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Agent-Based Model to Analyze the Role of the University in Reducing Social Exclusion

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Abstract: While conventional innovation has boosted economic growth in certain regions, it has not contributed to closing the social and economic gap in most developing countries. Humanity is going through a historic moment of great challenges. One of them is social exclusion, a matrix of factors that prevent human beings from achieving well-being: poverty, hunger, inequality, lack of access to basic resources and services, and lack of social ties that help improve these circumstances, among others. This study holds two hypotheses: (1) in this context, inclusive innovation emerges as a response to the inability of conventional innovation to contribute to solve the persistent challenge of social exclusion and (2) universities—key actors in innovation dynamics—should play a fundamental role in the generation of inclusive innovation, especially considering their natural commitment to society. Although the role of the university in innovation has been widely acknowledged and studied, no formal theoretical model has represented inclusive innovation in developing countries adopting a systemic, complex, adaptive, and functional approach and incorporating a diversity of agents, interactions, capabilities, learning processes, knowledge, and directionalities—this would enable us to understand the role of the university in inclusive innovation. This paper argues that innovation dynamics should be understood from a systemic perspective and using computational modeling and simulation methods, so that the inherent complexity of these systems can be taken into account. The analysis of innovation scenarios based on a formal theoretical model and its operationalization through computer simulation should contribute to the understanding of the role of the university in these system dynamics, which can be used to propose effective strategies to strengthen its participation. Therefore, this paper proposes a formal systemic agent-based conceptual model that can be used to study the role of the university in inclusive innovation and establish guidelines to improve its performance. This study implemented standard computer modeling and simulation, specifically adapted for agent-based modeling. The results obtained from the simulation scenarios were comparatively analyzed using statistical tests (ANOVA and Tukey) to determine the presence of statistically significant differences. As the main finding of the research, the proposed conceptual model was validated and proved to be useful for studying the role of the university in reducing social exclusion in the Global South, through the design and execution of computer simulation scenarios.

Keywords: innovation systems; university; inclusive innovation; agent-based model; social exclusion; computational modeling and simulation

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1. Introduction

At least since the publication of the works of Joseph Alois Schumpeter [1,2], innovation has attracted the attention of economists, sociologists, and other researchers interested in the dynamics of change leading to economic growth and transformation. Not surprisingly, innovation has been the focus of an enormous number of studies and publications about its origin, state, dynamics, and impacts. However, most innovation literature stems from and deals with the problems of the industrialized world, and it is concerned with economic growth and productivity, leaving the specific realities of developing countries and their pressing social and environmental challenges rather unattended. This article aligns with the view of many scholars (see, for example [3–8]), that calls for building a theory of innovation in and for the Global South that takes into consideration the specific realities of developing countries and contributes to achieving the goals set in the 2030 Agenda for Sustainable Development.

In this sense, with an approach that was different from that of OECD countries, a movement started in Quebec (Canada) at the beginning of the new millennium, aiming to contribute (from the human and social sciences) to an agenda for innovation. This initiative, based on the study by Taylor [9], sought to be the first response to a paradigm shift in terms of innovation as a means and not as an end, a means for development and social well-being. In this new paradigm, innovation was fostered not only by companies and for companies but also by any sphere, including the community.

Consequently, the first "social innovation" movements started to emerge [10]. These first changes were supported by other European countries (e.g., Great Britain), and although the initial attempts to incorporate them into public policy agendas were feeble, the results were evident at the end of the last decade when Canada and the United States adopted social innovation policies. For example, in 2009, President Obama created the Office for Social Innovation and Civic Participation, which had an annual budget of approximately USD 50 million until 2015. Furthermore, there is evidence of similar initiatives in Australia and New Zealand [11].

Social innovation refers to the design and implementation of new solutions that involve conceptual, process, product, or organizational changes, which ultimately aim to improve the welfare and well-being of individuals and communities [12]. Some initiatives developed within the framework of social economy and by civil society are innovative and have been demonstrated to address socioeconomic and environmental issues.

In addition to the above, the terms innovation for sustainability or sustainable innovation are now more commonly used, which is in line with the change in the mindset of the post-modern era, in which scientific, economic, and political efforts should be directed at solving structural problems, not only of the economy but also of mankind [13]. This new school of thought originated in developing countries, where, despite major efforts to achieve economic growth, there were wide gaps in wealth distribution and welfare [14]. Moreover, related concepts—such as social innovation, frugal innovation, and transformative innovation—appeared to respond to the challenges that "conventional" or "competitive innovation" had not addressed.

Grassroots innovation for sustainability is composed of networks of activists and organizations that devise new bottom-up solutions for development, that is, solutions that respond to a local situation, as well as the interests and values of the communities involved [15]. This definition may seem to be against the type of innovation that we currently know. However, grassroots innovation shares very similar characteristics with it and, in addition, embraces inclusion principles and local control over technological development processes and innovating social organizations [16]. In practice, it can also involve actions with and for individuals who work for more conventional science, technology, and innovation institutions [17].

Frugal innovations are defined as "simple products or services that are dramatically lower in cost, outperform alternatives and can be scaled up through adoption by people who do not need special expertise or equipment" [18]. As a result, frugal innovations can be used to produce new business models and redefine and redesign chain values and products to make them affordable and accessible to users who face strong restrictions [19].

In turn, transformative innovation addresses structural failures in the current innovation system. It proposes a change in the directionality and intention in innovation processes so that they support a change in the sociotechnical system [20]. This type of innovation aims to influence the science, technology, and innovation policy, producing a change in the system that enables a transition toward sustainability, that is, a transformative change that responds to the big challenges that humanity is currently facing [20].

As can be seen, all these approaches to innovation are emerging to tackle humanity's problems and challenges using science, technology, and innovation from the perspective of sustainability. They go beyond generating economic growth and aim to deal with the social and environmental aspects of sustainability.

This study highlights social exclusion as one of the biggest challenges facing humanity because it hinders excluded individuals from achieving social welfare and human development [21]. Therefore, social exclusion is much more than poverty. It is a matrix of events that profoundly deteriorate human life: poverty, lack of access to basic services (e.g., food, education, drinking water, and electricity), and lack of relationships and social ties that could minimize exclusion. These factors worsen the quality of life of those who experience this type of exclusion [21–24].

In particular, this paper focuses on the role that universities play in innovation dynamics—a key role of undeniable importance. This role has evolved over time, as shown in [25], resulting in the recent emergence of "the entrepreneurial university" as the new active center of innovation [26]. Clearly, universities have played a critical role as part of a complex array of institutions and interactions that produce economic growth.

However, economic growth has also brought undesirable consequences, such as increasing economic and social inequalities. These consequences are more relevant in the Global South due to specific realities that affect the dynamics and outcomes of its innovation systems. As argued by Schillo and Robinson [27], "[s]uch negative consequences are particularly obvious in the context of developing countries and extreme poverty, where innovation's contributions to inequalities are considered an issue of social and economic exclusion" (p. 34). It is in this context where the concept of "inclusive innovation" gains full relevance. According to these authors, this concept "has been developed to provide frameworks and action guidelines to measure and reduce the inequality-increasing effects of innovation" (p. 34) and provides "a plausible scenario for increased social and environmental sustainability on a global level" (p. 42).

Schillo and Robinson do not present specific considerations about the role of the university in inclusive innovation in the developing world. This is customary in most innovation literature, where the specific realities of the Global South are often overlooked and attention is focused on problems of the developed world and the pursuit of economic growth. It also applies to the literature on the role of the university in innovation. Fortunately, some researchers and analysts have investigated universities in the Global South and their roles in economic and social development, reframing their studies under the paradigm of sustainability.

Vessuri's reflections on the Latin American university are in line with this position. In [28–30], she acknowledged the importance of universities as key actors in the development of this region. She also emphasized that universities must assume an active role in the generation of knowledge, the training of highly qualified human resources, and the promotion of scientific and technological research. She also advocated for a university that was more committed to its social environment, which meant that it should redirect its research and teaching to address the specific needs and challenges of Latin America, working closely with other social actors (e.g., the productive sector, governments, and local communities).

This concern was also addressed by Arocena et al. [31] applying the notion of "developmental universities" [32], that is, higher education institutions that combine teaching, research, and outreach to promote development. Scientific and technological knowledge has been a source of great benefits to mankind, but "many of these benefits have largely been denied to large parts of the world population where social ills and inequalities remain unabated in the face of scientific progress" (p. 1). Consequently, Arocena et al. [31] hold that universities should actively participate in what they call the "democratization of knowledge"—a process through which people can more easily acquire and use knowledge resulting from scholarly and research activities by universities. In this way, the "developmental university" would efficiently contribute to overcoming inequality and underdevelopment. In addition, considering that innovation responds to systemic dynamics, the democratization of knowledge by the developmental university should take place in the context of inclusive innovation systems. Overall and from the perspective of the analysis proposed in this article, the following aspects mentioned by [31] regarding the role of the developmental university should be highlighted:

- The need for a change in direction toward sustainability;
- The research agenda and knowledge requirements of the marginalized and poor populations;
- The generation and use of that knowledge to produce inclusive innovations;
- The indispensable participation of the excluded population in innovation processes;
- The agency requirements (representative voice) that convert the excluded into agents of the system;
- The accumulation of complementary capabilities by the agents;
- The strengthening of collective action under a common sustainable directionality.

