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Modeling Sustainability: Insights from an Agent-Based Approach to Sustainable Urban Community Development

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Abstract

This work examines the potential of agent-based modeling (ABM) to explore and understand sustainability in urban communities. The study aims to identify how sustainable practices can emerge from localized decision-making and social dynamics by focusing on the interactions between households, residents, and their environment. The model can provide insights into the social, economic, and environmental dimensions of sustainability within an urban community by simulating predefined scenarios. While this study phase establishes the conceptual framework and methodology, future efforts will enhance the model's reliability with empirical data and involve stakeholders to refine its relevance to urban policy and planning.

Keywords

Sustainability, Households, Urban communities, Agent-based modeling.

1. Introduction

The world population has been increasing since the Industrial Revolution, which began in the 18th century. The United Nations predicts that the global population will continue to grow and peak at approximately 10.3 billion people by the mid-2080s, up from 8.2 billion in 2024 (United Nations, 2024a).

According to Clark (2023, p. 1), "An increasing world population, with its burgeoning middle classes, is leading to an unprecedented demand for consumer goods and other articles, resulting in an accelerating demand for resources." Our current (linear) economic model for satisfying this demand is based on the use of virgin resources that have been mined (at increasing cost), processed (often in several stages), consumed, and then eventually disposed of (often in an uncontrolled way leading to pollution”. This linear economy model is also known as the “take-make-waste” system.

Along with this, technological and scientific advancements have been made, bringing comfort and increased productivity to people. People’s living needs have also presented new challenges, including food supply, healthcare, housing, education, security, and transportation. All those needs are amplified by the increasing population, and fulfilling them endangers the planetary environmental systems (Richardson et al., 2023).

The United Nations introduced the concept of sustainable development as the capacity to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987, p. 37). Brundtland (1987) has shaped the idea of sustainability through three interconnected dimensions: economic growth, environmental protection, and social equality.

On the other hand, one aspect strongly related to sustainable development is housing, which promotes the well-being and quality of life of individuals. Social sustainability is often vague, making it a challenge for specialists to evaluate housing. Despite its importance, housing construction projects usually overlook the social dimension of sustainability (Rostamnezhad, Thaheem, 2022).

According to the United Nations (2024b), the global urban population in slums or informal settlements has remained at an alarming average of 25% since 2015.

In this context, housing is crucial for meeting one of the key priorities in people's well-being. A household refers to a social unit of people who live together and share living arrangements, regardless of the physical structure in which they reside. A residence relates to the physical place or location where someone lives. From both physical (material) and functional (service) perspectives, it should meet the occupant’s needs. The housing sector is mainly based on the linear economy. It is a significant consumer of resources, including both renewable and non-renewable materials and energy, and a substantial producer of waste and greenhouse gases (Ghafoor et al., 2023).

The design of a sustainable residence should follow a sustainable life cycle during its design, construction, and operation. During construction, materials must adhere to sustainable material use and storage principles, and the appropriate selection of materials and waste disposal practices must be observed. In operation, water and energy must be appropriately utilized, considering these resources. The same sustainable principles should be applied to food and clothing consumption, as well as when selecting household appliances.

Households that interact with one another form communities. A community is, according to the Cambridge Dictionary (2024), "the people living in one particular area or people who are considered as a unit because of their common interests, social group, or nationality.”

An urban community is part of a city. Urbanization is a complex socioeconomic process that has been growing rapidly in recent decades, bringing numerous challenges to society, the economy, and the environment. More than half of the planet’s nearly 8 billion inhabitants are concentrated in over 10,000 cities, creating significant opportunities and challenges for urban environments that face increasing demands for infrastructure, resources, and public services.

The impact of urbanization on the environment must also be considered, as rapid urbanization increases the pressure for more resources and infrastructure services, as well as housing and environmental effects, contributing significantly to global greenhouse gas emissions. The challenge is to balance economic, social, and environmental conditions to create resilient, inclusive, and environmentally friendly cities. Economic growth is a key driver of urbanization, but it must grow sustainably. Sustainable urban development requires smart investments in infrastructure, particularly in public transportation, renewable energy, and efficient housing (Kaminski, 2024).

