Spatiotemporal Agent-Based Simulation of Community Life Circles Integrating Discrete Choice and Agent-Based Modeling: Theoretical Model Construction and Research Framework

Authors

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Abstract

The service performance of a community life circle depends on understanding how residents' heterogeneous activities interact with facility layouts. Current research has shifted from static spatial analysis toward dynamic spatiotemporal activities, micro-level individual projects, and behavioral decision simulation. Yet it still faces limitations in quantifying individual preferences and systematically representing decision dimensions; the interaction between heterogeneous individuals and space, as well as bottom-up emergence mechanisms, remains insufficiently clarified. Taking the project-activity system of time geography as its theoretical prototype, this study proposes an integrated framework combining the mixed Logit model with agent-based modeling. It explains a three-stage model construction and operating framework: configuring resident and spatial agents with both dynamic and static attributes; designing and estimating decision mechanisms that reflect individual preference heterogeneity; and conducting ABM simulation that integrates planning, execution, and feedback. In this way, the statistical distribution of residents' preference heterogeneity is embedded in an agent simulation model, creating a feedback loop between theoretical modeling and practical validation. Four application scenarios are proposed: multidimensional dynamic evaluation of life-circle service performance; attribution analysis of interaction mechanisms between people and life circles; spatial polysemy shaping and scenario construction based on activity simulation; and scenario prediction and intervention assessment for life-circle development. The framework provides a computable model for analyzing the complexity and heterogeneity of human-space interaction in community life circles and supports human-centered, precise renewal governance.

Keywords

spatiotemporal behavior simulation; mixed Logit model; agent-based model; community life circle; human-centered planning

1 Research Progress in Life-Circle Theory and Methods

With the deepening of China's new urbanization strategy, urban spatial structure and social life have been profoundly reorganized, and social space has become more diverse, dynamic, and complex [1-3]. A planning research paradigm centered on static physical space can no longer effectively explain residents' diverse needs, dynamic behaviors, or their complex interactions with the spatial environment. Research on human-space interaction processes and decision mechanisms under multiscale spatiotemporal constraints is therefore essential for understanding the complexity and nested temporality of urban social space, and it is also required by the people-centered strategy of new urbanization [4-5].

In this context, the community life circle is an active field that carries and connects residents' multiple activities and continuously mediates material, informational, and emotional exchange. It is not only a micro-carrier of human-space interaction, but also a key intermediary linking individuals, society, and space. It has therefore become a crucial entry point for analyzing mechanisms of human-space interaction and implementing the idea of the people's city [6-7]. Such interaction is highly processual, reflected in the continuous evolution of activity paths and the sequential dependence of spatiotemporal decisions. It is also deeply complex, because it emerges from individual heterogeneity, social networks, spatial environment, institutions, and culture [8-9].

Existing studies, however, often rely on static data "fixed" in administrative districts or census units, or on cross-sectional data that homogenize individuals within groups. Such data provide snapshots at several time points, but they cannot effectively capture the activity processes of differentiated individuals under spatiotemporal constraints or their dynamic interaction with the built environment [4]. This theoretical and methodological limitation directly produces a mismatch between life-circle configuration and residents' real activity needs, making it difficult to support people-centered, high-quality spatial governance.

This study therefore focuses on two core questions in life-circle research. Theoretically, how can research move beyond static snapshot analysis and accurately explain the dynamic associations and emergent patterns between individual activity sequences and spatial decisions? Practically, how can tools be built to simulate real human-space interaction and provide refined, dynamic decision support for life-circle facility configuration and spatial optimization? To address these questions, the paper combines the concept of "project" in time geography, which emphasizes the dual constraints of subjective activity intentions and objective conditions as well as the dynamic linkage between activity sequences and spatial choices, with AI-driven agent-based modeling. It proposes a spatiotemporal agent simulation model for community life circles that integrates time, space, and activity [10-12]. Centered on resident agents with heterogeneous characteristics, the model uses a discrete choice model to represent the decision process of "spatial evaluation - choice - movement" and uses scenario simulation to reveal how individual residents interact with living space under multiple constraints. It thus offers a bottom-up analytical paradigm that dynamically responds to individual behavior.

1.1 From Static Space to Dynamic Spatiotemporal Activity

Driven by the deep integration of urban-rural planning, time geography, behavioral geography, and new technologies such as spatiotemporal big data, life-circle research has shifted from physical space to population activities and from node-based places to flow networks. Early studies were grounded in spatial ontology and continued traditional spatial planning theories such as concentric-zone theory and neighborhood units. They treated the life circle as a static, clearly bounded, ring-like spatial container [13]. From this perspective, research focused on internal spatial organization, aiming to reveal macro-structural features and combinations of residential, commercial, green, and other functional land uses [14]. Spatial econometric and GIS methods were also used to evaluate the service performance and equity of public service facilities, providing evidence for standardized spatial resource allocation [15-16].

