities* AND *Neural Networks;*

Sustainable regional development AND *Imbalances* OR *Disparities* AND *Fuzzy Logic;*

Sustainable regional development AND *Imbalances* OR *Disparities* AND *Agent-Based Model;*

Sustainable regional development AND *Imbalances* OR *Disparities* AND *Systems Dynamics;*

Sustainable regional development AND *Imbalances* OR *Disparities* AND *Social Network Analysis*.

The inclusion criteria were publications between 2010 and 2024 that addressed the central concepts. The search was refined to topics related to economics, development, geography, regional science, and public administration. The selected literature was examined through qualitative content analysis following the methodologies described by Mayring (2004) and Schreier (2024). Key thematic categories such as territoriality, sustainability, governance, and social capital were identified; these concepts facilitated the mapping of convergences and tensions across approaches. Furthermore, the organization and coding of information were managed using an Excel matrix.

In a subsequent stage, a preliminary relational framework was developed to integrate the key concepts, following an abductive logic (Timmermans and Tavory 2012). This exercise sought to connect the principles of SRD with the foundations of CAS and their associated tools, in order to identify which tool could provide a distinctive and alternative perspective in the analysis of regional disparities.

3.1. Complex Adaptive Systems Perspective

The initial findings showed that SRD can be conceived as a CAS, where actors with heterogeneous interests, resources, and capacities interact in a non-linear manner, generating emergent and unpredictable patterns (Levin et al. 2013; Naudé 2012). According to Buchholz and Bathelt (2021), adopting a relational perspective on actors enhances the understanding of territorial differences and regional adaptation processes.

This approach aligns with transdisciplinary perspectives that integrate economics, geography, political science, and sociology (ten Broeke and Tobi 2021). Moreover, (Merchand 2007) emphasizes that tools derived from general systems theory and chaos theory overcome the limitations of traditional methodologies, offering a holistic and integrated view of SRD. Complementarily, the use of tools developed primarily outside the traditional economic field—such as those rooted in complex adaptive systems theory—has gained

credibility and importance in the modeling of socioeconomic phenomena. These models are notable for their ability to provide policymakers with comprehensive and quantitative information that supports improved decision-making (Beaussier et al., 2019).

3.2. Analytical Tools Derived from CAS

The literature review made it possible to identify studies and methodologies associated with the analysis of complex phenomena applied to SRD, including neural networks, fuzzy logic, agent-based simulation, system dynamics, and social network analysis (SNA). The tools and the total number of works found across the different databases are presented in Table 1.

Table 1. Studies identified for each tool related to SRD

Methodology	Scopus	Web of Science	Google Scholar	Total
Neural Networks	31	77	115	223
Fuzzy Logic	0	61	55	116
Agent-Based Simulation	1	12	10	23
System Dynamics	59	43	126	228
Social Network Analysis.	30	208	98	336
Total	**121**	**401**	**404**	**926**

Source: Adapted from the review of databases (Scopus, Web of Science, and Google Scholar).

From the total number of studies identified for each tool, a screening process was carried out to eliminate duplicates and to retain only those works that effectively met the criteria based on the combination of defined search terms. In this sense, the number of studies that specifically address the analysis of divergences in SRD is presented in Table 2.

Table 2. Specific Studies by Tool Related to Divergences in SRD

Methodology	Total Studies	Specific Studies
Neural Networks	223	6
Fuzzy Logic	116	10
Agent-Based Simulation	23	12
System Dynamics	228	6
Social Network Analysis.	336	7
Total	**926**	**41**

Source: Adapted from the review of databases (Scopus, Web of Science, and Google Scholar).

Based on the specific studies identified for each tool, a more detailed analysis was conducted with the aim of identifying aspects related to SRD divergences across regions. This analysis examined the methodologies employed, the sources of information, as well as the economic elements considered in these comparisons. The most relevant findings for each tool are presented below.