The social impacts of this study are social well-being (residents' primary objective) and security (living without external threats) in a community. These impacts will be followed by monitoring of social, environmental, and economic effects. The goal is to develop a tool that can monitor activities carried out in the community. These activities could follow safe procedures and rules defined by the community. Instead, on the environmental side, it could include creating and maintaining leisure spaces, improving sustainable internal practices in a residence, and having access to transport and the internet. On the economic side, this could provide access to more attractive and well-located job opportunities. The results aim primarily to improve residents' lives, contribute to environmental sustainability, and reduce resource consumption in the community.

These impacts are linked to several UN Sustainable Development Goals (SDGs). Specifically, SDG11 – Sustainable Cities and Communities establishes a goal that is "about making cities and human settlements inclusive, safe, resilient, and sustainable." Other SDGs are also linked, such as SDG1 - No Poverty, SDG2 - Zero Hunger, SDG3 - Good Health and Well-being, SDG5 - Gender Equality, SDG6 - Clean Water and Sanitation, SDG7 - Affordable and Clean Energy, SDG8 – Decent Work and Economic Growth, SD12 - Responsible Consumption and Production, and SDG13 - Climate Action (United Nations, 2024b).

This study aims to understand how an urban community can achieve sustainability by fulfilling its needs (goals), promoting intrinsic behaviors (decision-making), and considering the interactions and influence among its members (network and relationships). The economic, environmental, and social sustainability dimensions must act synergistically in the community setting. Considering sustainability as an emerging attribute of complex systems, the proposed approach seeks to evaluate, in a smaller-scale context with a limited number of households, how sustainability can emerge from the interactions of a reduced number of interacting agents and, thus, contribute to the initial understanding of this phenomenon. Once sustainability is achieved, this representation of the community could serve as a foundation for subsequent, broader studies of cities, states, and countries.

While pursuing the stated goal, this study also seeks to address the following research questions:

- RQ1: Is it sufficient to use an agent-based approach to model and simulate the sustainability emergence within an urban community of residences?
- RQ2: Is it possible to map the emergent dynamic concept of a sustainable urban community using households as agents?
- RQ3: What are the limitations of this approach?

The remainder of the article is divided as follows: Section 2 presents previous related works that somehow connected to this present study, Section 3 presents the methodology used; Section 4 presents the results obtained in this research phase and the related implications; Section 5 presents the final considerations, with the limitations faced and indications of future research directions.

2. Related works

An urban community is a group of people in a small ecosystem within a city. Many similar demands to those of traditional large cities need to be addressed to develop communities economically, environmentally, and socially. However, actions by both public agents and private individuals must be synergistic to optimize the use of resources. To better understand how these communities operate, modeling, simulation, and analysis techniques are employed to extract essential data, enabling the development of long-term development plans. In this sense, some work has been carried out using the Agent-Based Modeling (ABM) approach in urban communities.

Mariano & Alves (2020) proposed a study on water resource management in peri-urban communities based on ABM and role-playing games (RPG). The inclusion of social processes in environmental simulations, where ABM modeling is used to simulate these complex systems, is considered crucial. The ABM model was developed on the GAMA platform. The modeling exercise was conducted in a peri-urban agricultural community located in the hydrographic basin of the Federal District, Brazil. The developed ABM was able to satisfactorily reproduce the relationship between land use and local water resources in the community's agricultural production, and could generate scenarios that were presented to the local community to illustrate the impacts on water resources resulting from their decision-making.

Gonzáléz-Mendez et al (2021) proposed the use of ABM for urban development planning, based on the relationship between city dwellers and the satisfaction of their basic needs with their physical environment, instead of traditional thinking in urban development often focused on the expansion and construction of places aimed at satisfying economic activities and market needs. As a result, the simulation platform developed in NetLogo can serve as a starting point for a collective and prospective vision of the city, focusing on participatory modeling with multiple stakeholders. The basis for using ABM and other simulation tools is to represent the microdynamics present in urban changes that result in emergent patterns. The developed ABM model can be linked to established knowledge, with ideas associated with territorial government and urban planning.