Arocena's and Sutz's proposal of developmental universities in inclusive innovation systems highlights most of the main and fundamental issues that must be addressed when considering the role of universities in inclusive innovation. However, we understand that building a formal conceptual model that integrates all the components of their analysis is beyond the scope of their proposal.

Nevertheless, we argue that to advance in the analysis of the role of the university in inclusive innovation, the conceptual and theoretical contributions usually found in qualitative research should be enriched with formal conceptual models that can support the development of theories based on computer simulation. To achieve that goal, this paper proposes a formal conceptual model that can be used to study the role of the university in inclusive innovation, taking into account the specific realities and requirements of the Global South to advance in its search for sustainable development. Said model could contribute not only to a better understanding of the complex dynamics of inclusive innovation but also to generating guidelines and strategies to improve the inclusiveness of innovation systems thanks to university participation.

Conceptually, this article is in the field of innovation studies; more specifically, it adopts the innovation systems approach. Nevertheless, it also draws on insights from other related approaches, such as the resource-based view [33,34] and the learning economy [35], to mention only two of the most relevant ones. In innovation studies, the concept of innovation systems has been widely used and applied to nations [36,37], regions [38], economic sectors [38], and technologies [39]. This systemic approach to innovation provides a useful framework for analyzing the role of universities because it emphasizes the importance of collaboration, institutions, and policies in promoting innovation, economic growth, and transformative change. These studies also provide insights into how innovation systems can be designed and implemented to address specific societal challenges and promote economic growth. Additionally, they encourage a discussion on different policy instruments and strategic approaches that can be adopted to support innovation and improve its effects on economic growth and system transformation [37,40,41].

In order to achieve the objectives of this study, computer simulation was employed as a methodological strategy to model a complex and heterogeneous innovation system, as well as the non-linearities present in the decision rules of its agents and their interaction patterns [42]. Computer simulation makes it easier to adapt the model so that it reflects changing political and economic conditions. As a result, we can assess the potential impacts of different policy interventions and strategic orientations, as well as explore "what if" questions. Then, the model can become a valuable computer platform for strategic analysis and decision-making. Furthermore, the interdisciplinary potential of this methodological approach makes it possible to gain a new understanding of innovation-related phenomena by coherently integrating valuable ideas and methods from different scientific fields. Finally, since computer simulation models can be empirically validated, the model's accuracy and reliability can be tested to ensure that it actually reflects real-world innovation systems and can support meaningful strategy recommendations.

According to [43], modeling is a problem-solving approach that is used when real-world prototyping is not feasible. It provides a better understanding of problematic settings by mapping a problem from the real world into a simplified representation in the world of models through a process of abstraction. From an applied perspective, modeling helps us analyze problems and obtain insights into the behavior of real systems to come up with possible solutions to specific problems. Computer simulation models are based on sets of rules that define how a system will change over time, given its initial state and a projection of environmental factors. In this context, simulation is defined as the process of executing a computer program that represents a model and observing its state changes over time.

Several computer simulation approaches can be used to represent and analyze the dynamics of complex systems. Some of the most common ones include agent-based modeling, system dynamics modeling, network-based modeling, cellular automata, Monte Carlo simulation, discrete event simulation, and evolutionary algorithms. Among them, the approaches most commonly employed for complex socioeconomic systems are system dynamics (SD), agent-based modeling (ABM), and discrete event simulation (DES). The first two are the best options when the variability of the system is important and the system is related to human behavior, as in the case of innovation systems [44]. According to [43], ABM can represent existing SD or DES models. Nevertheless, ABM can provide deeper insight into the system that is being modeled by capturing much more complicated behaviors, dependencies, and interactions among agents.

In this study, ABM was the methodological strategy. ABM has been increasingly used to study innovation dynamics and economic growth. It is based on the simulation of complex systems composed of interacting agents that follow simple rules but whose collective behavior can reproduce the macrolevel properties of real-world phenomena. The literature reports multiple applications of ABM in the study of innovation dynamics. Some examples are as follows:

- In [45], the authors employed ABM as a methodology to simulate neo-Schumpeterian economics, focusing on the role of innovation in economic growth.
- In [46], the authors proposed an agent-based model that combined Schumpeter's and Keynes' theories of growth and business cycles. They showed that the model could replicate stylized facts of economic growth and be used to propose policy implications. Later, Ref. [47] extended this model to incorporate multicountry dynamics and global divergence processes.
- Similarly [48], analyzed the impact of intermediaries on innovation systems. Based on the simulation of scenarios in an agent-based model, they highlighted the importance of intermediaries to facilitate the exchange of knowledge and collaboration between different agents and levels in the innovation system. They also discussed the challenges involved in measuring the impacts of intermediaries given the attribution problem.
- The authors of [49] developed an agent-based model to study learning in regional innovation systems. They found that learning is a complex process that is influenced by localized social networks, institutional structures, and the decisions of system agents, where learning capabilities and processes play a fundamental role.
- The authors of [47] explored the role of public policies in facilitating the recovery processes of lagging countries or regions. The authors used a combination of historical evidence and an agent-based model of several countries to examine the effectiveness of different policy interventions in promoting catch-up growth.
- The authors of [50] utilized an agent-based model to study the potential of mission-oriented policies and the entrepreneurial state to drive transformative innovation.

These examples illustrate the wide range of applications of ABM and show that it can be used to study the dynamics of innovation systems. ABM provides new insights into the mechanisms and drivers of change and a new understanding of the contribution of different agents, interactions, environmental factors, policy interventions, and strategic orientations to the performance of the system.

This paper is structured as follows: Section 2 presents the theoretical framework in which the research is carried out; this section includes a review of the literature on the evolution of conceptions about the university throughout history and a conceptual discussion on social exclusion and the way in which it can be addressed through inclusive innovation; the section ends with a reflection on the relationship between the university and social exclusion. Section 3 sets out the research methodology, which follows best practices for building and validating computer simulation models to support theory development. Section 4 is dedicated to the presentation of the results: (a) a conceptual model is proposed to analyze the role that the university can play in reducing social exclusion, and (b) the simulation scenarios are described, and the results obtained through the simulation runs are presented. Section 5 discusses the results, and Section 6 presents the conclusions of the research. Section 7 includes a discussion of the theoretical and practical implications of the research findings, and Section 8 ends with a reflection on the limitations and some directions for future research.

2. Theoretical Framework

First, this section provides a context for the origins of the university, its history, its importance in society, and the way it has evolved until it has become the standard type of higher education institution around the world. Second, it conceptualizes the phenomenon of social exclusion and its negative global effects. It discusses science, technology, and innovation (STI) as a way to tackle the different challenges humanity is facing. In addition, it holds that inclusive innovation can specifically address social exclusion. This theoretical framework establishes a connection between social exclusion, inclusive innovation, and the university. Finally, it argues that the university should be an important agent in generating inclusive innovation and, therefore, in reducing social exclusion.

2.1. The University: Universitas Magistrorum et Scholarium

Born with the name above, the university and its history date back to the Middle Ages in Europe according to some authors [51–53], to Morrocco (Fes El Bali) according to others [54], and to the period BCE in China (Shang Xiang school) according to yet others [55]. Ultimately, the history of the university was a natural result of individuals' desire to teach and learn. Without students and professors, the concept of the university becomes blurry.

Universitas magistrorum et scholarium—roughly translated as "community of teachers and students"—defines the essence of the university. Derived from universum, universitas means the whole, which defined the character of those spaces where intellectual activity was possible [53]. The earliest universities were established in the 6th century, and they have slowly evolved to become one of the fundamental actors in current society.

This study analyzes the "modern" university, which started toward the end of the Middle Ages and the beginning of the Renaissance (13th century) as a European creation. For centuries after that, the university has stayed in a distinguished position among social organizations, and its model has been replicated around the world to accomplish a social mission that is well appreciated: knowledge exchange [56].

Clearly, an important factor in the origins of the university was the historical moment: the Middle Ages. In that period, the most important institutions were the empire, the church, and the university. Among them, only one—the university—was born in a natural way and lives on to this day [57]. Maybe this is the reason why the university is called upon to be a leading actor in society—because it was originally based on the humble idea of a scholar willing to share knowledge to a student willing to learn.