As human activities became more mobile and nested, life-circle construction required theories and methods that start from activity systems to study human-space relations. The introduction of time geography created a key paradigm shift. With the concepts of space-time paths and prisms, researchers could describe actual activity trajectories and potential opportunity sets, shifting attention from static and node-based activity spaces toward activity processes and flow networks [17-19]. At the same time, advances in spatiotemporal big data enriched individual trajectory and urban activity data, pushing life-circle research toward activity-pattern induction, identification of life-circle levels and functions, and analysis of activity-space mechanisms [20]. Research has covered the delineation of life-circle hierarchy, structure, and types based on spatiotemporal trajectories [21-22], demand-behavior-supply matching of service facilities [23-24], evaluation of spatial use efficiency and vitality based on spatiotemporal behavior [25], built-environment mechanisms affecting spatiotemporal behavior [26-29], and social differentiation in life-circle behavior [30-31]. These studies provide strong theoretical support for precise functional identification, analysis of people-space interaction, and human-centered improvement of life quality.

1.2 From Macro Spatiotemporal Activity to Micro-Level Individual Projects

Time geography and behavioral geography have introduced a human-centered and activity-based perspective into life-circle research, but most studies still summarize spatiotemporal activity patterns at the aggregate level. They insufficiently consider individual differences, spatial perception, and socio-economic constraints, making it difficult to examine activity mechanisms and sequence associations under the dual constraints of individuals and environments. As a result, research often remains at ex post observation and cannot support ex ante prediction [2,8].

In response, related studies have proposed the concept of the project, emphasizing that activities are closely linked with individual intentions and plans while also being constrained by capability, coupling, and authority [32-33]. The project concept moves beyond classification by activity features and instead classifies activities by how individual intentions and external situations jointly organize activity. It deepens understanding of the joint effects of subjective agency and objective constraints in activity contexts and provides a new analytical framework for explaining the process mechanisms of spatiotemporal behavior and the complexity of activity systems [1,6].

Within this framework, domestic and international scholars have studied everyday project-activity systems in three areas. First, studies on social welfare and equity reveal differences in life projects, spatiotemporal difficulties, and social effects among different social groups. They focus on commuters, women, older adults, and low-income groups, analyzing constraints and coping strategies related to jobs-housing distance, family responsibilities, physical capacity, and economic capacity [34-41]. Second, studies examine how technological change reshapes the form and flexibility of projects. Smart mobility and delivery services can reduce capability constraints on movement and make complex, multi-purpose activity sequences possible [23,42-44]. Third, multimodal big-data surveys and visualization have developed. Location and trajectory data, social media data, and computational social science allow high-resolution representation of spatiotemporal activity paths among social groups and help identify constraints behind particular project trajectories, advancing project measurement from macro description to micro-scale precision and dynamic analysis [12,45].

1.3 From Project Conceptual Models to Behavioral Decision Simulation

The proposal and application of the project concept have moved everyday-life research from the macro collective level to the micro individual level. Existing studies have proposed algorithms for constructing individual activity spaces based on activity anchors [46]. Other studies have used discrete choice models based on random utility theory, combined with multi-agent simulation, to analyze destination and route choices under the joint constraints of agent intentions, built environment, and time allocation [47-49]. These studies confirm the feasibility of agent-based modeling for micro-behavior simulation, but most remain at the level of typified population simulation. The quantitative expression of individual preferences and differences still needs to be deepened.

This study therefore takes the project-activity system of time geography as its theoretical prototype. It understands decision-making as utility evaluation and choice by individuals with heterogeneous preferences within an opportunity-constraint field defined by the built environment. Operationally, it combines the mixed Logit model with agent-based modeling to construct a spatiotemporal agent simulation model of everyday activity. In the model, spatiotemporal agents represent individuals. Under the joint constraints of external conditions formed by the built environment and internal preferences, agents make activity decisions according to utility maximization. Preference parameters that reflect individual heterogeneity are estimated through the mixed Logit model, establishing a utility evaluation and decision mechanism under the joint action of "constraints-preferences." The model can quantitatively evaluate the contribution and effective thresholds of unobservable factors, such as individual preferences, to spatiotemporal outcomes of daily activities, and it can predict macro-level changes by adjusting parameters. It therefore deepens understanding of the interaction mechanism among individuals, decisions, activities, time, and space, and provides a decision basis for life-circle renewal and governance that reflects individual heterogeneity.