Nagai & Kurahashi (2021) present an exploratory ABM model of urban dynamics to simulate the relationship between residents, the promotion of interaction in their surroundings, and transportation policies in sustainable urban development. The objective was to extract insights into changes in urban forms, which depend on the behaviors of each resident. The model experimentally suggested the existence of a trade-off between increasing human interactions and promoting interaction in their surroundings, as well as the progression of residential diffusion. The work also discussed intervention policies for sustainable urbanization and transportation policies, focusing on changes in the specific spatial behavior of residential diffusion at urban edges, which results from the collective action of individual residents.

Vuthi, Peters, and Sudeikat (2022) conducted a literature review on ABM for analyzing urban neighborhood energy systems. This review was prompted by the growth of urban neighborhoods facing thermal transition needs, the increasing adoption of battery electric vehicles, and the expansion of renewable energy sources. The integration of energy systems, including electricity, heat supply, and mobility, in neighborhoods is essential, particularly in densely populated areas. These three sectors interact and offer synergies for improving efficiency and integrating renewable energy. The reviewed works demonstrated the diversity of uses of ABM, covering political, economic, environmental, and technical issues. A critical aspect identified in ABM studies is the energy communities involved: groups of actors (residents, users, and prosumers) in a neighborhood that can share electricity generated from solar energy and merge demands from homes, heat generators, and battery electric vehicles locally to increase self-sufficiency. Another finding was the application of ABM to various topics to support decision-making for energy stakeholders (communities, businesses, urban planners, and policymakers). With the knowledge acquired, the authors proposed an ABM model to analyze the effects of policies and local market mechanisms in urban neighborhoods.

Elkamel et al. (2023) proposed the use of ABM to analyze the Food-Energy-Water Nexus (FEW) as a basis for the sustainable development of an urban agriculture network. The study involved simulating interactions between FEW agents, i.e., consumers, producers, microgrid operators, water managers, and green vehicles, to assess the necessary and sufficient conditions of a FEW Nexus and understand the cross-sectoral trade-offs and inflection points that lead to the identification of synergistic effects and mitigation strategies. The novelty of the study lies in the integration of policy, technology, and management, utilizing the NetLogo simulation tool to develop ABMs, and conducting analyses in the southern regions of the state of Florida, USA, as scenarios.

Divasson-J, et al. (2025) conducted a systematic literature review to examine the applications of ABM in urban human mobility, focusing on the tools, methodologies, and approaches commonly used by researchers in the field. The analysis of model scales highlights the predominance of the area and city scales, with the intersection, metropolis, and street scales being less explored. In the analysis of technological environments, only 16.2% of the authors specified the computational tools used. However, the analysis highlights the growing use of specialized ABM tools, including SUMO (26.13%), AnyLogic (12.61%), NetLogo (9.91%), GAMA (7.21%), and MATSim (7.21%). The data collected showed that the application of ABM in urban mobility has grown exponentially over the last decade, with a peak in 2015-2016, influenced by the growing interest in climate change in 2016 and the European Union's development of climate targets for 2030.

ABM has been increasingly utilized in recent research to analyze complex socio-environmental systems and dynamics of sustainable development across various spatial and policy contexts. An example is the creation of an ABM of rural Medellín, Colombia, which illustrates how simulation modeling can inform policy analysis by modeling the interactions between rural communities, migration, and land cover changes under different policy scenarios (Castillo Grisales et al., 2024).

In a similar vein, Secchi et al. (2023) introduce a theoretical framework in which ABM is not only used as a method but also as a mechanism for theorizing sustainable development. It prioritizes integrating feedback, emergence, and adaptation at the systemic level in ABM design, particularly as a means to capture the nonlinear nature of sustainability transitions more effectively.