From those unplanned, natural origins, the university has taken different paths and orientations according to the societies in which it has been immersed. Something that cannot be ignored is the fact that the Catholic church played an important role in the creation of universities. For example, some French cathedrals had schools to teach the Holy Scriptures [58]. Early universities in other places also had their origins in different religions. For example, Buddhism (China), Hinduism (India), and Islamism (Middle East) established centers for thought and knowledge where religious teachings were studied [52,55].

According to the literature, the first (Western) university was created in Bologna in 1088 CE, which would be followed soon after by Oxford (1096) and Paris (1150). These universities aimed to provide a space to share knowledge, and little by little, they specialized in certain fields [58]. Note that there are several opinions on the foundation of the first university in the world. The first university could have been founded by Plato approximately in 388 BCE. Nevertheless, this study focuses on the origins of Western universities established in the Middle Ages, which are the foundations for the current university [52,56,57,59,60].

In the beginning, the main goal of the Western university was to organize the Christian society and save souls [61]. A series of disciplines were taught for this purpose. This type of medieval education consisted of two divisions of the seven liberal arts: the lower division (grammar, logic, and rhetoric) and the upper division (arithmetic, geometry, music, and astronomy). After that, each student had three options: law, medicine, or theology [56,61]. As a result, most medieval universities were composed of four faculties: arts (or philosophy), law, medicine, and theology.

For more than five centuries, universities were conservative institutions. It was at state academies—dependent on states, princes, or private circles—where the great currents of the Scientific Revolution emerged. Only in the 18th century did Western universities embrace secular education [56,57,59,61].

From then on, the university has been devoted to advancing science and responding to the needs of the state, which demands that higher education institutions (HEIs) produce knowledge. This has resulted in new disciplines and the evolution of the university in two educational models: the German one (developed by William von Humboldt) and the French one (developed at the time of Napoleon Bonaparte).

The German model conceives the university as the place to learn the principles and procedures of science. In its French counterpart, the university is the place to train professionals, and it has the power to grant degrees or certifications to practice those professions [52,56,58,61].

The professionalizing university (French model) was instituted by Napoleon I at the start of the 19th century (1806) when he founded the Imperial University of France. This centralized state organization provided school and university education as a "privilege of the state", whose mission was to educate intellectuals who had practical knowledge that was useful to society. In this model, professors—although great—did not conduct research. This type of university became a good alternative to the then-discredited old-fashioned traditional university that had not evolved since the Middle Ages [60].

2.2. The University as Creator of "Social Welfare"

Since its inception, the university has focused on social welfare as the common goal of all its activities. First, the university was a repository of knowledge and a center of access to information, which has been called its first mission. Second, it became a special place to develop knowledge by means of R&D processes—its second mission. Later, the university was assigned a third mission: to promote entrepreneurship by transferring knowledge and solutions to society (especially by creating start-ups and technology hubs). Currently, some authors propose a fourth mission for the university: to produce long-term solutions to social, economic, and environmental problems [62–64].

The debate on the mission of the university dates back to the 18th century, when Adam Smith posited that universities should generate knowledge to satisfy social needs [65]. Basically, he held that the knowledge produced at these institutions should be focused on the needs of the societies around them. This is the origin of the idea of the public mission of the university as a broad concept with multiple dimensions.

The missions of the university are related to its two main tasks: creating and sharing knowledge. Without them, the university as we know it would not exist. The mission of the university evolved approximately in the middle of the 20th century [66]. The origins of the third mission of the university go back to a conference at Harvard University held in 1963 by Clark Kerr, the president of the University of California (Kerr, 1963). On that occasion, he suggested the term multiversity and defined it as a college community that (based on its differences) can lay the foundations for the future while responding to present needs [67].

The third mission is an effort to include the university as a relevant actor not only in generating and sharing knowledge but also in solving society's problems by transferring knowledge in the form of solutions (technology) that promote innovation [68].

Science, technology, and innovation are instrumental in the third mission of the university. This is because universities—knowledge producers—are the places where science is naturally born, solutions are developed to apply said knowledge in the form of technological solutions, and knowledge is transferred to society. Their purpose is to achieve innovation as a social phenomenon of technology appropriation by a market [69–71].

However, in recent decades and due to complex problems facing humanity, society itself has started to demand that the university play an even more significant role. This has been evident in the literature since several authors proposed the triple helix model of innovation (university, industry, and government), which was based on the third mission of the university. According to this model, the role of the university should evolve from active to leading, that is, it should manage spaces, processes, and resources to unite all the actors in society to achieve something beyond economic growth and wealth: human welfare [66,68,72].

The concept of the fourth mission of the university was introduced in the 21st century to respond to the current demands of humanity, established in the United Nations Sustainable Development Goals (SDGs) [63,73,74]. Said concept makes explicit the relationship between the university and its role as a generator of sustainable models that have an impact on communities [66]. Likewise, the university should be a space for lifelong learning [62], and its actions should address SDG 4: "Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" [75].

2.3. Social Exclusion and Inclusive Innovation

In 2015, after monitoring the Millennium Development Goals, the UN created the 2030 Agenda for Sustainable Development. This more global and inclusive agenda proposed 17 SDGs and included the fight against climate change [76]. Some of the SDGs are about reducing social exclusion, which affects a great proportion of the world population.

Social exclusion is a phenomenon that goes beyond poverty: it is a matrix of events that hinders individuals from fully experiencing human development or well-being. This kind of exclusion is defined as a state in which "individuals and groups confront barriers to full participation in economic, social, and political life", as well as the process that generates and maintains that state [77].

In general, social exclusion emerges along one of three dimensions [78]: (a) exclusion based on identity, i.e., when people are excluded because they are different from the established norms and customs (gender, race, religion, political affiliation, etc.); (b) exclusion based on circumstances, a type of exclusion that is due to conflicts, displacement, poverty, or gender violence; and (c) exclusion based on socioeconomic conditions, in which low educational attainment, unemployment, or poverty can limit people's access to certain benefits, such as employment, loans, insurance, or political rights.

Social exclusion is a phenomenon of major significance and a challenge for humanity because due to it, people cannot be free, happy, and productive—that is, it hinders human welfare and development [21,79]. Current data indicate that nearly 32% of the world population is at risk of social exclusion [77,78]. Although this is a disheartening figure, it is also true that in recent decades, there has been unprecedented social progress. Nevertheless, this progress has been unequal, and even worse, inequality has grown. Therefore, the 2030 Agenda aims to create prosperity for all humanity, and its motto is “No one left behind” [80].

In 2022, between approximately 2.33 and 2.43 billion people were at risk of social exclusion. The Global South shows alarming figures in this respect: South, East, and Southeast Asia are home to 1.3 billion of those individuals, and India and China have 840 million of them. Approximately 52% of the population in Sub-Saharan Africa is vulnerable to exclusion. In Latin America, it is estimated that approximately 29% of its population is already experiencing social exclusion [78].

Therefore, STI institutions and processes should focus on addressing social exclusion as a pressing problem and challenge for humanity nowadays. As established in the SDGs, there will be no sustainable development for humanity without inclusion [77,80].

STI initiatives have been proposed to address these challenges. Unfortunately, less developed countries have not consolidated processes to generate innovation capabilities, which has caused them to lag behind.

Multiple approaches have been proposed to tackle this challenge. For instance, transformative innovation proposes a different direction and intention in innovation, creating a new STI framework that addresses actual and urgent needs of humanity. In this regard, Ref. [81] argue that this new paradigm is necessary because the world is undergoing a profound change. Likewise, Ref. [82] also claim that the current economic development model is not oriented toward sustainability, and, as a result, most science policy does not focus on this problem either.

Other concepts have emerged as well. For example, base-of-pyramid innovation [17,83,84] (in goods, services, processes, organization, marketing, and other forms) is accessible (easy to obtain) and affordable (low cost) and creates opportunities for the subsistence of excluded populations, especially those at the base of the pyramid (BOP) [85–88]. This kind of innovation is generated in a sustainable manner (with a focus on quality) [89] and goes beyond only technical innovations, low prices, or radical changes [85].

Grassroots innovation focuses on creating jobs, developing products or processes specifically for communities, and solving the main problems facing those communities. Its main characteristic is that individuals are agents of innovation, and their innovations are generally derived from community needs, difficulties, and challenges [15,82,90–92].

Social innovation is another concept along the same lines, but scholars have not reached an agreement on its definition [93–96]. Nevertheless, several authors suggest that social innovation is developing solutions that have a strong impact on society, go beyond a commercial goal, and solve problems that affect individuals and groups [93,94,97–100]. Although it is not a new concept, social innovation is emerging in developing countries, specifically in Latin America, to address the deficiencies of the current innovation model [101]. Latin American economists have discussed the way social innovation can be adapted to the geographic, economic, cultural, political, and social diversity of this region. They have used it in multiple theoretical studies to respond to the structural problems of their territories [102]. According to the United Nations Economic Commission for Latin America and the Caribbean (ECLAC), this type of innovation has the biggest impact on this region [103,104].