3.2.1. Neural Networks

Neural networks have been employed to forecast regional economic indicators such as GDP, inflation, unemployment, or HDI (Chen 2022; Churikanova and Lysenko 2021; Kuriksha 2021), thereby facilitating resource allocation and the detection of growth opportunities (Ugulava 2019). Although effective in pattern recognition (Gue et al., 2020), they present limitations in capturing interdependencies and feedback loops that characterize complex systems (Shi, James, and Guo 2004).

3.2.2. Fuzzy Logic

Fuzzy logic enables the simultaneous representation of social, economic, and environmental dimensions through membership levels, as demonstrated in the model of Andriantiatsaholiniaina et al. (2004). It has been applied to support the design of specific policies (Fedrizzi et al., 1993; Rizzo et al., 2022; Shevchenko, 2021), but its acceptance in economics remains limited due to its complexity, high computational demand, and the ambiguity of interpreting results (Díaz & Morillas, 2011; Ferrer-Comalat et al., 2021; Ratiu et al., 2009; Stojić, 2012; Trillas, 2015; Wu & Xu, 2021).

3.2.3. Agent-Based Simulation

Agent-based simulation facilitates the analysis of emergent dynamics arising from interactions among heterogeneous agents (Al-Zinati and Wenkstern 2019; Gómez Cruz 2018), integrating economic, social, environmental, and spatial dimensions (Akopov et al., 2017; Muto et al., 2020; Sebestyén & Varga, 2019). It has also been applied to the study of regional innovation systems (Ponsiglione et al., 2017; Quintero Ramirez et al., 2017). However, its validity is often context-specific and may oversimplify real-world behavior (Lippe et al. 2019; Macal 2016; Terra and Passador 2018).

3.2.4. System Dynamics

System dynamics analyzes interconnections and feedback loops under the premise that changes in one part of the system affect the whole (Martinez-Moyano 2019). Examples include models applied to territorial planning (Cheng, Li, and Zhang 2004; Lektauers 2015). Nevertheless, it faces difficulties in adequately representing the behavioral complexity of real economic systems (Ma et al., 2024; Pejic Bach et al., 2020).

3.2.5. Social Network Analysis

SNA not only captures the relational structure among actors but also facilitates the inclusion of environmental and socio-ecological (Semitiel García and Noguera Méndez 2004) dimensions in the analysis of SRD. This makes it a particularly valuable methodology for examining interdependencies and feedback processes in complex regional systems (Hu & Zhou, 2021; Reid et al., 2008; Semitiel García & Noguera Méndez, 2004). The work of Yokura et al. (2013) highlights its utility for mapping local cooperation and innovation, while Hu and Zhou (2021) applied it to analyze the influence of state financial intervention on urban structure and regional performance. More recently, Filenta and Kydros (2022,2023) have shown how network metrics allow for the evaluation of territorial inequalities.

3.2.6. Main Findings of the Review

Each tool presents distinct advantages and limitations. For example, neural networks are useful for forecasting economic indicators, yet less effective at capturing feedback loops (Shi, James, and Guo 2004). Likewise, fuzzy logic allows for representing uncertainty, but its interpretation may be ambiguous for decision-makers unfamiliar with such models (Trillas 2015). Agent-based simulation supports the modeling of micro-level interactions, though with limited scalability for generalizing across contexts (Macal 2016). System dynamics models can identify interdependencies and scenarios but still face skepticism in traditional economic domains (Radzicki 2011). Finally, SNA provides a structural perspective of actor interactions and has demonstrated its capacity to inform inclusive and sustainable policies (Filentaa and Kydros 2023; Zhou et al. 2022).

In this regard, SNA can provide a complementary and enriching perspective compared to pattern-based or simulation models, as it explicitly incorporates social, economic, and environmental relationships as integral parts of the system under analysis. This offers direct inputs for the design of comprehensive and sustainable public policies.

