

Article

Agent-Based Simulation and Mechanism Identification of Evacuation Efficiency in a Typical Built-Up Area Within a Desert Corridor County: A Case Study of Ruoqiang, Xinjiang

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Abstract

Research on evacuation in built-up areas within corridor-dependent counties is shifting from static shelter-coverage assessment toward dynamic simulation of spatial constraints, behavioral heterogeneity, and organizational capacity. This study takes a typical built-up area within Ruoqiang County, Xinjiang, as the simulation unit, rather than the entire county administrative area. GIS-based shortest-path analysis shows that the origin-to-nearest-shelter distance ranges from approximately 0.03 km to 0.64 km, indicating a short-distance pedestrian evacuation context. Based on multi-source spatial data from 2025, this study constructs an agent-based evacuation simulation framework and positions the model as a general evacuation-capacity experiment rather than a predictive simulation of a specific hazard process. Five scenarios are compared: fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. Under the ideal ordered-information assumption, the simulated system reaches complete evacuation within 9.25 min, whereas the fully disordered scenario enters a low-level plateau after approximately 4.88 min, with a final evacuation rate of about 13%. The 25%, 50%, and 75% ordered scenarios reach plateau levels of approximately 37–38%, 61–62%, and 71–72%, respectively. Origin-type results further indicate that origins near shelters, directly connected to shelters, or embedded in continuous road networks respond more strongly to improved organization, whereas origins near boundaries, in low-connectivity areas, far from shelters, or adjacent to bottleneck nodes are more likely to generate late-stage retention. This study reveals how destination cognition, route organization, and origin spatial conditions jointly shape evacuation efficiency in a typical built-up area within a corridor-dependent county under specified scenario assumptions.



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Keywords: typical built-up area; corridor-dependent county; agent-based model; spatial constraints; origin-type success rate

1. Introduction

Against the combined backdrop of global climate change, the increasing frequency of extreme disaster events [1], and the continuing modernization of national governance systems [2], disaster prevention and mitigation have gradually shifted from conventional post-disaster rescue and loss compensation toward an integrated governance approach covering pre-disaster prevention, emergency response, and post-disaster recovery. Within

this governance paradigm, evacuation is no longer merely a passive response at the end of the emergency-management chain; rather, it serves as a key nexus linking risk identification, spatial planning, infrastructure provision, residents' cognition, and organizational mobilization [1,3–6]. This is particularly important in county-level areas characterized by large spatial scales, strong environmental constraints, and dispersed settlement patterns. In such contexts, rapid and safe evacuation during disasters depends not only on the existence of individual facilities, but also on whether shelter destinations can be recognized, evacuation routes can be accessed, on-site organization can function effectively, and capacity resources can be dynamically redistributed [7]. County-level evacuation is therefore neither a purely transportation issue nor a single facility-service problem, but a coupled spatial, behavioral, and organizational process. In current county-level disaster-prevention practice, static service-radius analysis, experiential judgment, and facility-coverage indicators remain common analytical tools. These approaches are useful for assessing the spatial accessibility of shelters, but they have limited explanatory power for dynamic processes under real disaster conditions, such as how evacuees enter the system, recognize destinations, move along corridors, and are redistributed after local saturation [8–12]. This limitation arises mainly because traditional methods often assume homogeneity in cognition, judgment, and route choice, while treating roads, obstacles, capacity, and perception as static background conditions. As a result, they are unable to capture the complex and nonlinear behavioral evolution mechanisms that emerge in disaster contexts [13].

Ruoqiang County is located in southeastern Xinjiang. It covers a vast territory, while settlements and construction activities are concentrated in several oasis nodes, forming a distinctive spatial pattern in which point-like settlements are coupled with linear transport corridors. Unlike typical urban blocks, evacuation challenges in Ruqiang are not primarily characterized by high-density crowd congestion. Instead, they concern how individuals can rapidly identify safe destinations, move efficiently along limited corridors, and be redistributed under constrained shelter capacity within a large-scale desert environment. In addition, the openness of the desert landscape and the relative scarcity of environmental reference points make destination recognition and route organization particularly important for emergency evacuation. For such areas, evacuation efficiency refers not only to speed, but also to whether effective and safe movement can be completed within the critical time window during which exposure risk continues to accumulate.

Traditional evacuation studies often have two major limitations. First, they tend to treat evacuees as homogeneous agents, assuming no substantial differences in cognition, judgment, or route choice. Second, they often regard the spatial environment as a static background, making it difficult to represent how environmental constraints dynamically affect evacuation processes [14]. In contrast, agent-based models (ABMs) can represent evacuees as agents with perception, judgment, action, and interaction capabilities, and can explicitly model their dynamic relationships with roads, boundaries, obstacles, shelters, and other agents in spatial environments. Compared with static accessibility analysis, the advantage of ABM lies in its ability to translate local differences in cognition into system-level outcomes through rule-based settings and temporal updates, thereby revealing the micro-level behavioral mechanisms underlying macro-level evacuation performance.

On this basis, this study takes a typical built-up area within Ruqiang County as the simulation unit and integrates multi-source spatial data, including boundaries, roads, buildings, shelters, and population origins, to construct an agent-based evacuation simulation framework. The analysis does not represent evacuation across the whole county. Instead, it focuses on short-distance pedestrian evacuation within a selected local built-up area embedded in a corridor-dependent county context. Under unified conditions of spatial environment, movement speed, release mechanism, and shelter capacity, five behavioral

scenarios are established: fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. This study addresses three research questions. First, within the selected built-up area, how do differences in destination cognition and route organization affect simulated evacuation efficiency and its temporal evolution? Second, how do origin spatial conditions, such as road connectivity, distance to shelters, boundary location, and bottleneck proximity, shape differences in evacuation success rates? Third, what possible planning applications can be derived from the scenario-based results for improving local shelter-space organization and evacuation-route guidance? Theoretically, this study explains evacuation-efficiency differences from a coupled behavioral-spatial perspective in a typical built-up area within a corridor-dependent county. Practically, it identifies spatially constrained origins and route-organization weaknesses, thereby providing cautious planning implications rather than directly verified intervention effects.

2. Literature Review

2.1. *A Shift in Evacuation Research from the Perspectives of Evacuation Resilience and Transportation Resilience*

Resilience governance provides an important analytical framework for disaster prevention and mitigation research [15–17]. However, discussing evacuation solely from the perspective of general urban resilience remains too broad. Unlike resilience in the sense of post-disaster recovery or engineering protection, evacuation resilience places greater emphasis on whether a regional system can rely on existing road networks, shelter facilities, information transmission, and organizational response capacity to achieve safe relocation within a limited time after a sudden disturbance [10,18,19]. Correspondingly, transportation resilience focuses on the ability of road systems to maintain accessibility, carrying capacity, and the organization of evacuation flows under emergency conditions. Therefore, evacuation efficiency is not merely a matter of whether shelters are spatially covered or whether shortest paths exist; rather, it is a dynamic outcome jointly shaped by road networks, population distribution, shelter destinations, departure organization, and individual behavior.

Existing evacuation research has gradually shifted from static facility evaluation toward process-oriented and systematic analysis [20]. Traditional methods based on service radius, shortest paths, and facility coverage can assess whether shelter resources are spatially accessible, but they have limited capacity to explain how evacuees enter the system, recognize destinations, choose routes, and adjust their actions when routes are blocked, destinations become unavailable, or local congestion occurs during actual evacuation processes. In recent years, zone-based evacuation planning, transportation-network evacuation models, and agent-based simulations have received increasing attention. These approaches usually divide evacuation areas into spatial units and further analyze departure times, route organization, road capacity, and destination allocation across different units, thereby better capturing spatiotemporal differences in evacuation processes.