Two studies also illustrate the application of ABM to policy and spatial change in rural China's transformation. Lu et al. (2022) evaluate the effects of new-type urbanization policies on rural settlement patterns, demonstrating how individual-level decision-making influences the creation of aggregate spatial restructuring patterns. The study highlights ABM's ability to replicate the unforeseen effects of top-down policies. Supplementing this, Zhang et al. (2025) explore the phenomenon of hollow villages under an agent-based complex systems framework, including land attachment as a social explanatory variable. By incorporating cultural and emotional aspects of decision-making, the research develops a richer understanding of rural land uses.

Though previous work establishes varied applications for ABM, this work-in-progress is differentiated by its emphasis on the emergence of sustainability in urban neighborhoods through social interactions and local decision-making. The research is specifically interested in how sustainable behavior develops through social and physical interactions among residential populations and their surroundings.

The novelty of the current study is in its examination, in a more localized setting with a small number of homes, of how sustainability arises from the behavior of a smaller set of agents. This establishes the initial foundation for understanding this complex phenomenon, before its scale growth, in studying its implications in cities, states, and nations. The ultimate goal is to develop a microcosm simulation model, considering the context of an existing case study within communities, which will lead to an improved understanding of how to promote the quality of life for residents, increase environmental sustainability, and reduce resource consumption. Ideally, through this work, a mechanism for fostering double-loop learning regarding sustainable development is provided, utilizing it as a tool for questioning assumptions and systemic norms, ultimately supporting adaptive and transformative change.

3. Methodology

ABM has been utilized to examine complex socioeconomic systems, where individual behaviors and interactions give rise to emergent phenomena that are challenging to predict using analytical methods, including construction (Khodabandelu & Park, 2021). They are stochastic, bottom-up models in which individual agents are assigned specific attributes and programmed to interact with each other and their environment according to predefined rules. These models enable us to specify simple rules for agents and examine how these rules impact system-wide behaviors.

In social science, most phenomena occur not as the result of isolated individual decisions but from repeated interactions between multiple individuals over time (Smith & Conrey, 2007). ABM is an approach that enables understanding of such dynamic and interactive processes. It involves simulating a set of agents interacting with each other and the virtual environment while observing emergent patterns that arise from their interactions.

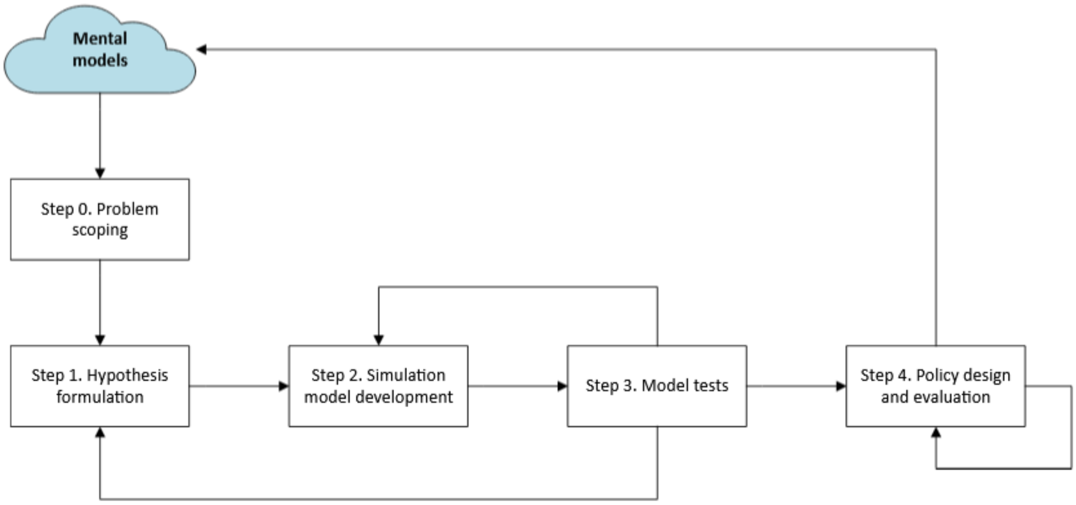
Modeling and simulation approaches are widely used in social science research. They enable experiments and analyses that are not feasible in the real world (due to temporal, economic, ethical, or other constraints). Several approaches, including agent-based modeling (ABM), have been used for decades.