2 Construction of a Spatiotemporal Agent Simulation Model for Community Life Circles

The model is described using the common ODD framework for agent-based models, namely "overview-design concepts-details" [50]. The overview includes simulation purposes, model agents, and variable selection; the design concepts discuss decision rules of spatiotemporal agents; and the model details include operation and validation.

2.1 Purpose of Model Construction

To address the inability of existing studies to capture heterogeneous individual preferences and their dynamic interaction with spatial environments, this study integrates discrete choice models and agent-based modeling to construct an agent simulation platform driven by individual preferences and fed back by spatiotemporal environments. It focuses on three core questions. Pattern recognition: what spatiotemporal activity patterns emerge from the dynamic interaction between heterogeneous activity-travel choices and multilayered spatial environments? Mechanism exploration: how do heterogeneous preferences interact with complex spatial-social systems through feedback, and what are the key factors and effective thresholds? Policy evaluation: what differentiated effects do alternative design schemes have on the life circle as a whole and on individuals?

2.2 Model Agents and Variables: Spatiotemporal Agent Settings

2.2.1 Resident Agents

Resident agents have active and adaptive decision-making capacity. Based on their goals, preferences, current states, and perceptions of the environment, they evaluate utility and actively choose destinations, routes, and temporal arrangements. Their attributes constitute the basic influencing factors of activity decisions. They include static and dynamic attributes, with parameters derived from macro-statistical data, micro-survey data, and model calibration results [51-52]. Static attributes define socio-demographic characteristics and long-term stable preferences and serve as the basis for generating initial activity patterns and decision parameters. Dynamic attributes record real-time states during simulation and are both the basis and result of decisions.

Table 1. Attributes and data sources of resident agents

Attribute	Variables	Main meaning	Data sources

group			
Static: socio-demographic attributes	Age; occupation; household structure; income; residential location; transport-tool ownership	Reflect differences in activity demand, mobility capacity, time constraints, activity sequencing, cost sensitivity, consumption capacity, spatial accessibility, mode choice, and potential activity range	Census data; community grid data; real-estate data
Static: internal preference parameters	Time sensitivity; cost sensitivity; facility-quality preference; crowding aversion; inertia coefficient	Express sensitivity to time and monetary cost, attention to facility environment and service quality, dislike of crowding, and preference for familiar spaces and facilities even when they are not optimal	Activity logs; mixed Logit parameter estimation
Dynamic: spatiotemporal state	Daily activity schedule; current location; current activity; movement state	Record planned and executed activity sequences, current coordinates, current activity type and start time, route, and remaining travel time	Activity logs; location-based service data
Dynamic: physiological and psychological state	Fatigue; urgency; satisfaction or accumulated utility	Reflect activity endurance, time pressure before the next fixed activity, and utility accumulated from completed activities	Activity logs; location-based service data
Dynamic: memory, resources, and constraints	Memory and learning; daily cost budget; daily time budget; to-do task list	Affect subsequent choices and record daily expenditure limits, remaining discretionary time, and fixed or flexible tasks to be completed	Activity logs; behavioral surveys; simulation updates

2.2.2 Spatial-Environment Agents of the Life Circle

The life-circle spatial environment is the decision object, activity carrier, and constraint framework of resident agents. It is represented as a two-dimensional plane composed of points, lines, and polygons: points represent service facilities that attract resident agents, lines represent movable paths, and polygons represent building entities. Spatial-environment agents have both static and dynamic attributes. Static attributes reflect three-dimensional qualities and topological structures of the spatial environment, forming an indicator system that covers street network structure, functional facilities, and environmental quality. These attributes are stored in two-dimensional space as attribute information and act as factors in resident agents' spatial cognition and evaluation. Dynamic attributes reflect time-varying features such as current occupancy and congestion; they feed back in real time through variables in the utility function and influence subsequent activity decisions.