Evacuation resilience in county-level and rural areas differs from that in high-density urban settings. Evacuation in dense cities often focuses on crowd congestion, intersection conflicts, exit bottlenecks, and local capacity constraints, whereas evacuation difficulties in county-level or low-density areas are more often reflected in dispersed settlements, limited route choices, large distances between public-service nodes, insufficient recognition of shelter destinations, and strong corridor dependence. For such areas, evacuation outcomes depend not only on whether roads are physically connected, but also on whether residents can quickly access effective corridors, identify evacuation directions, and form stable safe-relocation flows from different origins within a limited time. Therefore, county-level evacuation research needs to move beyond facility-coverage evaluation alone and

toward an integrated analysis of the relationship among origins, roads, shelters, and organizational modes.

Arid and desert regions further reinforce the need to examine evacuation resilience and transportation resilience. Existing studies on sandstorms and extreme arid environments show that risks in such areas are manifested not only in hazard intensity itself, but also in secondary effects such as reduced visibility, traffic disruption, weakened directional references, and difficulties in destination recognition. Relevant studies by the World Meteorological Organization and other institutions indicate that sand and dust storms often occur in arid and semi-arid regions, and one of their direct impacts is reduced visibility and disruption to road and air transportation. Traffic-safety cases also show that sudden visibility reduction caused by sandstorms can quickly translate into road-system risks. For example, strong dust weather in central California significantly reduced highway visibility and triggered a multi-vehicle collision. Such cases suggest that, in open arid environments, the safe operation of transportation systems depends heavily on visual conditions, directional judgment, and corridor control.

From the perspective of behavioral mechanisms, evacuation difficulties in extreme environments are not only about whether people can move, but also about whether they can recognize destinations and maintain correct directions. Kretz et al., in their perception- and behavior-oriented pedestrian evacuation simulation, incorporated sign visibility, hazard perception, and psychological response into the evacuation model, emphasizing the importance of visual information and sign recognition for individual response and route choice. Feng et al., using virtual reality and data-driven methods to study evacuation wayfinding in complex spaces, found that route choice at decision points is jointly influenced by spatial structure, task complexity, and available information. Although these studies mainly focus on buildings or complex indoor spaces, the mechanisms they reveal are also instructive for desert county contexts: when environmental reference points are insufficient, destination visibility declines, or route information is incomplete, individuals are more likely to rely on local perception for directional judgment, which may cause movement behavior to deviate from globally efficient evacuation paths.

Therefore, this study does not directly simulate visibility decay, heat-exposure accumulation, or dynamic road failure during sandstorms, extreme heat, or other specific hazard processes. Instead, it treats the arid desert environment as the spatial background and constraint condition of the study area. The core concern of this paper is how destination cognition and route organization affect pedestrian evacuation efficiency in a built-up area under given conditions of limited corridors, nodal origins, and shelter distribution. In other words, studies on desert and extreme environments provide the theoretical background for this research by showing that destination recognition, directional organization, and corridor use are especially important in such areas. The model developed in this paper further translates these factors into a comparative analysis of general evacuation capacity under ordered, disordered, and mixed evacuation scenarios.

2.2. Evacuation Models and Behavioral Mechanism Settings

Evacuation models provide an important foundation for disaster-evacuation research. Social force models, cellular automata models, and continuous-space models are commonly applied to high-density scenarios such as building interiors, transport hubs, campuses, and large public spaces, with a focus on microscopic processes including individual movement, obstacle avoidance, queuing, congestion, and exit bottlenecks. Network models and route-assignment models, by contrast, place greater emphasis on road nodes, link connectivity, path costs, and evacuation-flow allocation, and are therefore suitable for analyzing movement efficiency in open spaces and larger-scale road networks. These models

provide important tools for understanding evacuation processes, yet the dominant issues vary across spatial contexts. High-density spaces often focus on congestion, exits, and local bottlenecks, whereas low-density, corridor-dependent counties are more likely to face insufficient destination recognition, unstable road access, and limited alternative routes.

Research on route choice indicates that evacuees do not always follow globally shortest paths. Individuals who have access to shelter information, are familiar with the road environment, or receive organizational guidance are more likely to choose routes with clear shelter destinations. By contrast, when information is insufficient, signage is unclear, the environment is unfamiliar, or visibility is limited, individuals are more likely to rely on local perception and heuristic judgments, such as moving toward open spaces, following familiar roads, following others, or searching for safe destinations within visible range [21]. Evacuation efficiency therefore depends not only on individual movement speed, but also on whether individuals can establish a stable connection between their movement direction and a safe destination.

Shelter choice is also an important mechanism affecting evacuation efficiency. Existing studies usually associate shelter choice with distance, network accessibility, capacity, safety, familiarity, and information availability. Under complete information, individuals can select shelters according to the shortest distance or minimum network cost. In actual evacuation processes, however, whether a shelter is recognizable, whether it still has available capacity, and whether it can be reached through a continuous road network all affect individual choice outcomes. Once a shelter reaches its capacity limit, subsequent evacuees must shift from their preferred destination to alternative destinations, transforming evacuation from a one-time shortest-path choice into dynamic destination redistribution under capacity constraints. In this study, ordered evacuation, disordered evacuation, and mixed scenarios with different ordered proportions are designed precisely to identify the boundary effects of destination cognition and route organization on evacuation efficiency.

Agent-based models can place the above behavioral mechanisms within explicit spatial environments [9,22,23]. They can simulate interactions between individuals and roads, obstacles, boundaries, and shelters, thereby allowing researchers to observe how local behavioral rules accumulate into group-level evacuation curves, spatial clustering, retention patterns, and facility-occupancy outcomes [24,25]. By observing the local decisions and interactions of large numbers of agents under different disaster scenarios, such models can generate system-level outcomes, such as casualty scale, evacuation efficiency, service-interruption duration, recovery curves, and group-inequality indicators, thereby providing tools for understanding complex disaster processes and evaluating disaster-prevention and mitigation strategies [13,26,27]. At the same time, the explanatory power of evacuation ABMs depends on the transparency and reproducibility of model settings [28]. The ODD framework emphasizes the need to clearly specify model purpose, agent types, state variables, spatial extent, time step, behavioral rules, initialization, input data, sources of stochasticity, and output indicators. Accordingly, the following sections describe the spatial extent, agent rules, capacity constraints, and output indicators, while positioning the model as a scenario-based simulation for mechanism identification.

In addition, spatial clustering methods have been widely used in emergency-evacuation research for zone identification, population-concentration analysis, evacuation-unit delineation, and the identification of priority evacuation areas, and they are often combined with ABMs to enhance the spatial structure of model inputs [25]. Common clustering methods include k-means, c-means, and DBSCAN. Among them, k-means is suitable for delineating relatively regular spatial groups; c-means can represent evacuation units with fuzzy boundaries or overlapping service areas; and DBSCAN is appropriate for identifying local high-density clusters of population or risk points. Furthermore, clus-

tering results can be combined with multi-objective optimization algorithms to optimize shelter allocation, evacuation sequencing, and route organization. For example, methods such as the Parallel Bi-Objective Real-Coded Genetic Algorithm (P-RCGA) can balance multiple objectives, including evacuation time, road congestion, and capacity equity. These studies indicate that clustering methods can provide clearer spatial zoning and input-organization support for evacuation ABMs. This study draws on this logic by spatially grouping population origins to support subsequent comparisons of success rates across different origin types.