Frugal innovation (or jugaad innovation as it is known in India) refers to producing innovations with a limited amount of resources [105], that is, making the most of what you have. Frugal innovation identifies opportunities in the most adverse situations, considers the community to be the “market”, offers solutions to actual problems (instead of generating non-existent demands), and creates new value chains that make innovations accessible and affordable to those who need them [105–108].

In turn, inclusive innovation emerged as an alternative to achieve sustainable development. This type of innovation refers to goods and products created by and for those who have been excluded from the main current of development, particularly those who have the lowest incomes [109]. This type of innovation is accessible and affordable; provides solutions to reduce social, economic, political, and cognitive gaps; includes the excluded ones; seeks human welfare and environmental sustainability; and incorporates science and technology into processes that generate social welfare, human development, and environmental sustainability. Inclusive innovation is produced by and for communities in need, who can contribute their knowledge, customs, beliefs, and values [109–112]. That is the kind of innovation discussed in this study.

2.4. Inclusive Innovation and Its Relationship with the University

Inclusive innovation—as a result of R&D—is produced by leveraging innovation systems. Hence, since resources are being reassigned in innovation systems, producing inclusive innovation requires means of protection in the economic system, unlike other economic activities [113].

Consequently, innovation systems (ISs) play a fundamental role because they participate in generating these dynamics. Therefore, as an active part of ISs, the university is called upon to play a fundamental role in the generation of this kind of innovation.

Moreover, it can lead this transition between innovation paradigms, and it plays a dominant role because it is a hub where the knowledge, science, and technology that are needed to respond to humanity's problems are usually generated [114–116].

The missions and objectives of the university should be conceived and implemented under this new paradigm of inclusive innovation. Without neglecting the needs that should be met in the dynamics of the market, the university should focus on developing inclusive innovations that contribute to improving the socioeconomic, cultural, political, cognitive, and environmental conditions of communities that have been marginalized and excluded from lucrative markets [4,31,114].

3. Research Methodology

Based on the theoretical framework presented in Section 2 and considering the conceptual model proposed as a hypothesis in the previous section, we chose agent-based modeling as the most appropriate methodological strategy to analyze innovation systems and, in particular, the role of the university in inclusive innovation. Agent-based simulation models (ABSMs) facilitate the analysis of agents and their relationships in simulated scenarios, which can be used to gain insight into the conditions that lead to certain behaviors and performances of the system under study.

In addition, to study inclusive innovation, we needed to examine the bottom-up innovation process, that is, innovation that occurs at the base of the pyramid, which is typical of this approach. ABSMs are ideal for this type of study because they enable us to analyze the interactions among agents at the microlevel and their impact on the macrolevel. In other words, ABSMs favor bottom-up analyses—characteristic of inclusive innovation—mainly because they can be used to represent systems that include multiple heterogeneous agents. Such agents, who make simultaneous decisions following certain rules, can have different characteristics and be studied through the lens of their interrelationships and interactions, as well as the underlying phenomena in the system.

To develop the ABSM presented in this paper, we identified the variables and factors involved in the phenomenon under study (i.e., inclusive innovation). This allowed us to build a theoretical structure for the conceptual model based on three basic characteristics: (a) the existence of a conventional innovation system, (b) the existence of an inclusive innovation model, and (c) the university as the agent under study.

Based on these three characteristics hypotheses, we developed a conceptual model of an inclusive innovation system that encompassed the environment, the elements in the system, the agents, the capabilities of these agents, and, therefore, their classifications and the way they will interact. This model was created to answer one question [117]:

What is the role of the university, as an agent in innovation systems, in the generation of inclusive innovation?

Afterward, we built a computer simulation model to analyze the role of the university in inclusive innovation. Applying the selected methodological strategy (i.e., ABSMs), we operationalized the model based on the previously developed conceptual model [118]. This operationalization consisted of defining the model's flowchart (which shows the relationships and decision rules that compose the proposed model) and programming it in NetLogo® version 6.1.1 to analyze the phenomenon.

NetLogo® is a programmable modeling environment that can be used to simulate natural and social phenomena. It was created by Uri Wilensky in 1999, and it has been continuously developed at the Center for Connected Learning and Computer-Based Modeling [119]. This study used NetLogo® because it was developed to model and simulate complex and dynamic processes, which are two characteristics of the phenomenon studied here (i.e., inclusive innovation). It can model and simulate multiple agents that are affected by many variables as time passes and interact with each other [120]. In addition, it offers multiple advantages: it can be downloaded free of charge, runs on different operating systems (Windows, Mac OS, and Linux), has a user-friendly interface, is fully programmable, has accessible syntax, incorporates a large number of primitives, and creates runs or executions that can be reproduced in other platforms [120].

After NetLogo® was selected as the modeling environment, the model was operationalized using the following characteristics and decision rules: (a) the emergence of needs, opportunities, problems, or ideas (NOPIs) that foster innovation within the system; the agents' search for NOPIs based on their location; and the agents' involvement based on their directionality; (b) the decision to take the path of social inclusion or the economic one based on the rule of complementarity; (c) the way of achieving inclusion based on the agency capability, following the management of teaching–learning spaces that make it possible to increase the capabilities of the excluded agents; and (d) the possibility to improve the search for other agents to provide the necessary capabilities through complementarity.

Then, we programmed the innovation capabilities, as proposed by [48], whose model is governed by market pull dynamics (from exploration to exploitation). To represent these capabilities, we incorporated the NOPIs, shared the benefits, and added them to the surplus stock. Afterward, we subtracted the costs of maintaining capabilities as well as the transaction costs. We also included the accumulation of used capabilities (learning) and the non-accumulation of unused capabilities (unlearning).

Subsequently, we performed the computer verification of the simulation model to ensure that the computational model complied with all the instructions proposed in the conceptual and operational model. For this process, we used the trace validation technique.

We checked the logic of all the procedures built on the NetLogo® platform and compared them with the submodels in the flowchart, which must be their equivalents, that is, their behavior must correspond to what is rationally proposed in the model, both conceptually and operationally. This enabled us to establish that the model effectively followed the instructions, and we could fix errors identified in the process. The computer verification demonstrated that the assumptions and rules defined in the model were respected in the programming.

Next, we performed conceptual and operational validations of the proposed simulation model. The conceptual validation employed two methods: (a) the historical rationalism method (HRM), which could be used to contrast the statements and assumptions that supported the model with premises derived from logical deductions based on the theory, and (b) a comparison with the conceptualization of similar agent-based models.

For the operational validation, we conducted two types of tests: (a) extreme tests, which consisted of an extreme and improbable combination of variable and parameter values in the system, whose behavior was previously known, and (b) a comparison of output behaviors, where confidence intervals were used to compare the output behavior of the simulation model with that of the actual system.

Once the model was verified and validated, we ran the simulation scenarios and analyzed their results to fully comply with the general objective of this study, confirming that the proposed model was applicable in the analysis of the role of the university in inclusive innovation seeking to reduce social exclusion. We created eleven different scenarios divided into two groups of analyses to study the performances of different variables and test the innovative and inclusive performance of the system. These scenarios represent several situations: the reduction of agents excluded from the system, the participation of excluded agents in the development of innovations, the use of opportunities, the behavior of transaction costs as a variable of trust in the system, and the behavior of capabilities in the system.

Subsequently, two types of statistical analyses were performed using Microsoft Excel®: (a) a statistical analysis using ANOVA tests to establish if there was a significant difference between each pair of scenarios and (b) Tukey tests to determine which scenario presented significant differences in each of the variables under study.

By analyzing these scenarios, we obtained different results on the performance of the system, which led us to determine the role of the university in inclusive innovation in each of the defined scenarios.

4. Results

This study held two hypotheses: (1) in this context, inclusive innovation emerges as a response to the inability of conventional innovation to contribute to solve the persistent challenge of social exclusion and (2) universities—key actors in innovation dynamics—should play a fundamental role in the generation of inclusive innovation, especially considering their natural commitment to society.

Two main results emerged from our hypotheses: first, a conceptual model validated in its ability to faithfully represent the phenomenon under study, which was presented as a hypothesis in Section 3, and second, confirmation of the possibility of using the proposed model to study the role of the university in reducing social exclusion, through the design and execution of computational simulation scenarios using ABSMs.

4.1. The Conceptual Model

The hypothesis in this study was that inclusive innovation emerges as a possibility to overcome the limitations of the conventional approach to innovation, specifically regarding the fight against social exclusion. This occurs as a result of the dynamics of an innovation system, which can be represented by a conceptual model. The university, as a key participant in the innovation dynamics, is called upon to play an important role in the generation of inclusive innovation, especially considering its natural commitment to society. Hence, it is important to understand the role of the university in the generation of inclusive innovation dynamics.