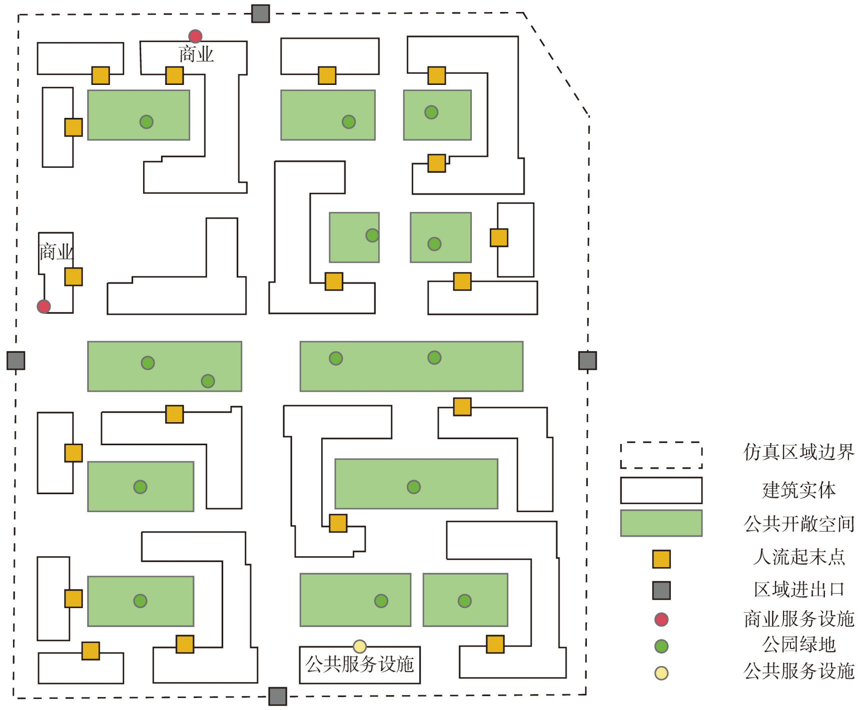

Figure 1. Virtual space environment.

Table 2. Space-environment index system

Primary indicator	Secondary indicator	Meaning	Data sources
Street network	Length; width; road-network density; closeness or integration; betweenness or choice	Measure road length and width, network density within different life-circle ranges, street accessibility and potential to attract destination-oriented flows, and probability of being passed by through-flows	Planning data; OpenStreetMap and other big data
Functional facilities	Scale; distribution; density; floor area ratio; mix; opening hours	Measure the scale, spatial distribution, density, floor area ratio, functional mix, and service time of facilities in a life circle	POI big data; field mapping
Environmental quality	Green coverage; sky-view factor; street width-height ratio; frontage ratio	Reflect park and street greening, sky visibility at street nodes, ratio of street width to building height, and ratio of building frontage to road red-line length	Remote-sensing images; field mapping

2.3 Model Design: Decision Mechanism Settings and Parameter Estimation

The decision mechanism of agents is the computational bridge between micro-level individual behavior and macro-level system phenomena. Compared with previous research, the core breakthrough of this model is the introduction of the mixed Logit model. Parameter heterogeneity distributions are used to label individual differences among resident agents, allowing agents with personalized parameters to make decisions and interact in a virtual environment. This makes it possible to reveal more deeply the effects of unobservable individual preferences on spatiotemporal patterns and spatial performance in the life circle. The model includes two steps: defining the activity choice set and constructing and estimating the utility function of activity plans.

2.3.1 Defining the Activity Choice Set

Based on activity logs and life-circle spatial-environment data, the model generates a feasible activity-pattern set C_n for each resident agent under capability, coupling, and authority constraints. The set consists of activity patterns j_n such as "home-work-home" or "home-send child to school-work-shopping-home." Each pattern has attributes such as travel time, monetary cost, and activity type, which are then used for utility evaluation in activity choice.

2.3.2 Utility Function Construction and Parameter Estimation

After a personalized feasible activity-pattern set C_n has been generated, each resident agent evaluates and chooses among feasible daily plans according to heterogeneous preferences, linking decision-maker attributes with activity-choice alternatives. A discrete choice model based on random utility theory is introduced. Specifically, the mixed Logit model is used to construct and estimate the utility function and parameters for each activity pattern j, thereby driving probabilistic choice behavior.