2.3. Research Gaps in Corridor-Dependent County-Level Evacuation and the Case Significance

Existing evacuation ABM studies have mainly focused on high-density urban spaces, building interiors, transport hubs, campuses, and large public facilities, while relatively limited attention has been paid to county-level built-up areas, rural regions, and corridor-dependent spaces [15,29]. Compared with high-density cities, evacuation challenges in these areas do not necessarily manifest as crowd congestion or exit bottlenecks. Instead, they are more likely to arise from dispersed population origins, limited route choices, insufficient recognition of shelter destinations, and inadequate alternative paths. If an explanatory framework centered on congestion, exits, and local movement bottlenecks continues to be applied, it may be difficult to fully reveal the mechanisms underlying variations in evacuation efficiency in county-level built-up areas [24,30,31].

Corridor-dependent counties have considerable theoretical significance. Such areas often exhibit a spatial organization characterized by “point-like settlements, linear corridors, and limited destinations,” with public services, daily mobility, and emergency organization relying on a small number of backbone corridors. Under these spatial conditions, the mere presence of shelters does not mean that individuals can recognize them in time, and physical road connectivity does not necessarily mean that individuals can quickly access the network and continue moving in the correct direction. Therefore, evacuation efficiency is shaped not only by facility layout and geometric road distance, but also by destination cognition, route organization, and the spatial conditions of evacuation origins.

Ruoqiang County is typical of this spatial type. It covers a vast territory, while population and construction activities are mainly concentrated around oasis nodes and transport corridors, creating a clear distinction between the overall county-scale space and the activity scale of local built-up areas. This study selects a typical built-up area of Ruqiang County as the case not as a substitute for an ordinary urban block, but as a context through which to examine the behavioral and spatial mechanisms of general evacuation capacity in county-level built-up areas characterized by corridor dependence, dispersed nodes, and sensitivity to destination recognition. In this sense, the study can provide a reference for shelter-space organization, evacuation-route identification, and zone-based guidance in similar county-level areas.

3. Data Preparation and Methodology

3.1. Study Area

Ruoqiang County is located in southeastern Xinjiang. It covers a vast territory, while urban development, population activities, and public services are mainly concentrated around oasis nodes and transport corridors. The agent-based simulation in this study does not cover the entire administrative area of Ruqiang County. Instead, it selects a typical local built-up area within the county as the simulation object and focuses on the pedestrian evacuation process among population origins, road networks, building obstacles, and shelters within the built-up area. This design helps avoid misinterpreting

short-distance pedestrian evacuation within a local built-up area as long-distance relocation across townships or the entire county.

From the perspective of model representation, the study area has three main spatial characteristics. First, it shows strong corridor dependence. The road system in the built-up area mainly organizes pedestrian movement through backbone roads and local branches, and whether individuals can quickly access effective corridors directly affects subsequent evacuation efficiency. Second, evacuation origins and destinations are distributed in a nodal pattern. The model includes 134 evacuation origins and six shelters, representing the spatial relationship between population release points and safe destinations within the built-up area. Third, buildings, boundaries, and impassable spaces jointly form local spatial constraints, affecting route access, detouring behavior, and destination approach. Therefore, this study defines the study area as a typical built-up evacuation scenario within a corridor-dependent county. The model analysis does not attempt to reproduce any specific disaster process, nor does it seek to statistically generalize the findings to all county-level evacuation scenarios. Instead, under given spatial structures, population origins, and shelter conditions, it compares how different levels of destination cognition and route organization affect evacuation efficiency in a local built-up area.

3.2. Technical Route

This study develops a technical framework for evacuation-capacity analysis in a typical built-up area within Ruoqiang County, a corridor-dependent county context (Figure 1), following the sequence of “area identification–data integration–spatial grouping–simulation modeling–result diagnosis–planning implications.” First, based on the spatial pattern of the study area, the distribution of population origins, road-connectivity conditions, and shelter locations, the simulation area is identified through spatial clustering and manual verification. On the basis of area identification, fundamental datasets, including the study-area boundary, road network, buildings and obstacles, shelter locations and capacities, and population origins, are further integrated. After coordinate standardization, spatial clipping, topological checking, and attribute organization, these datasets are compiled into a spatial database for agent-based simulation. The road system, impassable spaces, shelter destinations, and population release locations are then transformed into model-recognizable spatial objects according to a structured representation of “boundary–corridor–obstacle–destination–origin.” In the simulation-modeling stage, the evacuation process is defined as a general evacuation-capacity experiment. Under unified conditions of physical environment, movement speed, release mechanism, and shelter capacity, five behavioral scenarios are constructed: fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. By comparing evacuation curves, key threshold times, final evacuation rates, and origin-type success rates across different ordered proportions, the model identifies how destination cognition and route organization affect evacuation efficiency. Finally, based on the overall simulation results and spatial-grouping outcomes, the study further discusses weaknesses in evacuation systems in corridor-dependent county-level built-up areas and derives corresponding planning implications.

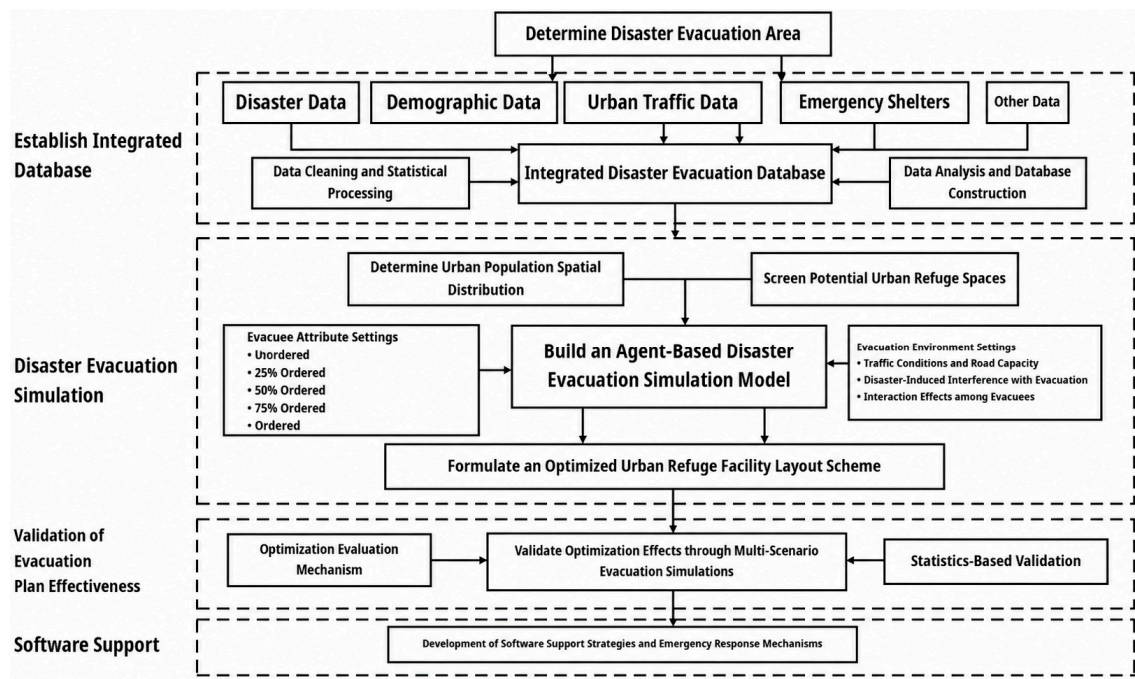


Figure 1. Technical route.