Simulations, especially ABM, enable us to compress time and space while testing hypotheses, exploring theoretical scenarios, and evaluating intervention policies. ABM is a computational approach used to simulate the interactions of individual agents (i.e., autonomous decision-making entities) within a given environment (or virtual world), observing the collective effects of these interactions over time.

Thus, as this study seeks to investigate the socioeconomic dynamics of the shift toward sustainable housing, it will develop and employ a simplified representation of a hypothesized local community. This simplified representation will consist of an agent-based model, which will support the analysis of different scenarios and the design and evaluation of potential intervention policies capable of stimulating such a transition.

The process used to achieve the proposed objective is illustrated in Figure 1.

Figure 1. Proposed development process adopted.



It departs from mental models and existing knowledge for problem scoping and definition. Then, a hypothesis is formulated based on identifying entities (or agents) and how they interact over time, which is translated into a complete simulation model. The developed simulation model is then tested following good practices to build confidence in its formulation before being used for scenario analysis, policy design, and evaluation.

In addition to the overall process depicted in Figure 1, several methods, protocols, and tools will be used during each workflow step, as summarized in Table 1.

Table 1. Methods, protocols, and tools used in the study.

Step #	**Methods, protocols, and tools**
0. Problem scoping	Literature review
1. Hypothesis formulation	Literature review Interviews with subject matter experts Participatory modeling approaches

	ODD
2. Simulation model development	ODD NetLogo
3. Model tests	NetLogo Good practices
4. Policy design and evaluation	Simulation model

A systematic literature review (SLR) is a research method for reviewing, updating, critiquing, and improving knowledge about a specific topic (Carrera-Rivera, 2022). This ongoing study employs the SLR for problem scoping and hypothesis formulation (Steps #0 and #1). It helps to identify and retrieve existing knowledge on sustainable development in urban communities and housing. It also identifies secondary data sources for the following steps when defining the model's implementation, calibration, and testing.

Additional sources of knowledge are planned, in addition to the SLR, including peer-to-peer interviews with subject matter experts and participatory modeling approaches for gathering complementary knowledge (Step #1). We will conduct peer-to-peer interviews with experts to identify initial concepts, theories, key variables, patterns of behavior over time, and decision-making rules. Then, we will employ a participatory modeling strategy with relevant stakeholders, which consists of a "purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality" (Voinov et al., 2018, p. 233).

The "ODD" (Overview, Design concepts, and Details) protocol will be employed to describe the proposed formulation, making it more understandable, complete, and reproducible (Grimm et al., 2020). Besides being applicable as a formal protocol for obtaining a standardized document for describing the structure and dynamics of ABMs, it is also helpful as a workflow for supporting and guiding the model design process (Step #2).

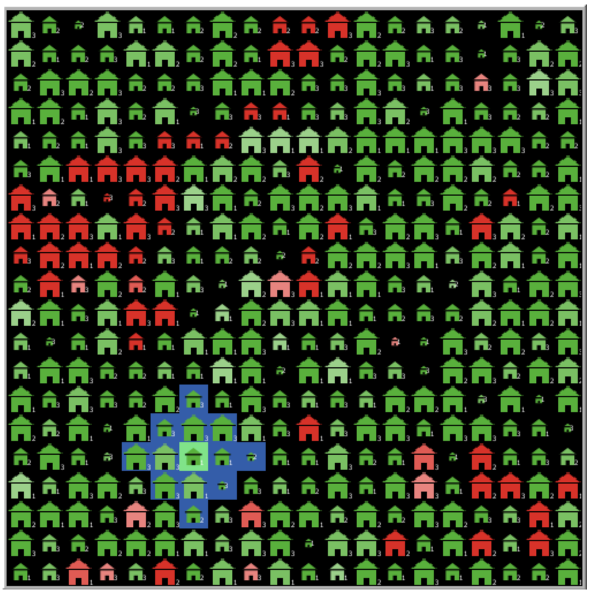
The NetLogo (Wilensky, 2023), a multi-agent programmable modeling environment, will be used to translate the retrieved knowledge, concepts, and formulations gathered from the previous steps into a complete and executable simulation model (Step #2), which will be used to test the stated hypotheses, evaluate potential scenarios, and design and assess candidate intervention policies.