For resident agent n, the random utility U_nj of choosing activity pattern j consists of an observable deterministic term V_nj and an unobservable random term epsilon_nj:

```text
U_nj = V_nj + epsilon_nj                                        (1)
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The observable utility V_nj is defined as a linear combination of the attributes X_nj of activity pattern j:

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V_nj = beta_n X_nj
= beta_n1 T_nj + beta_n2 C_nj + sum_{m in M} gamma_nm D_jm     (2)
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Here, beta_n = (beta_n1, beta_n2, gamma_n1, gamma_n2, ...) is the random preference-coefficient vector of resident agent n. It varies across individuals to capture preference heterogeneity. T_nj is the total travel time of activity pattern j, C_nj is the total monetary cost of activity pattern j, M is the set of all activity types, including work, shopping, and leisure, m is a specific activity type in M, and D_jm is a binary dummy variable. If activity pattern j includes activity type m, D_jm = 1; otherwise D_jm = 0. gamma_nm is resident agent n's preference coefficient for activity type m. gamma_nm > 0 indicates preference for that activity type, while gamma_nm < 0 indicates aversion.

The core setting is that beta_n is not a fixed constant but a vector randomly varying across individuals, capturing preference heterogeneity that cannot be explained by observable variables. The maximum simulated likelihood method can be used to estimate the distribution of these parameters from residents' activity-log survey data and to obtain a quantitative statistical distribution of preference heterogeneity in the study area. During subsequent ABM initialization, each resident agent n independently draws a specific random coefficient vector beta_n from the estimated distribution, which is then fixed. Each agent thus has a unique, stable decision logic consistent with empirical behavioral regularities. This advances the model from simple rule-based inference to simulation based on empirical behavior and improves explanatory power and predictive validity.

2.4 Model Operation and Validation

2.4.1 Model Initialization

Model initialization aims to generate a virtual field consistent with the real life-circle spatial environment and population characteristics. It can be implemented on simulation platforms such as NetLogo and AnyLogic and includes three sequential modules. First, the spatial environment is digitized. Based on high-precision GIS data, the road-network topology, building footprints, public service facility points, and other digital geographic information are imported or vectorized in the simulation platform, and static and dynamic attributes are configured according to the indicator system for spatial-environment agents. Second, resident agents are generated. Using algorithms such as iterative proportional fitting and multidimensional census data, a list of virtual resident agents consistent with the real demographic characteristics of the life circle is created. For each agent, a unique random coefficient vector beta_n is drawn from the preference distribution previously estimated by the mixed Logit model, representing the agent's internal preferences. Third, resident agents are spatially matched and initialized. The generated resident-agent list is allocated to residential buildings according to statistical units, completing initialization of spatial anchors. Activity choice sets are then generated according to the agents' social roles, and at the beginning of the simulation one activity plan is selected and executed probabilistically to obtain an initial schedule and spatiotemporal state.

2.4.2 Dynamic Plan-Execute-Feedback Operation

After initialization, the model enters an iterative cycle composed of low-frequency daily planning decisions, high-frequency activity-facility-route decisions, and spatial feedback. The cycle has four steps. First, spatial state setting and perception. At the beginning of each simulation step t, the environmental state is set or updated according to the results of the previous round of resident-agent actions, becoming the input for spatial perception in the current round. Second, resident-agent decision-making and action. Trigger conditions for daily planning and activity execution are set, followed by a two-level decision model of daily planning and activity-facility-route choice. At the daily planning level, each agent calculates the random utility U_nj of each pattern j in its personalized feasible activity-pattern set C_n based on its specific preference coefficients beta_n, and draws one pattern according to the choice probabilities generated by the mixed Logit model as the overall activity plan j *for the day. At the activity-facility-route choice level, based on the selected activity pattern j*, the agent chooses a specific facility f from the set of currently spatiotemporally reachable facilities according to the utility function, thereby completing destination choice. Route utility is then calculated from expected travel time, and a route is chosen probabilistically with the Logit model [52]. Third, data recording. The model records complete spatiotemporal trajectories, activity logs, accumulated utility, and decision sequences for each resident agent, as well as macro-level usage states such as pedestrian density and activity types at spatial facilities. These data support subsequent model validation and evaluation of planning effects. Fourth, data updating and model iteration. After these steps, resident-agent internal states and spatial states are updated, and a new round of perception, decision, action, and recording begins. Through iteration, resident decision behavior continuously reshapes spatial states, such as creating or relieving congestion, while updated spatial states become input parameters that influence subsequent decisions. Multiple levels of spatiotemporal activity patterns then emerge dynamically.