3.3. Data Preparation

The basic data used in this study include the study-area boundary, road network, buildings or obstacles, shelter locations and capacities, and population origins. All datasets are from 2025. Among them, the population data were obtained from statistical and spatial materials provided by government agencies and were mainly used to determine the total population of the study area and the basis for its spatial allocation. Spatial data, including administrative boundaries, road networks, buildings, and shelters, were mainly derived from the basic geographic information of Amap and were further organized through field-based knowledge and manual verification. The study-area boundary was used to define the effective evacuation area within which agents could move. Road-network data were used to construct the accessible path system for ordered evacuation. Building and obstacle data were used to implement basic obstacle-avoidance constraints by defining non-traversable spaces. Shelter location and capacity data were used to define the safe-destination system, while population-origin data were used to control release locations and the overall simulation scale. Together, these datasets form the spatial basis of the model.

Data preprocessing consisted of five main steps. First, the administrative boundary, roads, buildings, shelters, and population origins were processed in a unified coordinate system to ensure that all spatial objects could be overlaid within the same spatial reference. Second, roads, buildings, shelters, and other spatial features were clipped according to the study-area boundary, and objects outside the study area were removed. Third, the road network was subject to topological checking and node conversion: road polylines were transformed into nodes and links that could be used for network analysis, and endpoint nodes with identical coordinates were connected to form an accessible path system. Fourth, buildings, walls, and other non-traversable spaces were rasterized and encoded as obstacle cells to restrict agents from crossing them. Fifth, shelter centroids were extracted and capacity attributes were organized, converting shelters into target objects with both location and capacity constraints.

The spatial allocation of population origins was based on building area. Specifically, the total population or administrative-unit population provided by government agencies was first matched with building spatial data. Building area was then used as the allocation

weight to assign population to corresponding buildings or building groups. Finally, the allocated population of each building or building group was aggregated to generate evacuation origins. The basic assumption of this method is that, in the absence of mobile-phone signaling data or individual trajectory data, building area can serve as a reasonable proxy for the potential carrying capacity of residential and activity populations. This study did not use mobile-phone signaling data, nor did it apply continuous interpolation based solely on community-level population density. Instead, discrete population origins that better reflect the built environment were generated through building-area-weighted allocation. The final model included 134 evacuation origins and a total evacuation population of 65,000.

Unlike evacuation studies of ordinary urban blocks, data organization in the Ruoqiang case places greater emphasis on a structured representation of “boundary–corridor–obstacle–destination–origin.” This is because pedestrian evacuation in a local built-up area within a county-level context depends more strongly on corridor skeletons and destination recognition than on multi-path selection within a dense road network. The boundary defines the external constraints of the system; corridors determine the skeletal efficiency of movement; obstacles define non-traversable spaces; the destination system constitutes the set of endpoints for safe relocation; and population origins determine how agents continuously enter the system.

In the processing of population origins, this study draws on the logic of spatial clustering to identify groups based on the distribution of origins and their surrounding spatial conditions. This step serves model initialization and result diagnosis. On the one hand, it identifies the spatial clustering characteristics of population origins, providing a basis for continuous release and initial-location allocation. On the other hand, it forms different origin types, providing a grouping basis for subsequent success-rate statistics. Since the focus of this study is mechanism identification rather than large-scale regional optimization, the clustering process is not developed as an independent optimization model. Instead, population origins are classified into six spatial types, O1–O6, by considering spatial indicators such as network distance, road connectivity, building-related detours, proximity to boundaries, and proximity to bottleneck nodes.

3.4. Model Construction and Basic Rules

3.4.1. Model Positioning and Settings

This study defines the model as a general evacuation-capacity experiment rather than a predictive simulation for a specific disaster type. The model does not explicitly represent hazard diffusion, road damage, visibility reduction, or heat-exposure accumulation during sandstorms, earthquakes, floods, landslides, or extreme heat events. Instead, under given conditions of roads, obstacles, boundaries, population origins, and shelters, it compares how different levels of destination cognition and route organization affect evacuation efficiency. The desert environment and corridor-dependent characteristics of Ruoqiang County are used primarily to define the research background and spatial constraints. Accordingly, the model results are interpreted as differences in evacuation capacity within the selected built-up area, rather than as the risk-evolution outcomes of a specific disaster event.

In terms of model parameters, this study specifies key variables including total population, batch release size, release interval, individual movement speed, shelter capacity, time step, maximum tolerable evacuation time, and the proportion of behavioral modes. To control for differences in individual movement ability and to highlight the effects of destination cognition and route organization, individual movement speed is uniformly set at 1.3 m/s. The maximum tolerable evacuation time is set at 30 min, and agents who have not reached a shelter after this threshold are classified as evacuation failures. Shelters accept evacuees according to their capacity limits. Once a shelter reaches its capacity,

subsequent agents must reselect another shelter with available capacity. This setting reflects the basic redistribution process under limited shelter resources, but it does not separately simulate complex facility scheduling or emergency-management interventions. Specific model information is shown in Table 1.

Table 1. Key model parameters.

Indicator	Value or Description
Number of shelters	6
Shelter capacity setting	Calculated according to relevant Chinese emergency-evacuation standards and shelter area
Number of evacuation origins	134
Total evacuation population	65,000
Release interval	30 s
Road-network construction method	Each polyline vertex in the road shapefile was converted into a node; links were established between consecutive vertices; endpoint nodes with identical coordinates were connected to form the road network

To identify continuous changes in evacuation efficiency under different levels of organization, five behavioral scenarios are designed: fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. These scenarios share the same physical environment, population size, movement speed, release mechanism, and shelter-capacity conditions, and differ only in the proportion of ordered and disordered agents. In this study, ordered evacuation refers to an idealized information-organization condition in which agents can identify available shelters and use road-network information for route choice. Disordered evacuation refers to a local-perception condition in which agents lack stable global destination knowledge and mainly move according to locally perceived open directions. These scenarios should be interpreted as comparative information-organization assumptions rather than empirical predictions of actual evacuation behavior. The fully ordered scenario represents an ideal upper-bound condition, while the fully disordered scenario represents a lower-bound condition. The mixed scenarios are used to examine the transition between these two boundary assumptions. The numerical outputs of these scenarios should be interpreted as conditional results under the specified parameter settings, rather than as robust policy estimates.

3.4.2. Model Environment Construction

Considering that this study needs to represent road movement, obstacle detouring, boundary constraints, and local direction choice at the same time, the model adopts a hybrid modeling approach that combines road-network constraints with a rasterized environmental representation. Roads are assigned connectivity relationships and path attributes and serve as the main movement skeleton for ordered evacuation. Buildings, walls, and other impassable facilities are encoded as obstacle cells. Shelters are represented as target cells with spatial coordinates and capacity attributes. Population origins are used to indicate the release locations of evacuation demand, while the study-area boundary defines the activity range of individuals. This approach preserves the topology of the road network while also representing real-world processes such as non-traversable spaces, local detouring, and boundary restrictions.