These dynamics can be understood from a systemic perspective of innovation using computer modeling and simulation methods, which can represent the characteristic complexity of these systems. In this way, scenario analyses based on simulation models can contribute to the understanding of the role of the university in these dynamics, which can be the basis to propose effective participation strategies that promote these dynamics.

Computer simulation models are based on theoretical models (often called "conceptual models") that are then operationalized and translated into the selected computer language to run the simulations. Since a conceptual model acts as a dynamic hypothesis, it must be validated to build confidence in its ability to represent the system under study. The model proposed in this article to study the role of the university in inclusive innovation, with the aim of reducing social exclusion in the Global South, is schematically presented in Figure 1. The main characteristics of this model were the following:

a. The basic function of the system is to produce innovations, which is achieved through three knowledge processing components: generation, diffusion (or dissemination), and use. In this article, knowledge refers to either scientific and technological knowledge, or traditional knowledge, or a mixture of both. Each of the components of the system function requires specific capabilities on the part of the agents. Thus, according to their capabilities and the components to which they are associated, agents can be classified into explorers, intermediaries, and exploiters, with a whole constellation of subcategories depending on the mix of directionalities and capabilities of each agent. Innovation capabilities accumulate through learning processes and are expensive to maintain; on the other hand, capacities can be lost through unlearning processes.

b. The innovation process is triggered by the appearance of the NOPIs, which represent the needs, opportunities, problems, and ideas that demand new or substantially improved products and processes by potential users. The appearance of NOPIs responds to spatial factors (of a geographic, cognitive, or marketing nature), so that there are some agents in the system that, due to their location, are very likely to know of the existence of a NOPI and respond to it.

c. Each particular NOPI incorporates the characteristics of the innovation demanded by its potential users. These characteristics refer, on one hand, to the directionality that is intended to be given to innovation, which can be aimed either at economic or social ends. On the other hand, each NOPI also characterizes the type and level of innovation capabilities required of the system agents interested in participating in the innovation process. Depending on their directionality, the NOPIs can be conventional NOPIs, if they require an economic directionality, or inclusive NOPIs, if they demand a social directionality. In the first case, the conventional NOPIs trigger the dynamics of conventional innovation systems; in the second case, the dynamics of inclusive innovation systems emerge.

d. Once a NOPI is structured, agents search for other agents with compatible directionality and complementary capabilities to respond to the NOPI. Eventually, a set of interacting agents is formed, being able to configure a successful response to the NOPI and benefit from their participation in the innovation process. From there, the innovation process develops its complete life cycle, producing the respective outputs: conventional innovations from conventional NOPIs and inclusive innovations from inclusive NOPIs. In any case, agents pay for establishing interactions with other agents and for being able to participate in the innovation process, but they also derive benefits from their participation, including economic rewards that allow them to strengthen their role in the system.

e. Therefore, there is a conventional innovation system with agents (explorers, intermediaries, and exploiters) that generate, disseminate, and use knowledge (mainly scientific and technological) to produce conventional innovations. They do so by employing multiple conventional complementary capabilities: research, development, dissemination, production, and marketing. To interact with each other in the system, agents pay "transaction costs", which can be low, medium, or high depending on the degree of trust between them.

f. Likewise, there is an inclusive innovation system with agents (explorers, intermediaries, and exploiters) that generate, disseminate, and use knowledge (including traditional knowledge) to produce inclusive innovations. The excluded agents are an essential part of this system and participate in its dynamics as a requisite for innovations to respond effectively to the requirements of the excluded populations. Therefore, the excluded agents are system agents that represent the excluded populations in the dynamics of the system that produces inclusive innovations. Like other agents in the system, excluded agents must accumulate capabilities that allow them to be productively involved in innovation processes with other agents, in response to inclusive NOPIs.

g. Together with the active participation of the excluded agents in the system, for the inclusive innovation system to work, a new set of innovation capabilities is required: the inclusive innovation capabilities. These are the preservation of traditional knowledge; technology appropriation; agency; the management of teaching–learning spaces; and production and marketing, based on appropriate technology. As in a conventional innovation system, there are "transaction costs", learning and unlearning processes, and costs paid and benefits obtained from the participation in the innovation process throughout the innovation life cycle.

h. The object of study of this article was the university (as an agent), whose directionalities and capabilities were analyzed in relation to its missions. Therefore, universities are central in the representation of the innovation system depicted in Figure 1. According to their mission, universities are classified as "teaching university", "research university", "outreach university", and "sustainable university". They play different roles in the innovation system, depending on their directionality and capabilities, which allows them to participate in the innovation process and contribute to system performance in many different ways. For this reason, the proposed model makes it possible to study the role of the university in inclusive innovation and the reduction of social exclusion, which is done through computer simulation, as presented in the following section.

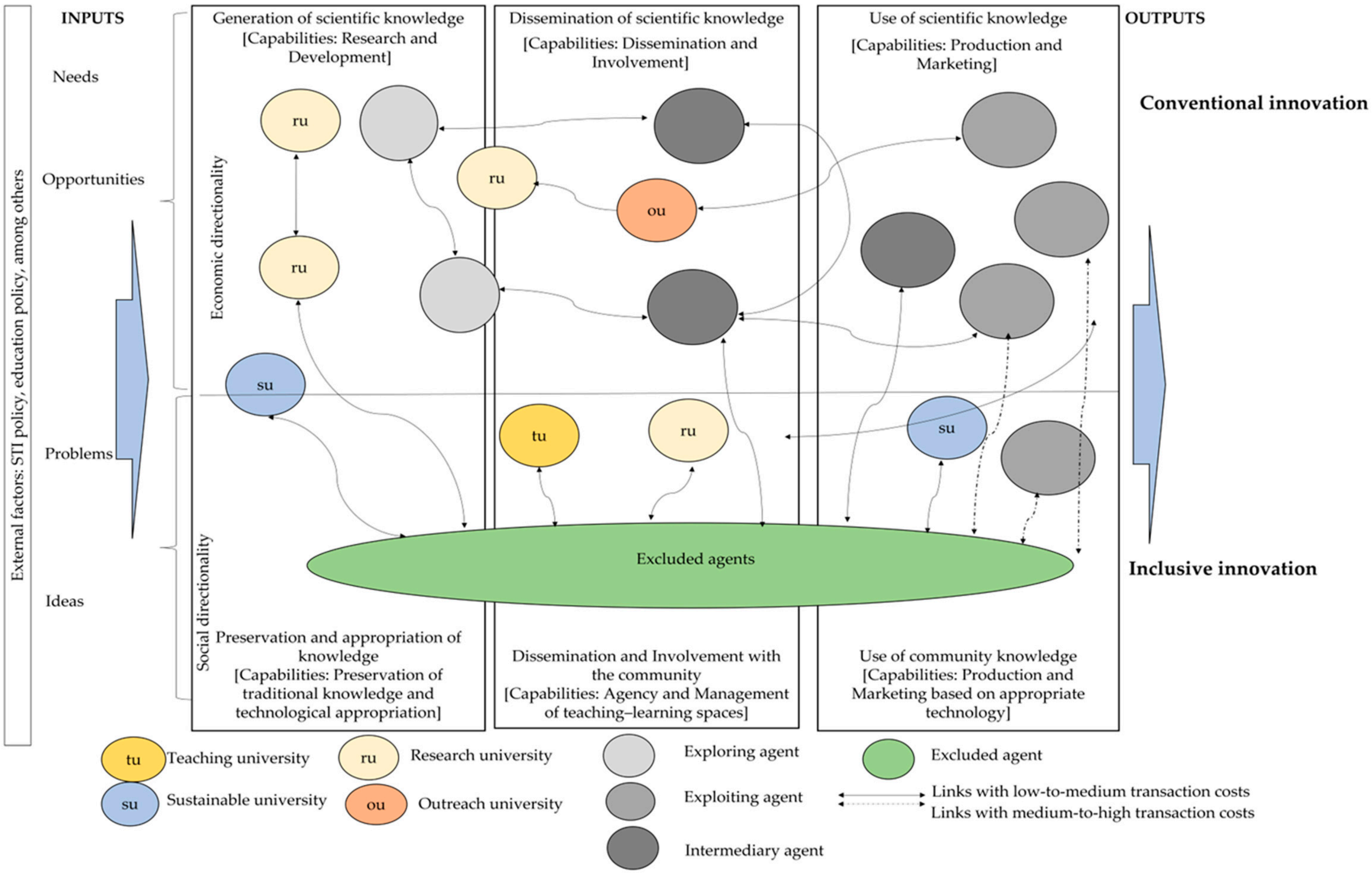

Figure 1. Conceptual model to analyze the role of the university in inclusive innovation [118].

4.2. The Role of the University in Reducing Social Exclusion, through the Design and Execution of Computational Simulation Scenarios Using ABSMs

Next, this section presents the scenarios designed, the variables chosen for the analysis, the statistical tests applied, and the results obtained from the simulation of each scenario.