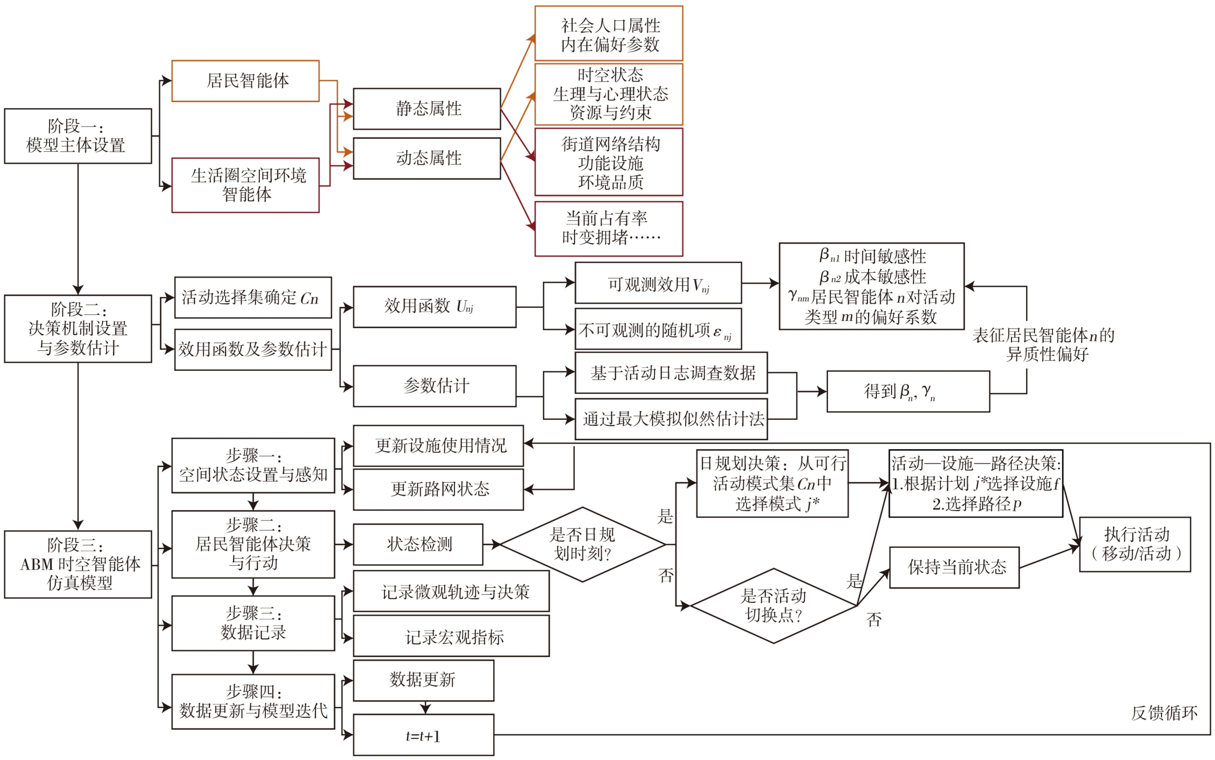

Figure 2. Parameter estimation and simulation workflow for the spatiotemporal agent-based model.

2.4.3 Model Validity Verification

To evaluate model validity and credibility, and to ensure that the model can serve as a reliable computational experiment platform for explaining residents' activity decision mechanisms and predicting spatial intervention effects, a two-level validation framework combining macro-pattern matching and micro-logic testing is established. First, macro-behavioral pattern matching is conducted. The model is run until it reaches a stable state, or the average of multiple days of simulation is used. Spatial correlation analysis and temporal goodness-of-fit are applied to compare simulated and observed heat maps of pedestrian density and spatiotemporal distribution, as well as daily or weekly visit curves for different spatial facilities. K-S tests or quantile comparisons are also used to compare the distributions of daily activity-chain counts, single-trip distances, and activity durations generated by the simulation and obtained from surveys, thereby testing whether the model reproduces stable macro spatiotemporal activity regularities in the study area. Second, sensitivity analysis and internal validity verification are conducted. One-factor sensitivity analysis independently changes input parameters such as facility capacity and the standard deviation of preference distributions, and examines whether the direction and magnitude of changes in core outputs such as facility visits are reasonable. Extreme scenarios, such as sharp holiday increases in activity demand or facility closure, are also simulated to observe whether the model generates predictable behavior such as congestion or service vacuums in some areas, thereby testing the robustness of the model logic.

3 Applications of the Spatiotemporal Agent Model for Community Life Circles

3.1 From Static Measurement to Dynamic Perception: Multidimensional Dynamic Evaluation of Service Performance

Traditional static accessibility analysis based on facility points and buffer overlays cannot fully consider individuals' actual activity ranges and behavioral boundaries under the dual constraints of spatiotemporal capability and group interaction. It therefore cannot realistically represent the dynamic service performance of spaces and facilities for heterogeneous individuals. By embedding the mixed Logit model and preference heterogeneity parameters, the spatiotemporal agent model represents the spatial environment as a system of opportunities and constraints that varies by person. On this basis, it simulates the activity-travel decisions of heterogeneous residents under multiple constraints and their continuous feedback with space. It can evaluate the life circle dynamically and human-centeredly from three dimensions: nodes, networks, and places, covering facility performance, social services, and system resilience.

At the node level, the model simulates facility choice under real constraints. It can diagnose the difference between the theoretical service population and the actual service population of a single facility and evaluate supply-demand matching and use efficiency. Evaluation indicators can thus be upgraded from "coverage or no coverage" and "geometric coverage range" to "effective coverage ratio" and "spatiotemporal fluctuation map of service quality." It can also identify service blind spots caused by time conflicts, price thresholds, and other barriers, providing more precise decision support for facility layout, type positioning, and operation management.

At the network level, the model regards the life circle as a complex system composed of facility nodes and resident flows. By simulating scenarios such as key facility failure or addition of new nodes, it can evaluate the overall resilience and structural efficiency of the service network, identify key hubs and vulnerable links, and analyze functional redundancy and substitution among facilities, thereby supporting improvement of efficiency and equity in the service-facility system.

At the place level, the model focuses on space as a carrier of social interaction. By tracking spatiotemporal activity trajectories, it can quantitatively evaluate inclusiveness and spatiotemporal differentiation in public-space use and diagnose potential gathering places or conflicts among groups. By simulating the introduction of new business types or adjustments to spatial rules, it can preview changes in place vitality under different design interventions, shifting spatial evaluation from measurement of functional containers to assessment of place-cultivation potential.

3.2 From Macro Association to Micro Mechanism: Interaction and Attribution Between People and Life Circles