The environmental objects in the model mainly include five categories: road objects, obstacle objects, shelter objects, population-origin objects, and boundary objects. Evacuees are modeled as the core agents and have attributes such as current location, movement

speed, current destination, behavioral mode, cumulative travel time, remaining tolerable time, arrival status, and failure status. During movement, agents must follow several basic rules: they cannot cross obstacles or move beyond the boundary; when blocked ahead, they perform local detouring or recalculate a route; after reaching an available shelter, they exit the evacuation process; if the target shelter is full, they continue to select a direction or destination according to the corresponding behavioral mode; and agents who still have not reached a shelter after the time limit are recorded as failures.

On this basis, this study constructs five evacuation scenarios by changing the proportion of ordered and disordered agents, namely fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. These scenarios are used to compare evacuation-performance differences under different assumptions of destination cognition and route organization.

3.4.3. Continuous Release Mechanism

Instead of adopting the simplified assumption that all individuals are generated simultaneously at the beginning of the simulation, this study uses a continuous release mechanism to construct the evacuee population. Specifically, the system releases a fixed number of individuals from population origin points at predefined time intervals until the cumulative number of evacuees reaches the total population size. After the simulation starts, a fixed number of individuals, denoted by q , is released from the population origins every $\Delta\tau$ time interval until the total population reaches the preset size N . If the time of the k -th release is denoted by t_k , then:

$$t_k = k \cdot \Delta\tau \quad (k = 0, 1, 2, \dots)$$

The number of individuals released in the k -th batch is denoted by q_k , and under the constraint of total population size it satisfies:

$$\sum_{k=0}^m q_k = N$$

This setting simulates the process through which individuals gradually enter the road system after perceiving the disaster, responding to the event, and leaving buildings or gathering points. Compared with one-time population release, continuous release better approximates the gradual perception of risk and staged entry into the evacuation system during real disasters. It also makes it possible to observe temporal phenomena such as corridor utilization, shelter-capacity occupation, tail-end convergence, and phase-specific congestion. More importantly, this mechanism reflects how congestion formation, shelter occupancy, and the decision conditions faced by later evacuees change over time.

3.4.4. Behavioral Mode Settings

(1) Ordered evacuation mode

The ordered evacuation mode assumes that individuals know the location of the nearest available shelter that can still receive evacuees and tend to choose destinations that are easier to reach through the road system. Under this mode, individuals first identify shelters that have not yet reached capacity from the set of available shelters. Let the set of available shelters at time t be denoted by S_t :

$$S_t = \{O_j(t) < C_j\}$$

where $O_j(t)$ denotes the number of occupants in shelter j at time t , and C_j denotes the capacity limit of shelter j . The destination choice of individual i at time t can then be expressed as:

$$j_i^*(t) = \operatorname{argmin}_{j \in S_t} d_{ij}^{\text{net}}(t)$$

where $d_{ij}^{\text{net}}(t)$ denotes the network distance or network cost for individual i to reach shelter j through the road network. This formulation indicates that ordered individuals do not simply select shelters according to Euclidean distance but instead choose the currently optimal destination based on road-network accessibility. Once a destination is determined, individuals enter the road system and move along the optimal path, turning at intersection nodes according to the assigned route. Their movement logic can be summarized as “moving along roads, turning at nodes, and continuing along roads.” As long as the current destination shelter remains available, individuals continue moving toward it. If the destination becomes full during the evacuation process, a target reassignment procedure is triggered, and the individual searches for another available shelter with relatively low network cost.

This mode corresponds to a relatively high level of organization and spatial cognition. It can be understood as a scenario in which residents have received sufficient evacuation training, are familiar with shelter locations, are supported by a clear signage system, or are guided by effective on-site organization.

(2) Disordered evacuation mode

The disordered evacuation mode assumes that individuals do not know the location of the nearest shelter and lack stable global path cognition. Instead, they can only search within their local visual field for directions that appear more open and move accordingly. Let Θ denote the set of directional angles within the 360-degree field of view of individual i at time t . For any direction $\theta \in \Theta$, the openness function $Wi(\theta, t)$ is defined to represent the perceived openness of that direction, jointly determined by passable distance, obstacle density, and local visual accessibility. Before an individual identifies the direction of a shelter, the movement direction of a disordered individual can be expressed as:

$$\theta_i^*(t) = \operatorname{argmax}_{\theta \in \Theta} Wi(\theta, t)$$

This equation indicates that individuals preferentially move toward more open directions within their current perception range, rather than following the globally shortest path. The position update can be expressed as: $x_i(t + \Delta t) = x_i(t) + v\Delta t \cdot \overrightarrow{e_{\theta_i^*(t)}}$. When a disordered agent enters the shelter-recognition range, or when an available shelter is detected within its local perception range, its behavior shifts from open-direction movement to destination-oriented movement. Let R_s denote the shelter-recognition radius of agent i . The set of locally recognizable and available shelters is defined as:

$$S_i^{\text{loc}}(t) = \left\{ s_j \in S \mid \operatorname{dist}(x_i(t), s_j) \leq R_s, \quad u_j(t) < \operatorname{Cap}_j \right\}$$

If $S_i^{\text{loc}}(t) \neq \emptyset$, the agent selects the nearest shelter or the shelter with the lowest travel cost from the locally recognizable shelter set:

$$S_i^{\text{loc}}(t) = \operatorname{arg} \min_{s_j \in S_i^{\text{loc}}(t)} d((x_i(t), s_j))$$

The agent then moves toward the selected destination. If the target shelter becomes full or the route is blocked, the agent returns to the local-perception state and continues to choose its movement direction according to the openness function. Therefore, disordered evacuation does not represent completely random movement; rather, it is a heuristic action

process under local information conditions. Its main limitation lies in the inability to consistently use global shelter information and road-network information. This behavioral mode is closer to realistic situations characterized by a lack of drills, insufficient information, unclear signage, or weak on-site organization. It represents not complete randomness, but direction choice under “local rationality.” Individuals tend to move away from constrained or narrow areas, but because they lack destination cognition, their behavior cannot always be aligned with the globally efficient evacuation path.

To further identify the continuous variation in evacuation efficiency under different levels of organization, this study introduces mixed evacuation scenarios with 25%, 50%, and 75% ordered agents, in addition to the two boundary scenarios of fully ordered and fully disordered evacuation. The 25% ordered scenario represents an evacuation process under low-level destination cognition and weak organizational conditions. The 50% ordered scenario reflects an intermediate state in which ordered and disordered behaviors coexist. The 75% ordered scenario characterizes an evacuation process with a relatively high level of organization but with some disordered agents still present. By introducing these mixed scenarios, the study moves beyond a simple upper–lower bound comparison and further examines how increases in the proportion of ordered behavior affect evacuation-curve morphology, key threshold times, and final evacuation levels, thereby revealing in greater detail the mechanism through which destination cognition and route organization influence pedestrian evacuation performance in local built-up areas.

3.4.5. Origin-Type Success-Rate Statistics

Based on the spatial grouping of population origins generated during data preprocessing, the main model outputs include the overall evacuation rate, key threshold times, evacuation curves under different scenarios, and origin-type success rates. The overall evacuation rate is used to characterize system-level evacuation efficiency under different evacuation scenarios. Key threshold times are used to compare the time required for different scenarios to reach specific evacuation proportions. Origin-type success rates are used to identify differences in evacuation outcomes under different spatial conditions. This study classifies population origins into six types: origins near shelters with direct connectivity (O1), medium-distance origins with continuous road-network access (O2), origins requiring building-related detours (O3), origins near boundaries or in low-connectivity areas (O4), origins far from shelters (O5), and origins near major bottleneck nodes (O6). Among them, O1 and O2 mainly represent origins with relatively good accessibility; O3–O5 represent origins strongly constrained by detours, boundaries, or distance; and O6 is used to identify evacuation performance near critical movement nodes. The origin-type success rate is defined as the proportion of agents released from a given origin type who successfully reach a shelter within the maximum tolerable evacuation time. By comparing the success rates of O1–O6 across the five evacuation scenarios, this study further evaluates whether differences in overall evacuation efficiency are spatially consistent and how origins under different spatial conditions respond to changes in the ordered proportion.