4. Link Between SNA and SRD Indicators

In international contexts, it has been noted that the density of local networks positively influences regional competitiveness (Gautam Ahuja 2000; Lundvall 1992). For example, Ter Wal and Boschma (2009) identified that the position of actors within collaborative networks conditions the capacity for territorial innovation. Similarly, Batterink et al. (2010) studied research networks and found that structured cooperation enhances the outcomes of development projects.

The international literature has described that the structural properties of networks are associated with innovation capacity, institutional resilience, and regional competitiveness. Borgatti et al. (2009) highlight that metrics such as centrality and density are predictors of organizational performance. Balland et al. (2015), as well as Crespo et al. (2014), argue that regions with dense networks and strategically positioned actors exhibit superior performance in innovation and productive diversification; Additionally, network governance based on triple helix actor networks could improve institutional efficiency and promote DRS (Ziaril and Mohammadi 2016).

However, Huggins and Thompson (2017) point out that there is limited empirical evidence supporting the extent to which actor networks influence regional development or growth outcomes. Additionally, in Latin America, the application of this approach remains scarce, and no studies have been identified that systematically link SNA metrics across different regions with SRD performance through indicators associated with the Colombian Departmental Competitiveness Index (IDIC).

5. Methodological Proposal

Subsequent to the establishment of the characteristics of SNA as a tool for analyzing SRD, and from a comparative perspective, this stage proposes the development of a correlation matrix. The data will be drawn from the results of structural SNA metrics (e.g., network size, average degree, diameter) applied to different regions, together with the socioeconomic indicators of those same regions. In the case of Colombia, the indicators to be considered will be those associated with the Departmental Competitiveness Index (IDIC).

The methodological proposal is structured in three stages, which are described below:

Stage 1

In this first stage, official information sources containing indicators related to SRD performance levels will be used to identify regions with different levels of performance. Where possible, these regions will be classified into intervals to allow comparative analysis. The indicators will be represented by Yi, as the values of the dependent variables or comparative measures for each region, respectively.

As the objective is to potentially describe some of the causes behind the differences in SRD levels across regions, regions showing divergent performance in SRD indicators will be identified using data from official sources. Where possible, these performance levels will be classified into intervals such as high, medium-high, medium, and low.

Stage 2

Once the regions with different performance levels have been established, a preliminary review will be conducted to assess the availability of information (primary and secondary) necessary to apply SNA methodology (Hanneman and Riddle 2005; Wasserman 1994). The goal is to obtain relevant information on the structure and resulting network metrics. These metrics will be represented by Xi, as the values of the independent or comparative variables, including general network measures such as network size, average degree, diameter, among others.

Stage 3

Following the collection of information in Stage 1 (SRD performance indicators) and the subsequent analysis of results in Stage 2 (network metrics), a correlation analysis will be conducted between these two sets of data. The following methodology will be employed: firstly, the correlation coefficient will be obtained from the pairs of variables (*Xir, Yir*), the correlation coefficient will be obtained, where *X* represents the SNA metric and *Y* represents the performance indicator. Here, *i* varies by metric and indicator, and *r* varies by each analyzed region. For example: *X11 = Network Size, Y11 = Regional GDP; X21 = Average Degree, Y21 = GDP per capita*. These pairs of variables for Region 1 will then be used to calculate the corresponding Pearson correlation coefficient, as shown in Table 3.

Table 3. Pairs of variables (*Xir, Yir*)

Network Metric	SRD Indicator	Network Metric	SRD Indicator
X11 = Network Size	Y11 = Regional GDP	X21 = Average Degree	Y21 = GDP per capita
X12 = Network Size	Y12 = Regional GDP	X22 = Average Degree	Y22 = GDP per capita
X13 = Network Size	Y13 = Regional GDP	X23 = Average Degree	Y23 = GDP per capita
X1n = Network Size	Y1n = Regional GDP	X2n = Average Degree	Y2n = GDP per capita
Pearson r	r =	Pearson r	r =

Source: Methodological proposal for correlation coefficient

The use of the Pearson correlation is justified by its ability to measure the strength and direction of the linear relationship between two continuous variables. Additionally, other statistical methods such as regression analysis could be considered for further exploration of

causal relationships, as well as introducing control variables to account for potential confounding factors.