Once the model is developed, it will be tested following the ABM's best practices (Step #3). A one-at-a-time sensitivity analysis will be conducted with a different seed for each run. NetLogo enables the model to run many times while varying its settings. The obtained outputs enable one to define the space of possible behaviors and identify the combinations of settings that elicit the desired behaviors (Wilensky, 2023).

The last step involves designing and evaluating candidate intervention policies (Step #4). After building confidence in the developed simulation model, it will simulate potential outcomes when specific policies are introduced into the virtual environment. We will then evaluate the emergence of new dynamic behaviors from exogenous influences. Examples of policies that could be evaluated include financial incentives for adopting green technologies (e.g., lower energy consumption appliances), taxes on high waste generation and water consumption, and advertising campaigns for behavioral changes (e.g., reducing consumption).

Figure 2 shows an initial representation of the proposed virtual world. The “virtual community” is represented as a square with 20 x 20 patches containing three types of agents: houses, residents, and the environment (i.e., patches). Each patch has a household containing the physical structure and a number of residents (ranging from 1 to 4). The household is represented by a house icon, which illustrates some of its characteristics: sustainability orientation (color gradient between green and red), social status (the bigger the icon, the higher the social status), and the number of residents (small white number on the bottom right of the house’s icon).

Figure 2. The model’s virtual world with its agents, some of their characteristics, and interactions



At every time step, the residents of each household interact with one another and with their neighbors, represented by the blue area in Figure 2, which can vary according to social status, to make decisions based on a set of predefined rules. Those decisions will alter the state of all agents within the virtual community, influencing the subsequent iterations of the simulation and driving the emergence of new patterns (e.g., clusters of sustainable or unsustainable neighbors, represented by red and green areas).

4. Results and implications

This research aims to understand the dynamics of an urban community, from households to their residents, in the context of sustainable development. For this, the proposed ABM model defines a set of residences as a multi-agent system. From the environment's stimulus to the community, we can create hypothetical scenarios to investigate how to evolve a sustainable community.

As a first outcome, we intend to create a simulation model to study how a community can become more productive and make cost-effective decisions, including facility maintenance, tree planting, and the implementation of new leisure areas. This can encourage residents to reflect on their everyday needs and participate more in decision-making, creating greater awareness about sharing resources and preserving values and spaces. As a tool, we can examine whether sustainable development initiatives are economically viable, whether the effort to maintain sustainable practices indeed benefits residents' well-being, or whether sustainable development routines can be easily incorporated into a community's everyday life.

As the second outcome, we can examine how a community can evolve based on sustainable development strategies within the Sustainability Pillars (Ghimire, 2023). Urban planning and community governance can be improved, making the area more attractive for new residents, assisting public authorities with their needs, and meeting demands for new investments. Furthermore, it can improve the integration with the rest of the city.

From evolving the community, good practices for sustainable development can be identified. For example, it can serve as an experimental laboratory to orient actions for broader strategies based on sustainability dimensions, such as environmental, economic, and social.

The proposed agent-based model seeks to provide a platform for fostering double-loop learning on sustainable development in urban communities. Double-loop learning encourages questioning and reassessing underlying assumptions and systemic norms to promote adaptive and transformative change (Argyris, 1976). The model enables stakeholders to identify the issues, structures, and decision-making rules that drive community behavior by simulating interactions among residents, households, and the environment. For instance, the simulation could reveal how implicit norms regarding natural resource consumption or neighborhood interactions influence sustainability outcomes. The model can stimulate learning and promote paradigm and mindset shifts rather than incremental adjustments by testing candidate intervention policies using the simulation model.