3.4.6. Model Plausibility Check and Uncertainty Analysis

This model is positioned as an exploratory scenario model for mechanism identification rather than a predictive model calibrated using historical evacuation records or field-drill trajectories. To improve the credibility of the model results, this study verifies the model from three perspectives: model logic, temporal scale, and stochastic stability. First, a GIS-based shortest-path verification is conducted. The shortest road-network distance from each population origin to the nearest shelter is calculated and converted into a theoretical shortest walking time using a walking speed of 1.3 m/s. This theoretical time is

then compared with the simulated arrival time under the fully ordered scenario to assess whether the model's temporal scale is reasonable. Second, because continuous release and behavioral-type assignment in mixed scenarios involve stochastic processes, the five scenarios are repeatedly simulated using multiple random seeds. The mean, standard deviation, and uncertainty intervals of the final evacuation rate, key threshold times, and plateau time are then calculated to examine the stability of the simulation results.

4. Results

4.1. Simulation Results

Figure 2 illustrates the spatial evolution of evacuees during the model simulation. The left panel presents a global view of the study area, where the red dashed rectangle marks the local area selected for subsequent detailed analysis. The right panel shows enlarged views of this local area at consecutive time points, revealing the staged dynamics of the evacuation process along the temporal sequence. In the figure, red cells represent agents who are still in the evacuation process, while green cells represent agents who have successfully completed evacuation. Overall, at the initial stage of evacuation, individuals are scattered across building clusters and road spaces. They then gradually converge toward major movement corridors and open areas, resulting in a clear increase in local population density and spatial clustering. As the evacuation progresses, more agents successfully complete evacuation, and the number of remaining evacuees in the study area decreases continuously. The spatial distribution shifts from an initially dispersed pattern to an organized corridor-based transfer pattern. In the later stage, only a small number of individuals remain within the local area without completing evacuation. The overall process therefore exhibits clear temporal progression and spatial convergence. These results indicate that the agent-based model can effectively capture the dynamic evacuation process from dispersed generation, route convergence, and gradual clearance. It also provides an intuitive basis for identifying key retention areas and high-pressure movement nodes in subsequent analysis.

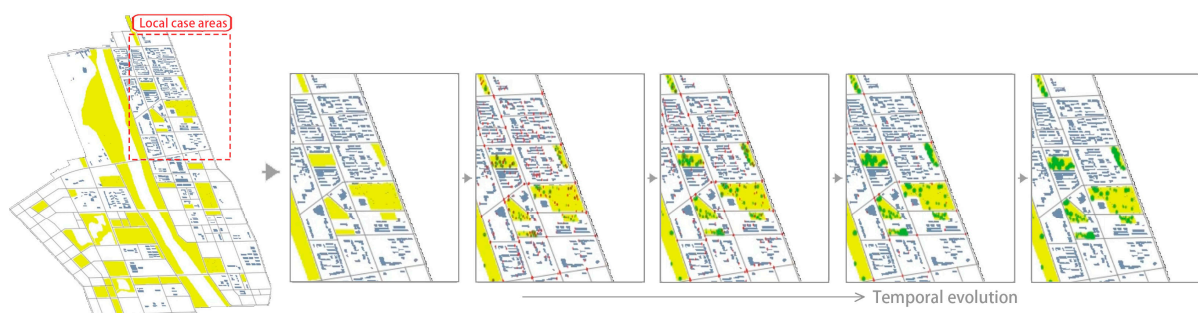


Figure 2. Model simulation process.

4.2. Overall Comparison of Evacuation Patterns

Figure 3 shows the temporal changes in the evacuation ratio under five scenarios: fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. Overall, as the proportion of ordered agents increases, the evacuation curves shift upward, and both the final evacuation level and the early-stage growth rate show an increasing trend. The five scenarios do not exhibit a simple equidistant linear progression; rather, they show differentiated temporal patterns in terms of growth rate, inflection-point position, and plateau level. The fully ordered evacuation curve represents an ideal upper-bound condition rather than an observed real-world evacuation outcome. Under the assumptions of clear destination recognition and usable route information, the evacuation ratio reaches 50% at 1.47 min, approaches 90% at 2.90 min, and reaches 100% at 9.25 min. This result

indicates that, within the model setting, idealized destination cognition and route organization can support a continuous and efficient simulated evacuation process. By contrast, the fully disordered evacuation curve remains at a low level and increases slowly. It reaches 10% at 2.33 min, enters a plateau after approximately 4.88 min, and finally stabilizes at about 13%. This result suggests that, in the absence of stable destination cognition and route organization, the evacuation process quickly enters a low-level stagnant state.

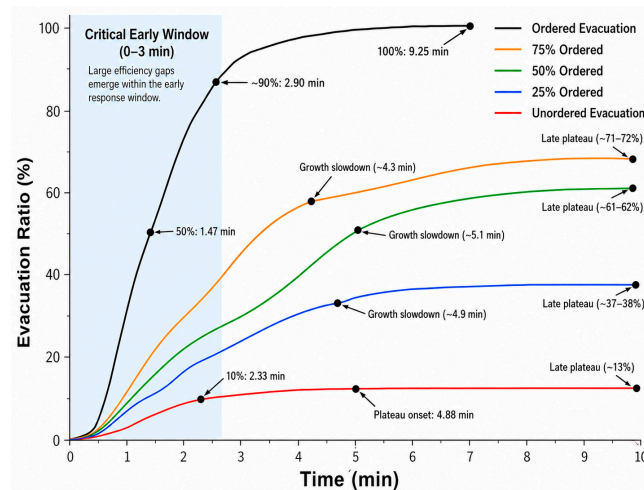


Figure 3. Simulated evacuation efficiency under different ordered-proportion scenarios.

The three mixed scenarios fall between the two boundary scenarios, but their curve shapes differ. The 75% ordered scenario maintains rapid growth in the early stage, slows down after approximately 4.3 min, and eventually forms a plateau of about 71–72%. The 50% ordered scenario shows a more evident intermediate transition pattern, with growth slowing after approximately 5.1 min and eventually stabilizing at about 61–62%. The 25% ordered scenario shows a relatively limited increase, enters a deceleration stage after approximately 4.9 min, and reaches a final plateau of about 37–38%. The relative positions of the three mixed-scenario curves indicate that increasing the proportion of ordered agents can continuously improve evacuation levels, although the magnitude of improvement varies across stages. A higher ordered proportion mainly improves early- and middle-stage evacuation efficiency, whereas a lower ordered proportion can raise the final plateau level but is insufficient to move the system into a highly efficient convergence state.

The 0–3 min interval marked in the figure represents the critical early window. Within this period, the fully ordered scenario shows rapid simulated evacuation under the ideal ordered-information assumption, and the 75% ordered scenario also shows substantial growth. In contrast, the 25% ordered and fully disordered scenarios remain in a low-level climbing stage. This indicates that efficiency differences among scenarios are reflected not only in the final evacuation ratio, but also in whether destination-oriented movement can be rapidly formed during the early window. Differences in early-window growth further shape the subsequent plateau level and tail-end convergence of the evacuation curves.