Traditional research often stops at macro-statistical association between people and space and cannot reveal the micro-drivers of observed phenomena. The spatiotemporal agent model builds an interactive bridge among resident preference heterogeneity, activity-travel decisions, and the spatial environment. It can model and analyze two key mechanisms.

At the micro level, the model characterizes the coupling and adaptive mechanism between individual spatiotemporal behavior and multidimensional environments. By embedding mixed Logit decision rules and dynamic spatial feedback, it can precisely simulate the cycle of spatial perception, utility evaluation, activity movement, and attribute updating. On this basis, the micro-roots of any macro phenomenon can be traced. For example, low facility use can be traced through the decision chains of all resident agents and attributed to mismatched opening hours, which are coupling constraints, excessive cost, which is an authority constraint, or poor quality, which is a preference constraint. This mechanism-analysis capability deepens evaluation from "whether a facility is used" to "why it is not used" and "who would use it," directly supporting precise public-service policies differentiated by population.

At the macro level, the model reveals how macro order emerges from micro individual interactions. Adaptive behaviors of heterogeneous individuals superpose, interact, and iterate in shared space, eventually generating macro socio-spatial patterns that cannot be predicted by simple addition, namely local order [8]. The spatiotemporal agent model can not only represent activity patterns and local order, but also identify factor combinations, critical conditions, and pathways that produce a particular order by adjusting inputs. By setting initial rules and spatial parameters, planning can guide self-organization toward more resilient, vibrant, and inclusive local orders, shifting from deterministic blueprint-style control to adaptive interventions that cultivate positive possibilities.

3.3 From Functional Configuration to Place-Making: Spatial Polysemy and Scenario Construction Based on Activity Simulation

Traditional planning focuses on the physical functional configuration of space and has difficulty seeing the social activities and spirit of place that space carries. By simulating the activity choices and interaction mechanisms of heterogeneous residents under real constraints, the spatiotemporal agent model allows planners to evaluate space not only by "what is missing," but by "why existing spaces cannot support richer projects." It can therefore explore prospectively how refined spatial interventions stimulate active and diverse daily activities and interactions among different individuals in the same time and space. Place-making is upgraded from form-aesthetic design to social-process design based on behavioral dynamics. Specifically, the model supports two complementary place-making strategies driven by activity simulation.

First, it enables precise insertion of spatial catalysts to activate the polysemic potential of nodes. The polysemy of a space depends on how well it matches users' projects [50]. By analyzing factors influencing resident decisions and activity trajectories, the model can diagnose gaps between existing spatial supply and diverse activity demand in terms of facilities, business types, and accessibility. It can then simulate dynamic responses in activity types, intensity, and social patterns after catalyst elements of different locations and types are introduced. This shifts design from experiential judgment to precise prediction based on behavioral emergence and helps ensure that each micro-renewal effectively activates space, giving it flexible potential as a social living room or lively market.

Second, it helps systematically weave spatiotemporal encounter networks to stimulate system vitality. A single space has limited polysemy, while connecting multiple complementary or similar nodes can catalyze richer scenarios through network effects beyond the simple sum of individuals. The model can simulate the process by which connection creates polysemy. For example, planning a pedestrian-friendly route linking a community garden, convenience store, elderly-care service point, and bus stop can not only predict the overlap between commuting and leisure flows, but also simulate new activity chains such as en-route shopping and walking-based social interaction. Such systematic weaving of spatiotemporal encounter opportunities reconstructs the life circle from a collection of functional plots into a flowing stage that supports encounters, spontaneous activities, and continuous exploration.

3.4 From Description of the Present to Simulation of the Future: Scenario Prediction and Intervention Assessment

The spatiotemporal agent model provides a highly controllable simulation experiment platform for planning and policy evaluation, shifting evaluation from post-implementation assessment to prospective prediction. Its core applications are twofold. First, it supports optimization simulation of resource allocation. By simulating planning schemes under different goals and constraints, it can predict macro-level changes in spatiotemporal pedestrian distribution, facility use loads, transport network pressure, and social benefits. It can also enter the micro mechanism, tracking changes in individual travel chains, average travel time, and accessibility differences among social groups in response to spatial change. This dual perspective of macro phenomena and micro attribution upgrades planning evaluation from static comparison of schemes to dynamic insight into behavioral response, providing a decision basis from complex-system simulation for identifying optimal resource-allocation strategies and balancing efficiency and equity.