Table 1 below details the eleven scenarios proposed here to simulate and analyze the relationship between the university and inclusive innovation and identify the generation (or non-generation) of social inclusion.

Table 1. Scenarios simulated in this study to analyze the relationship between the university and inclusive innovation.

No.	Name	Characteristics
1	Problem scenario	Conventional agents with no inclusion capability, universities with economic directionality.
2	Problem scenario + teaching university agent	Conventional agents with no inclusion capability, universities with economic directionality, only teaching university with inclusion capability and economic and social directionality.
3	Problem scenario + research university agent	Conventional agents with no inclusion capability, universities with economic directionality, only research university with inclusion capability and economic and social directionality.
4	Problem scenario + outreach university agent	Conventional agents with no inclusion capability, universities with economic directionality, only outreach university with inclusion capability and economic and social directionality.
5	Problem scenario + sustainable university agent	Conventional agents with no inclusion capability, universities with economic directionality, only sustainable university with inclusion capability and economic and social directionality.
6	Agents with inclusion capability, university agents with no inclusion capability	Agents with inclusion capability, universities with economic directionality but no inclusion capability.
7	Agents with inclusion capability, only teaching university agent with inclusion capability	Agents with inclusion capability, universities with economic directionality but no inclusion capability, only teaching university with economic and social directionality and inclusion capability.
8	Agents with inclusion capability, only research university agent with inclusion capability	Agents with inclusion capability, universities with economic directionality but no inclusion capability, only research university with economic and social directionality and inclusion capability.
9	Agents with inclusion capability, only outreach university agent with inclusion capability	Agents with inclusion capability, universities with economic directionality but no inclusion capability, only outreach university with economic and social directionality and inclusion capability.
10	Agents with inclusion capability, only sustainable university agent with inclusion capability	Agents with inclusion capability, universities with economic directionality but no inclusion capability, only sustainable university with economic and social directionality and inclusion capability.
11	Random	Random agents, simulate.

Table 2 describes the variables that were analyzed in each scenario to determine the behavior of the innovation system under the given conditions and establish the role of the university in inclusive innovation.

Table 2. Variables analyzed in this study to establish the relationship between the university and inclusive innovation.

Variable Analyzed	Description
Number of agents excluded	It presents the number of agents excluded and not excluded from the system, i.e., how the dynamics of the system cause these numbers to increase or decrease.
Participation of excluded agents	The participation of the excluded agents is analyzed based on the linkages that are formed. They measure the real participation of excluded agents in successful linkages within the system.
NOPIs used	It shows the number of (both) inclusive and conventional NOPIs that are successfully used in the system. The behavior of the inclusive NOPIs is analyzed because using them is the purpose of this inclusive innovation system.
Behavior of transaction costs	The behavior of these costs is an indication of the trust that has been developed among the agents in the system.
Conventional innovation capabilities	Research capability: produce and adapt knowledge and technologies.
	Development capability: experimentally develop products, processes, marketing methods, and organizational forms.
	Dissemination capability: capture R&D and technology results and take advantage of their benefits.
	Involvement capability: promote relationships among agents and build trust to use complementary capabilities in joint R&D&I projects.
	Conventional production capability: operate and maintain the production infrastructure efficiently and adapt and improve existing production technology.
	Conventional marketing capability: identify present and future market needs, develop new products, establish distribution channels, provide customer service, and disseminate innovation.
Inclusive innovation capabilities	Capability to preserve traditional knowledge: promote (make known), protect (care for), and preserve (maintain in its natural state) traditional knowledge.
	Technology appropriation capability: incorporate technology in an adequate, significant, and timely manner into the solution to daily problems.
	Agency: represent and give a voice to the excluded agents so that they can interact with the conventional agents in the system.
	Capability to manage teaching–learning spaces: foster spaces for co-creation among the system's agents, favoring the participation of excluded agents.
	Appropriate technology production capability: efficiently produce, adapt, and/or improve technological solutions using appropriate technology that can be produced at low cost or that integrates the excluded population into the process.
	Appropriate technology marketing capability: identify the present and future needs of an excluded community, develop new products, establish distribution channels, provide customer service, and advertise appropriate technology considering the needs of the excluded community.

To observe the dynamics of the inclusive innovation process, we carried out five simulations over a period of 25 years with the same number of agents (birth rate = 0%) for each scenario. This yielded a representative result for each scenario.

Figure 2 shows the behavior of the variable "behavior of excluded agents" as an example. It details the number of the excluded agents within the system in the eleven scenarios. The analysis of this variable is important because ultimately, the idea of an inclusive innovation system is to reduce the number of excluded agents by integrating them into its dynamics.

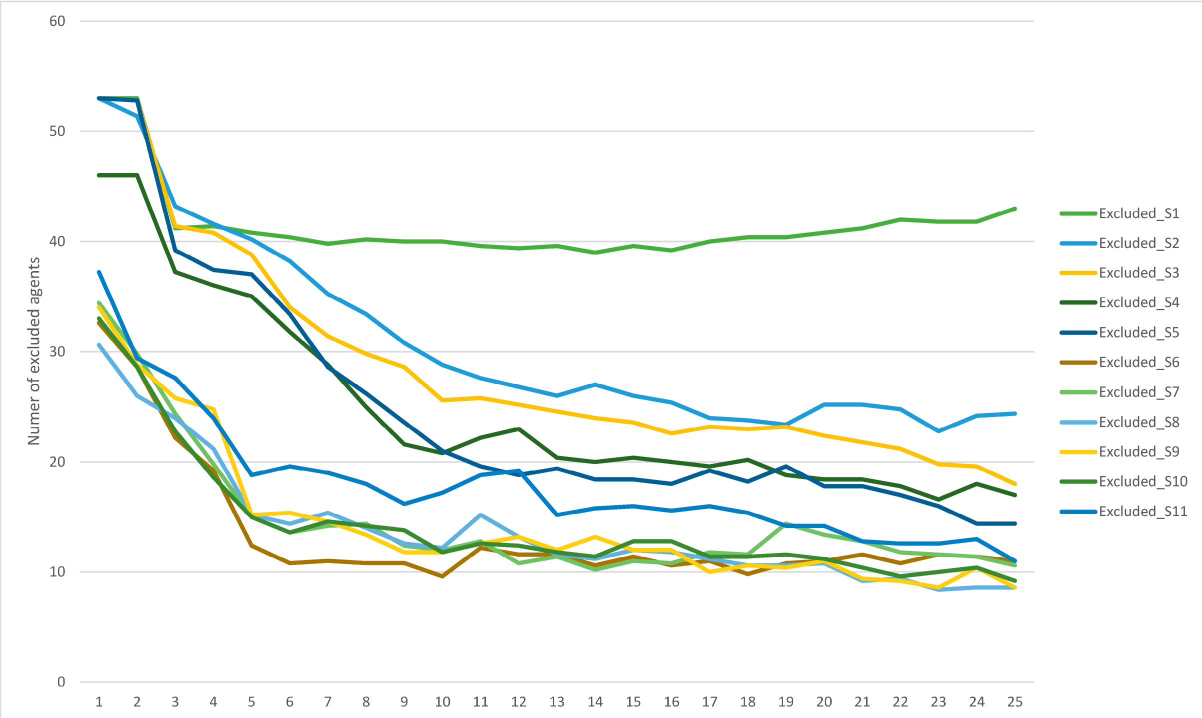

Figure 2. Behavior of excluded agents (example).

We applied a single-factor ANOVA test to the variable mentioned above in each of the eleven simulated scenarios. To this end, we averaged the five simulations executed per scenario over the 25 proposed periods (25 ticks) in order to accept or reject the null hypothesis, i.e., the number of excluded agents is equal in all the scenarios with a 95% confidence level. Table 3 reports the results of this ANOVA test.

Table 3. ANOVA results of the variable "behavior of excluded agents".

ANOVA		Degrees of Freedom	Mean Squares	F	Probability	Critical Value of F
Origin of Variances	**Sum of Squares**					
Among groups	20,792.4442	10	2079.24442	37.158778	6.9829×10^{-45}	1.86667259
Within groups	14,772.2976	264	55.9556727			
Total	35,564.7418	274				

Since the significance level was 0.05 and the p-value = 6.9829×10^{-45}, which is lower than the significance level, the null hypothesis was rejected, and the following alternative hypothesis was accepted: the number of excluded agents is different in at least one scenario with a 95% confidence level. Having accepted this alternative hypothesis, we concluded that there were significant differences in the number of excluded agents between scenarios. Using the Tukey test, we could identify which scenarios were different from each other.