4.3. Differences in Evacuation Success Rates Across Origin Types

Table 2 shows changes in the success rates of different origin types under the five evacuation scenarios. Overall, as the proportion of ordered agents increases, the success rates of all origin types rise, but the magnitude of improvement varies considerably across spatial types. Under the fully disordered scenario, the success rates of all origin types remain generally low. Among them, O1, representing origins near shelters with direct connectivity, has the highest success rate, ranging from 22% to 30%. O4, representing origins near boundaries or in low-connectivity areas, has the lowest success rate, ranging

from only 4% to 8%, while O5, representing origins far from shelters, reaches only 5% to 10%. This indicates that, in the absence of clear destination cognition and route organization, spatial location exerts a strong influence on evacuation outcomes. Short distance and direct connectivity can substantially increase the probability of agents accidentally reaching shelters.

Table 2. Success rates of different origin types.

Origin Type	Spatial Characteristics	Disordered	25% Ordered	50% Ordered	75% Ordered	Ordered	Interpretation
O1	Near shelters and directly connected	22–30%	46–58%	70–82%	90–97%	100%	Most sensitive to improved destination cognition
O2	Medium distance and continuous road network	12–18%	35–46%	58–72%	82–92%	100%	Improves steadily as the ordered proportion increases
O3	Building-related detours	7–13%	24–36%	45–60%	70–84%	100%	Detours weaken the benefits of the same ordered proportion
O4	Near boundaries or in low-connectivity areas	4–8%	16–28%	36–52%	60–78%	100%	More likely to generate residual retention
O5	Far from shelters	5–10%	20–32%	40–58%	66–82%	100%	Determines tail-end delay in the system
O6	Near major bottleneck nodes	8–15%	28–40%	50–66%	72–86%	100%	Affected by bottleneck-related movement pressure

Note: The success rate ranges for evacuation origin types O1–O6 represent the minimum and maximum success rates observed across multiple random seed repetitions ($n = 30$) for the same origin type.

Under the mixed evacuation scenarios, the success rates of all origin types gradually increase as the ordered proportion rises. In the 25% ordered scenario, the success rate of O1 increases to 46–58%, and that of O2 increases to 35–46%. However, the success rates of O4 and O5 remain only 16–28% and 20–32%, respectively, suggesting that a low proportion of ordered behavior can improve evacuation outcomes in short-distance and road-continuous areas, but its effect remains limited for boundary areas, low-connectivity areas, and distant origins. Under the 50% ordered scenario, the success rates of all types further increase. O1 reaches 70–82%, O2 reaches 58–72%, and O3 and O6 reach 45–60% and 50–66%, respectively. This indicates that, under a moderate level of organization, more medium-distance and detour-constrained origins begin to convert into effective evacuation.

In the 75% ordered scenario, most origin types achieve relatively high success rates. O1 reaches 90–97%, O2 reaches 82–92%, while O3 and O6 reach 70–84% and 72–86%, respectively. Nevertheless, O4 and O5 remain comparatively lower, at 60–78% and 66–82%, respectively. This suggests that even under a high ordered proportion, origins near boundaries, in low-connectivity areas, or far from shelters may still constitute important sources of late-stage retention. Under the fully ordered scenario, the success rates of all origin types reach 100%, indicating that under ideal assumptions of clear destination cognition and usable route information, differences in success rates across origin types are largely removed within the simulated system.

Overall, the origin-type success-rate results indicate that improvements in evacuation efficiency do not occur uniformly across space. Origins near shelters, directly connected to shelters, or embedded in continuous road networks respond most strongly to increases in the ordered proportion, whereas boundary areas, low-connectivity areas, distant origins, and origins near bottleneck nodes improve more slowly. This further suggests that, under mixed evacuation scenarios, increases in the overall evacuation rate are mainly driven by early improvements at highly accessible origins, while origins subject to stronger spatial constraints are more likely to generate tail-end delay and residual retention.

4.4. Behavioral Mechanism Interpretation

Destination-recognition capability is mainly reflected in evacuation growth within the critical early window of 0–3 min and in key threshold times. Road-network utilization capability is mainly reflected in the growth patterns and plateau states of the evacuation curves under different scenarios. Spatial-constraint response is reflected in the success-rate differences among the six origin types, O1–O6. Therefore, the interpretation of behavioral mechanisms is based on three dimensions of results—curve changes, threshold times, and origin-type success rates—rather than being a simple repetition of the simulation results.

First, destination-recognition capability is a direct factor affecting early evacuation efficiency. Under the fully ordered scenario, agents have clear shelter destinations from the release stage and can rapidly enter the road system and move toward available shelters. As a result, rapid growth is formed within the critical early window of 0–3 min. By contrast, agents in the fully disordered scenario lack stable destinations and can only move according to locally open directions. Although they also generate movement, their movement direction does not necessarily point toward safe destinations, making the system prone to entering a low-level plateau at an early stage. The three mixed scenarios lie between the two boundary scenarios, indicating that an increase in the ordered proportion can gradually strengthen destination-oriented movement. However, a low proportion of ordered behavior remains insufficient to move the system into a highly efficient convergence state.

Second, road-network utilization determines whether individual movement can be transformed into effective evacuation. Ordered agents organize their movement according to the road network, and their behavioral process is closer to a continuous sequence of “destination recognition–route access–node turning–continuous approach.” This process helps transform individual movement into effective evacuation flows converging toward shelters. Disordered agents are also constrained by boundaries and obstacles, but their movement strategy prioritizing locally open directions cannot ensure consistency with globally efficient routes. As a result, they are more likely to experience deviation, detouring, and inefficient wandering. Therefore, the difference between the two scenarios does not arise from differences in movement speed, but from differences in how the road network is utilized.

Finally, the spatial conditions of origins play a moderating role in evacuation efficiency. The success-rate results for different origin types show that O1 and O2, representing origins near shelters, directly connected to shelters, or embedded in continuous road networks, respond most strongly to increases in the ordered proportion. O3–O5, representing origins requiring building-related detours, origins near boundaries or in low-connectivity areas, and origins far from shelters, improve more slowly. O6, representing origins near major bottleneck nodes, is affected by both destination recognition and local movement pressure. This indicates that increases in the overall evacuation rate do not occur uniformly but first appear at origins with better accessibility and stronger route continuity. For origins subject to stronger spatial constraints, tail-end delay and residual retention may still occur even when the ordered proportion increases.