The combination of elements derived from network metrics—such as size, average degree, and density, among others (Hanneman and Riddle 2005; Wasserman 1994). enables the exploration of correlations between the relational structure of regions and their performance in indicators associated with SRD.

In Latin America, studies have been limited and mostly focused on urban or sectoral innovation networks, without establishing a direct link with composite indicators of competitiveness or sustainability. In this regard, the present proposal aims to identify this academic gap for future research addressing divergences in SRD across regions, states, or departments at the second administrative level of countries, using CAS and SNA as the methodological framework.

6. Discussion

The review of the different theories and concepts that have shaped SRD shows that an integral analysis cannot be carried out from a single dimension. Early approaches placed particular emphasis solely on economic growth measured through GDP. In contrast, the inclusion of social, institutional, and environmental dimensions has framed SRD as a complex and multidimensional phenomenon (Capello 2019; Neely 2015). This complexity largely justifies the need for alternative approaches capable of identifying interdependencies and non-linear dynamics—approaches proposed within the framework of CAS (Beaussier et al. 2019). From this standpoint, a number of instruments exist that facilitate the modelling of interactions and interdependencies among actors, as well as their territorial dimensions. It is evident that SNA is distinguished by its capacity to incorporate the social dimension whilst concomitantly unveiling relationships that transcend the confines of mere social phenomena.

One contribution of this work is to propose the systematic association of network metrics obtained from modeling the networks of various regions within countries with the performance indicators of the SRD, which in the particular Colombian case is the Departmental Innovation Index for Colombia (IDIC). This articulation allows for a comparison between regions and thus establishes an empirical approach for a possible explanation of the persistent divergences in the SRD. In this case, there are few studies that address this combination, focusing on European or Asian contexts (Balland, et al. 2015; Crespo, et al. 2014). demonstrating a high novelty and relevance for Latin America, where divergences are quite noticeable not only between countries but also between regions. Despite the theoretical evolution in the DRS, these divergences remain and, in many cases, are accentuated.

7. Conclusions

The historical and conceptual review developed in this study shows that Sustainable Regional Development (SRD) has shifted from linear, growth-centered economic approaches toward more complex theoretical and methodological frameworks that integrate social, environmental, spatial, and institutional dimensions. This theoretical and conceptual evolution has generated the need to identify tools capable of capturing the interdependence, adaptability, and non-linear dynamics that characterize regional development processes.

In this regard, the association and incorporation of the Complex Adaptive Systems (CAS) paradigm allows regions to be interpreted as open and evolving systems, where interactions among actors generate emergent patterns and relational governance becomes a key factor for development. Within this context, Social Network Analysis (SNA) emerges as a particularly suitable tool to represent, measure, and analyze the relational configurations that shape the adaptive capacity of regions in terms of SRD.

The methodological analysis carried out demonstrates that, although multiple tools derived from CAS—such as neural networks, fuzzy logic, agent-based simulation, and system dynamics—are applicable, SNA offers unique advantages for the study of SRD, especially when integrated with composite metrics such as the Departmental Competitiveness Index (IDIC). This integration represents an innovative contribution to the Latin American context

and, in particular, for the Colombian case, where no prior studies have been identified that combine both perspectives.

The proposal to correlate network metrics (e.g., density, centrality, modularity) with IDIC dimensions opens a research avenue that links relational structures with socioeconomic and institutional outcomes. This correlational approach provides the possibility of designing more precise and adaptive public policies, grounded in empirical evidence and in a deeper understanding of territorial dynamics (Jiménez Romera and Piaggio 2020).

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