To use this test, we should calculate the value of the honestly significant difference (HSD). Therefore, we need the value of the multiplier qα(v1,v2), the mean squared error (mean square within, MSW), and the size of the n groups:

$$\mathrm{HSD} = q_{\alpha}(v_1,v_2)\ (\mathrm{MSW}/n)^{1/2} \tag{1}$$

where

$q_{\alpha}(v_1,v_2) = 4.55$;

$\alpha = 0.05$ (for a 95% confidence level);

$v_1 = 11$ (number of groups);

$v_2 = 264$ (degrees of freedom);

MSW = 14,772.2976 (sum of squares within groups in the ANOVA table);

n = 25 (size of each group).

When the values were replaced in the equation above, we obtained HSD = 6.80712072652267, i.e., the value that can be used to compare the differences between the means of the eleven scenarios. Table 4 reports the differences between these means. The scenarios highlighted in grey exhibited significant differences between them (i.e., those that are not highlighted did not exhibit significant differences).

Table 4. Differences between the means of the variable "behavior of excluded agents" in the eleven scenarios (The scenarios highlighted in grey exhibited significant differences between them).

	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**
S1		11	13	17	17	28	27	27	27	27	24
S2			2	6	6	17	16	16	17	17	13
S3				4	4	15	14	14	14	14	11
S4					0	11	10	10	10	11	7
S5						11	10	10	10	11	7
S6							−1	−1	−1	−1	−5
S7								0	0	0	−3
S8									1	1	−3
S9										0	−4
S10											3
S11											−4

Subsequently, we performed a comparative analysis of each variable to examine its differences, similarities, and behaviors in the scenarios and thus answer the research question of this study (i.e., what is the role of the university in inclusive innovation?). Table 5 shows the matrix constructed for the analysis of these scenarios, as well as the performance of the variables analyzed here. In this matrix, we used a four-level comparative performance scale: worst performance (W), poor performance (P), good performance (G), best performance (B), and no performance (NP).

Table 5. Matrix for scenario analysis (scenario/performance variable).

Results of Matrix Analysis											
Scenario/performance variable	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
Number of excluded agents	W	P	G	G	G	W	B	B	B	B	B
Participation of excluded agents in successful linkages	G	G	W	W	G	W	P	P	P	P	B
Inclusive NOPIs used	W	G	G	G	G	W	B	B	B	B	W
Transaction costs	B	G	G	G	G	P	G	B	G	G	W
Research capability	P	P	G	B	W	P	G	G	G	G	B
Development capability	W	P	G	B	P	P	B	G	B	G	W
Dissemination capability	W	B	G	W	W	P	B	G	B	G	W
Involvement capability	P	G	B	W	P	G	G	B	B	B	W

Table 5. *Cont.*

Results of Matrix Analysis											
Conventional production capability	W	P	B	G	P	G	G	G	G	G	W
Conventional marketing capability	P	P	B	B	W	P	W	G	B	G	B
Capability to preserve traditional knowledge	NP	B	G	G	G	G	G	G	G	B	B
Technology appropriation capability	NP	G	G	G	B	G	G	G	G	G	B
Agency	NP	G	G	G	G	G	G	G	G	G	B
Capability to manage teaching–learning spaces	NP	G	G	G	G	G	G	G	G	G	B
Appropriate technology production capability	NP	G	G	G	G	G	G	G	G	G	G
Appropriate technology marketing capability	NP	G	G	G	G	G	G	G	G	G	G

5. Discussion

The analysis of this matrix produced eleven results:

1. The worst scenario was S1, known as the problem scenario. It was good only in terms of transaction costs.
2. S2 performed best in two out of sixteen variables (12.5%): dissemination capability and capability to preserve traditional knowledge.
3. S3 performed best in three out of sixteen variables (18.75%): involvement capability, conventional production capability, and conventional marketing capability. The worst performance of this scenario could be observed in the participation of excluded agents in successful linkages.
4. S4 performed best in three out of sixteen variables (18.75%): research capability, development capability, and conventional marketing capability. Its worst performance could be observed in the participation of excluded agents in successful linkages, dissemination capability, and involvement capability.
5. S5 performed best in one out of sixteen variables (6.25%): technology appropriation capability. Its worst performance was in research capability, dissemination capability, and conventional marketing capability.
6. S6 did not perform best in any of the variables and showed the worst performance in the number of excluded agents, participation of excluded agents in successful linkages, and inclusive NOPIs used. This demonstrated the importance of introducing a university with inclusion capability into the innovation system, even if it was inclusive, to contribute to social inclusion. Additionally, this scenario performed poorly in research capability, development capability, dissemination capability, conventional marketing capability, and transaction costs. This means that if an inclusive innovation system does not have a university agent with inclusion capability, its innovation and inclusion performance is worse.
7. S7 performed best in four out of sixteen variables (25%): number of excluded agents, inclusive NOPIs used, development capability, and dissemination capability. Its worst performance was found in conventional marketing capability.
8. S8 performed best in four out of sixteen variables (25%): number of excluded agents, inclusive NOPIs used, involvement capability, and transaction costs. It did not present any worst performance and only performed poorly in the participation of excluded agents in successful linkages.

9. S9 performed best in six out of sixteen variables (37.5%): number of excluded agents, inclusive NOPIs used, development capability, dissemination capability, involvement capability, and conventional marketing capability. It did not exhibit a worst performance and only presented poor performance in the participation of excluded agents in successful linkages.
10. S10 performed best in four out of sixteen variables (25%): number of excluded agents, inclusive NOPIs used, involvement capability, and capability to preserve traditional knowledge. It did not exhibit a worst performance and only presented poor performance in the participation of excluded agents in successful linkages.
11. S11 performed best in eight out of sixteen variables (50%): number of excluded agents, participation of excluded agents in successful linkages, research capability, conventional marketing capability, capability to preserve traditional knowledge, technology appropriation capability, agency, and capability to manage teaching–learning spaces. Nevertheless, it performed worst in six out of sixteen variables (37.5%): inclusive NOPIs used, transaction costs, development capability, dissemination capability, involvement capability, and conventional production capability. This means that having an innovation system in which all agents have inclusion capability does not necessarily have a favorable impact on the innovation performance of the system.

These results are consistent with the literature regarding the need to improve the inclusion capabilities of the university. Specifically, Ref. [114] stressed the importance of three actions: establishing relationships with vulnerable social actors and focusing research programs on these communities; improving education technically and ethically to enhance social, frugal, and inclusive innovation; and promoting and favoring the confluence, in teaching–learning spaces, of non-conventional actors—i.e., informal sectors and communities excluded from the conventional innovation system (e.g., indigenous peoples, Black communities, farmers, and female heads of household).

In this sense, Albuquerque et al. [121] hold that the university should improve its inclusion capability and become an agent of change, creating structures that favor the participatory construction of knowledge. It should lead new social processes and structures that would help communities to respond to the challenges of their livelihood, while benefiting from the interaction and the local knowledge of the communities. In addition, they maintain that the university should strengthen its relationships with other organizations within the innovation system and build trust to lower transaction costs. Such relationships can be consolidated by means of intensive social outreach and research.

Additionally, Kruss et al. [122] emphasize the importance of strengthening the relationship with the agricultural sector because it is essential for the social, economic, and environmental spheres. Therefore, if a university aims to be sustainable, it should develop relationships with companies, communities, and agents from the agricultural innovation system and work with this sector on the four missions of the university (i.e., teaching, research, outreach, and sustainability). Likewise, the university should reconsider its institutional boundaries and be open to collaboration with non-traditional partners (i.e., the informal sector), especially in the Global South because this stimulates innovation at the local level. This can be achieved using socially sensitive knowledge transfer models that promote collective agency and produce a systemic change in society [123].

These results are also in line with the paper by Adeoti et al. [124], who emphasized the need to strengthen the relationships between the university and the informal sector to materialize these types of innovations. They also highlighted the importance of strengthening partnership networks to include multiple stakeholders and address economic and social problems, which could be an interesting way of leveraging inclusive innovation because there are incentives for participating in these types of networks.

Last, these results support the idea of the "democratization of knowledge", which can be achieved by promoting the production and use of knowledge and incorporating incentives into research agendas to find solutions that lead to social inclusion [115]. In this sense, innovation should foster social inclusion by two methods: (1) not only promoting economic competitiveness to find solutions to social inclusion problems but also creating jobs with innovations by and for marginalized populations and (2) connecting high-level technology and science with social policies.

6. Conclusions

Social exclusion is one of the biggest challenges facing humanity nowadays. This type of exclusion goes beyond poverty: it is a matrix of events that hinders humanity from welfare and fully enjoying life. It includes poverty, neglect, destitution, lack of access to basic services (e.g., food, healthcare, housing, and education), and poor social relationships and ties. All of these increase social dissatisfaction and prevent individuals from overcoming this state of neglect [125].