Moreover, applying double-loop learning (Argyris, 1976) in this context enables the co-creation of sustainable strategies by actively engaging with the feedback loops inherent in the system. As the model provides insights into the interplay between social, environmental, and economic dimensions, it supports a learning process that fosters a deeper understanding of how community agents interact and behave to achieve their intrinsic goals. By using the model to experiment with policies and strategies, such as electrification, recycling, or behavioral change campaigns, the community can iteratively adapt its approach to sustainability and move towards a collective learning process that triggers the emergence of sustainable urban communities.

Although the proposed analysis will be conducted in a small and hypothetical scenario represented by the agent-based model, the obtained results could be tailored and extended to real and larger contexts by calibrating the model's parameters, initial conditions, and decision-making rules. Thus, it can potentially promote and contribute to the sustainable development challenges that communities and cities face.

5. Final remarks

5.1. Current stage and limitations

The modeling of complex systems is essential initially due to the costs involved when compared to the actual implementation of these systems, even if they are prototypes. The inherent structure of complex systems is challenging to validate using formal mathematical analysis due to their nonlinearity, emergent behavior, and sensitivity to initial conditions. On the other hand, there is a growing interest in understanding their behavior, primarily for applications such as forecasting economic trends, population migrations, and climate change, among others. Thus, validating complex systems is a challenging issue to address, particularly without relying on cycles of modeling, exhaustive testing, and comparison with reality. According to Petty (2022), modeling is often the best — and sometimes the only — way to study and experiment with them.

The model still requires demographic data and definitions of the more specific characteristics of a target community. The current stage of the research work focuses on step #1, collecting data from experts on the activities of a peripheral rural community in São Paulo city, within the context of the City Hall economic development programs, to gain a more detailed understanding of the day-to-day processes of its residents and how sustainability development could emerge.

Understanding the economic activity of this community is the starting point for tracing the path of how this activity is carried out, identifying the needs and difficulties within the community, determining the main agents involved in this process, reasoning on how the different agents interact and the decision-making processes involved, and assessing whether sustainability actions are present in this activity.

In this step, the goal is to design the ODD model in layers incrementally, starting with the definition of agents and their participation in the economic process's value chain. Next, we intend to detail and validate the model with experts before proceeding to step #2.

5.2. Implications

This research contributes to the growing body of knowledge on urban community development by proposing an ABM that seeks to capture individual behaviors, collective dynamics, and spatial interactions within economically vulnerable rural-urban communities. The model will leverage theories of complexity and participatory development, offering a bottom-up perspective on sustainability transitions at the community level.

The design of agents and their interactions will be grounded in real-world dynamics observed through stakeholder consultations and expert input. Agents represent actors along a local economic value chain, such as producers, consumers, intermediaries, and institutional actors, and their interactions are governed by adaptive rules that reflect learning, cooperation, and access to resources. This reflects the informal, feedback-driven nature of community development processes.

The model will reproduce emergent phenomena, including self-organization, coordination breakdown, or positive spirals of sustainable behavior. They do not arise from programming but through agent choice and interaction under scarcity. This facilitates the theoretical examination of the ways in which well-facilitated local choice can, in turn, produce systemic change.

The model can serve as a virtual laboratory for scenario analysis. It can be used to simulate the likely outcomes of policy interventions — such as providing microcredit, promoting green entrepreneurship, or improving mobility infrastructure — in marginalized communities.

Insights from the model's output can inform decision-makers about the timing and targeting of economic development programs. It also helps anticipate unintended consequences of intervention policies, such as resource bottlenecks or the exclusion of vulnerable groups. The tool can also serve as a platform for stakeholder engagement and co-design, especially in the context of smart city initiatives and participatory planning.

Conflict of Interest Declaration

The authors declare that they have no conflicts of interest. All co-authors have reviewed and agreed with the contents of the manuscript, and there are no financial interests to report.

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