Second, it supports refined evaluation of policy interventions, especially quantitative testing of non-spatial soft policies. By adjusting time rules in the model, such as facility opening hours, price levers such as time-based discounts, or permission settings such as group-specific services, the transmission effects of management strategies on resident behavior and system performance can be simulated and predicted. For example, the model can precisely calculate the effect of extending nighttime opening hours of community service facilities on increasing use by working populations, or assess how price subsidies improve activity opportunities for low-income households. This ability to translate abstract policies into adjustable parameters and conduct policy experiments allows decision-makers to anticipate complex consequences before implementation, optimize intervention intensity and targets, and improve the specificity, effectiveness, and inclusiveness of public policy.

4 Research Outlook

This study constructs a four-in-one model of individuals, activities, time, and space for spatiotemporal agent simulation of community life circles. It innovatively integrates the mixed Logit model's capacity to analyze individual heterogeneity with the agent-based model's capacity to simulate interactive emergence, and it proposes three key perspectives for interaction analysis. First, subjective-objective interaction between individuals and space: the mixed Logit model labels differentiated preferences of resident agents through parameter heterogeneity distributions, and agent-based modeling then simulates spatiotemporal regularities, spatial differentiation, and mechanisms of interaction between differentiated individuals and space. Second, cross-scale interaction between micro individual decisions and macro group patterns: spatiotemporal agent simulation can reveal how local and micro individual decisions interact nonlinearly and generate ordered macro spatiotemporal patterns. Controlled experiments can further identify the key factors and effective thresholds that drive pattern formation. Third, short- and long-term interaction between people and space: at the short time scale, the model can analyze population activities at different times of day and their use of space; at the long time scale, historical data collection and scenario simulation can analyze changes in population activities and spatial structure driven by demographic change, information technology, and policy shifts. Through these three perspectives, the model precisely depicts individual differences in life circles, explains interaction mechanisms between individuals and space, and prospectively predicts life-circle planning and service performance. It therefore provides human-centered decision support for efficient spatial use, service-performance improvement, and community vitality creation.

The present study mainly completes framework construction, mechanism inference, and method integration. To truly empower implementable, human-centered life-circle planning practice, further research is needed in two areas. First, deep acquisition of individual spatiotemporal activity data and expression of heterogeneity. At present, large-scale micro-level spatiotemporal activity data face a trilemma of breadth, precision, and depth. Future breakthroughs lie in integrating multi-granularity and multimodal spatiotemporal data, combining high-precision and semantically rich GPS trajectories and activity logs with broad-coverage mobile signaling data. On this basis, machine learning and data inversion can reconstruct complete attributes and activity semantics for large-scale individuals, extract digital tags representing stable individual behavior, and embed them as latent variables in the mixed Logit choice model. This would enable end-to-end modeling of data, behavior, and preferences, making heterogeneous spatial choices measurable and explainable. Second, dynamic simulation of bidirectional human-space interaction and long-term evolution. Existing models have limited ability to describe the dynamic feedback loop in which people affect space and space reshapes people, as well as long-term evolutionary mechanisms. At the micro level, methods such as recurrent neural networks (RNNs) can be introduced to describe how individual activities accumulate and feed back into spatial cognition and evaluation, thereby influencing subsequent choices. At the macro level, system dynamics models can be combined to simulate the long-term and nonlinear effects of demographic change, built-environment renewal, and planning policy intervention, thereby evaluating the sustainable impacts of planning. With these extensions, a spatiotemporal agent model can be built that not only explains complex individual-space interaction mechanisms, but also simulates and evaluates the long-term benefits of planning schemes, providing a methodological core for computable and simulable human-centered urban planning.

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