There is a global strategy to promote several innovation paradigms that address the current challenges of humanity. Such paradigms include social innovation, grassroots innovation, frugal innovation, and inclusive innovation, which offer a different view of the processes of science, technology, and innovation to achieve not only economic growth but also inclusive development. These initiatives have been consolidated in India, Africa, Asia, Latin America, and other developing countries in the Global South, where poverty, inequality, inequity, and other social problems are predominant. These new approaches highlight the need for different innovation paradigms that address these problems in a realistic way, rather than continuing to build unsustainable economic growth that only benefits a few.

This article proposed a formal theoretical representation of an innovation system as an agent-based model, which can be used to study the role of the university in inclusive innovation while considering the specific realities of the Global South and its pressing societal challenges. This model captured the systemic complexity inherent in the dynamics of innovation and served as a laboratory platform to study "what if" scenarios employing computer simulations. The model passed the conceptual and operational validity tests within the scope defined by the assumptions and conditions introduced in the design phase, as occurs with all formal theoretical models. Afterward, the model was operationalized to run eleven scenarios that were previously defined to examine the role of the university in inclusive innovation. This scenario analysis provided several meaningful insights:

The need for a shift of perspective: from conventional to inclusive innovation:

Conventional innovation can work well from the point of view of economic growth, productivity, and competitiveness. Furthermore, the performance of this innovation system can be satisfactory, and the contribution of the university could be evaluated positively. However, seen from the perspective of the excluded populations, conventional innovation can be a problem, as shown in the simulation scenarios. For example, scenario 1 (S1), precisely called the problem scenario, performed worst in most of the selected performance variables, except in "transaction costs". This result is consistent with the fact that conventional innovation systems eliminate the difficulties associated with the interactions between conventional and excluded agents.

The introduction of the notion of "inclusive innovation capabilities" and its differentiation from "conventional innovation capabilities":

According to the resource-based view and the learning economy, organizations need to accumulate capabilities to achieve strategic objectives. In fact, there is abundant literature on the type of capabilities that organizations need to successfully compete in the marketplace and maximize profits. However, changing the perspective from conventional to inclusive innovation systems requires a whole new set of capabilities, which we call "inclusive innovation capabilities". These capabilities are complementary to conventional ones in the sense that both types of capabilities are necessary to build inclusive innovation systems. The following are some inclusive innovation capabilities:

- The capability to promote, protect, and preserve traditional knowledge, so that it contributes—together with scientific and technological knowledge—to successful innovative solutions to societal challenges;

- The capability to appropriate foreign scientific and technological knowledge in an adequate, significant, and timely manner as needed to provide sustainable local solutions to community problems;
- Agency, which gives voice to and empowers excluded agents to interact with other agents in the system;
- The capability to manage teaching–learning processes, offering spaces and opportunities so that agents can share knowledge and co-create original solutions, thus favoring the participation of excluded agents;
- The capability to appropriate technology, that is, to devise production solutions that meet the cost, quality, and sustainability requirements of local communities, thus integrating the excluded agents into the process;
- The capability to appropriate technology, that is, identifying present and future needs of an excluded population, introducing new products to potential users, establishing distribution channels, providing customer service, and advertising innovations, while considering the needs of the excluded communities.

These inclusive innovation capabilities are a necessary complement to the social directionality of inclusive agents. This is because a social strategic commitment and objectives cannot be successfully fulfilled without the support of those capabilities needed to act and interact systemically and thus take meaningful collective action.

It is not necessary to remove conventional innovation from an innovation system to transform it into an inclusive innovation system. On the contrary, as scenarios S2 to S11 showed, it seems that eliminating the agents and interactions related to conventional innovation does not improve the inclusive performance of the system. This is a remarkable result, as it suggests that conventional innovation systems could evolve into inclusive ones given the right systemic conditions.

Systemic conditions for inclusion:

As an overall result of the simulation scenarios, the following seem to be the necessary conditions for an innovation system to be inclusive:

- The presence of inclusive NOPIs and agents that can identify and respond to them, triggering the inclusive innovation process with the participation of agents that have the required innovation capabilities;
- Agents with social directionality, that is, with a strategic commitment to contribute to societal sustainability goals, which makes them capable of recognizing inclusive NOPIs and, furthermore, of interacting with the excluded agents to configure inclusive NOPIs;
- The presence of agents whose innovation capabilities, both conventional and inclusive, complement each other so that they can participate collaboratively in successful innovation processes to respond to specific NOPIs;
- The existence of contextual factors that contribute to the economic viability of agents—associated with a positive balance between operating and learning costs, on one hand, and the economic benefits received during the life cycle of the innovations, on the other.

Inclusive innovation systems need inclusive universities:

The university has had one main objective throughout history: to produce social welfare. In addition, it is part of innovation systems because it can produce knowledge and technological development. For these reasons, the university is considered an institution that can generate inclusive innovation and thus help to reduce social exclusion. Based on these premises, this study proposed a theoretical–conceptual model that adopted a systemic, complex, adaptative, and functional approach. This model—composed of different types of agents, interactions, capabilities, learning processes, knowledge, and directionalities—was used to study the role of the university in inclusive innovation.

An inclusive university is one that has an inclusive orientation and inclusive innovation capabilities. However, although the participation of inclusive universities tends to favor the inclusive performance of an innovation system, as shown by the computer simulations, their role and contribution depend on the systemic conditions provided by other components of the system: the NOPIs, the participating agents, the directionality and the capabilities of agents, the interactions established between them, and other circumstances given by certain contextual factors. This is an important finding as it highlights the interdependence of the multiple roles played by different agents in the innovation system.

In summary, the role of the university in inclusive innovation depends on a variety of factors associated with the complexity of innovation systems. Although the model proposed here is a step forward in understanding this complexity, much more research is needed to unveil the dynamics that fully explain the inclusive performance of innovation systems and the contributions to this performance by specific agents, including the university.

7. Theoretical and Practical Implications

The hypothesis in this study is that inclusive innovation emerges as a possibility to overcome the limitations of the conventional approach to innovation, specifically regarding the fight against social exclusion. The university, as a key participant in innovation dynamics, is called upon to play an important role in the generation of inclusive innovation, especially considering its natural commitment to society. Hence, it is important to understand the role of the university in the generation of inclusive innovation dynamics.

Computer simulation models are based on theoretical models (often called "conceptual models") that are then operationalized and translated into the selected computer language to run the simulations. The model proposed in this article to study the role of the university in inclusive innovation, with the aim of reducing social exclusion in the Global South.

Regarding the practical implications of this study, the role of the university was analyzed from a systemic and complex perspective, focused not only on the generation of innovation but also on inclusive innovation. As a result, the social dimension of innovation was also incorporated, going beyond the conventional approach of productivity and competitiveness. This study demonstrated that the university is a fundamental agent in the generation of inclusive innovation and, therefore, the reduction of social exclusion.

These results provided insight into the performance of the system in terms of innovation and inclusion, which depend on the capabilities and mission of the university. They also showed that the university should undertake different missions depending on its purposes. Consequently, decision makers, researchers, and public university policy makers should address the problem of social exclusion in the mission of each university.

Based on these results, the public STI policy in the Global South should be reformulated because inclusive innovation processes require not only innovation capabilities but also inclusion capabilities (i.e., preservation of traditional knowledge, technology appropriation, agency, management of teaching–learning spaces, and production and marketing of appropriate technology). These capabilities should be stimulated and promoted among the agents that compose the system. Furthermore, the university—naturally devoted to social welfare—can be a suitable space to promote, develop, and strengthen those capabilities and actively generate inclusive innovation processes.

8. Limitations and Future Research

We acknowledge that a model is only an abstraction of reality that can be used to define a problem, and there may be other characteristics that were not taken into account in the development of this model. Therefore, the information and results produced by the model should be carefully considered because a model, despite its robustness and power, is nothing more than an approximation to reality from the perspective of its designer. This entails a significant bias that is expected in the probability of occurrence of events; however, it is one of the limitations of this type of study. Additional experiments can be conducted to enrich and adjust the model and thus improve its performance and approximation to reality.

Computational modeling and simulation and other techniques can provide more information about phenomena of this type than only qualitative or quantitative methods alone. This means that computational modeling and simulation has opened the doors to a kind of exploration in which both methods (qualitative and quantitative) can be implemented. This minimizes the error in both, and it enables a holistic and integral analysis, which is necessary to investigate this type of phenomenon.

Future studies can examine inclusive innovation systems applying several computational modeling and simulation techniques, which can enrich the methodological approach presented here. They can minimize and compare errors based on the premise that they are adaptive complex systems. Other case studies can refine and recalibrate this model to apply it to other agents and their role in inclusive innovation.

Finally, further research in this field can implement additional simulations to investigate the impact of new policies on the model and address the following questions: How can a policy influence the parameters of an innovation system so that it responds to the desired purposes? What is the effect of policy on the behavior of the agents? How does the system change? What would be the best policy depending on the desired results?

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