4.5. Model Plausibility Check and Uncertainty Results

To further examine the temporal scale of the model and the stability of scenario results, this study conducts model verification and uncertainty analysis based on the overall evacuation results. To further connect the simulated evacuation times with the spatial scale of the study area, the GIS-based shortest-path times were converted into network distances using the assumed walking speed of 1.3 m/s. The resulting shortest-path distances from origins to the nearest shelters range from approximately 0.03 km to 0.64 km, with an average distance of approximately 0.12 km. The maximum shortest-path distance is therefore well

below the theoretical walking distance corresponding to 9.25 min at 1.3 m/s. This confirms that the simulation represents short-distance pedestrian evacuation within a local built-up area rather than county-wide relocation. Table 3 compares GIS-based shortest walking times with simulated arrival times under the fully ordered scenario. Overall, the simulated arrival times under the fully ordered scenario are slightly higher than the theoretical GIS-based shortest-path times, and the two are of a similar magnitude. The average travel time estimated from GIS shortest paths is 1.52 min, while the simulated average arrival time under the fully ordered scenario is 1.73 min, with a relative difference of 13.8%. The median travel time estimated from GIS shortest paths is 1.32 min, while the simulated median arrival time is 1.47 min, which is consistent with the time at which the fully ordered scenario reaches a 50% evacuation ratio in Figure 3. For the 90th-percentile time, the GIS estimate is 2.52 min, while the simulated result is 2.90 min, with a relative difference of 15.1%. For the longest travel time, the GIS estimate is 8.20 min, while the simulated completion time is 9.25 min, with a relative difference of 12.8%. The results show that simulated travel times under the fully ordered scenario are not systematically shorter than the theoretical GIS-based shortest walking times, indicating that the model does not exhibit obvious unrealistic acceleration. Because the simulation process also includes continuous release, node turning, local detouring, and capacity constraints, it is reasonable for simulated arrival times to be slightly higher than GIS-based shortest-path estimates. In addition, the correlation coefficient between GIS time and simulated time is 0.95, indicating strong consistency between the model output and independent road-accessibility estimates. This suggests that the model's temporal scale and road-movement rules are basically reasonable.

Table 3. Verification results comparing GIS-based shortest walking times and simulated arrival times under the fully ordered scenario.

Verification Indicator	GIS Shortest-Path Estimate	Fully Ordered Simulation Result	Absolute Difference	Relative Difference
Minimum travel time	0.42 min	0.48 min	0.06 min	14.3%
Average travel time	1.52 min	1.73 min	0.21 min	13.8%
Median travel time/T50	1.32 min	1.47 min	0.15 min	11.4%
75th-percentile travel time	2.04 min	2.34 min	0.30 min	14.7%
90th-percentile travel time/T90	2.52 min	2.90 min	0.38 min	15.1%
95th-percentile travel time	3.20 min	3.70 min	0.50 min	15.6%
Maximum travel time/completion time	8.20 min	9.25 min	1.05 min	12.8%

Table 4 further presents the stability results of the five evacuation scenarios under repeated simulations with multiple random seeds. T10, T50, and T90 represent the times required for the cumulative evacuation ratio to reach 10%, 50%, and 90%, respectively, and are used to characterize the start-up speed, mid-stage efficiency, and late-stage convergence capability of the evacuation process. If the final evacuation rate of a scenario is lower than the corresponding threshold, the threshold time is recorded as “not reached.” Overall, the final evacuation rates and key threshold times remain stable across scenarios, and the relative ranking among scenarios does not change. The fully ordered scenario has a final evacuation rate of 99.8%, a T50 of 1.47 min, a T90 of 2.90 min, and a completion time of 9.25 min, indicating stable model output under ideal organizational conditions. The fully disordered scenario has a final evacuation rate of 13.1% and a plateau onset time of 4.88 min, indicating that disordered movement consistently exhibits a low-level plateau pattern.

Table 4. Uncertainty results for the five evacuation scenarios under repeated simulations with multiple random seeds.

Scenario	Number of Runs	Mean Final Evacuation Rate	Standard Deviation	Approximate 95% Simulation Interval	T10	T50	T90	Plateau or Completion Time
Fully disordered	30	13.1%	0.7%	11.7–14.5%	2.33 min	Not reached	Not reached	Plateau onset: 4.88 min
25% ordered	30	37.6%	1.3%	35.0–40.2%	1.45 min	Not reached	Not reached	Growth slowdown: 4.90 min
50% ordered	30	61.4%	1.4%	58.7–64.1%	1.25 min	5.08 min	Not reached	Growth slowdown: 5.10 min
75% ordered	30	71.7%	1.1%	69.5–73.9%	1.03 min	3.55 min	Not reached	Growth slowdown: 4.30 min
Fully ordered	30	99.8%	0.3%	99.2–100.0%	0.70 min	1.47 min	2.90 min	Completion time: 9.25 min

The three mixed scenarios show continuous transitional characteristics. The 25% ordered scenario has a final evacuation rate of 37.6%, higher than the fully disordered scenario, but it does not reach the 50% evacuation threshold. The 50% ordered scenario has a final evacuation rate of 61.4%, reaching the 50% evacuation threshold but not the 90% threshold. The 75% ordered scenario has a final evacuation rate of 71.7%, with a further increase in early-stage growth, but it still does not reach the 90% evacuation threshold. The final evacuation levels of the five scenarios show a stable ranking of “fully ordered > 75% ordered > 50% ordered > 25% ordered > fully disordered,” indicating that an increase in the proportion of ordered agents has a consistent positive effect on evacuation efficiency.

Taken together, the GIS accessibility verification and repeated simulations with multiple random seeds indicate that the model results show good consistency in temporal scale and scenario ranking. The simulated arrival times under the fully ordered scenario are slightly higher than the GIS-based theoretical shortest-path times, which is consistent with the model settings that include continuous release, node turning, and local constraints. The stable ranking of final evacuation rates and key threshold times across the five scenarios indicates that the model can robustly reflect the effect of changes in the ordered proportion on evacuation efficiency.

5. Discussion

5.1. Main Findings

The first major finding of this study is that destination recognition and organizational level significantly affect evacuation efficiency, and this effect is first reflected in the early evacuation window. The simulation results show that the fully ordered scenario produces rapid growth and tail-end convergence within a relatively short time, whereas the fully disordered scenario enters a low-level plateau at an early stage. The 25%, 50%, and 75% ordered scenarios display a transitional process in which evacuation gradually improves from inefficient diffusion to destination-oriented movement. This indicates that increasing the proportion of ordered agents changes not only the final evacuation rate, but also whether an evacuation flow can be formed in the initial stage. This finding is consistent with existing evacuation-behavior studies showing that information availability, environmental cognition, and route guidance affect evacuation efficiency; that is, whether individuals know the location of destinations and have route information directly influences their movement direction and overall system performance [32–34].

The second major finding is that road-network utilization acts as a key mediator through which destination cognition is transformed into effective evacuation. Under the fully ordered scenario, individuals can continuously approach shelters along the road network, making their movement more likely to become effective evacuation. Under

the disordered scenario, although individuals may also move according to locally open directions, such heuristic actions based on local perception do not necessarily lead them continuously toward safe destinations. As a result, the phenomenon of “movement without effective evacuation” may occur. This finding echoes existing wayfinding studies suggesting that local information does not necessarily lead to globally efficient paths. It also indicates that, in corridor-dependent county-level built-up areas, the mere existence of roads does not mean that they can be effectively used; individuals must also be able to identify and continuously access effective routes [32,35,36].

The third major finding is that improvements in evacuation efficiency show clear spatial unevenness. The success rates of different origin types indicate that origins near shelters, directly connected to shelters, or embedded in continuous road networks are most sensitive to increases in the ordered proportion, whereas origins near boundaries, in low-connectivity areas, far from shelters, or close to bottleneck nodes improve more slowly. This means that improving organizational level can enhance overall evacuation efficiency, but its effects do not automatically apply evenly to all spatial units. Compared with evacuation studies of high-density urban areas, building interiors, or transport hubs, the inefficiency mechanism in the present case is not primarily manifested as exit congestion or queuing. Instead, it is more strongly reflected in insufficient destination recognition, unstable road access, and differences in spatial constraints across origins [37,38].

In summary, the results of this study are consistent with existing evacuation-behavior research emphasizing the importance of information, route cognition, and organizational guidance. They also further contribute to the spatial-mechanism explanation of evacuation in corridor-dependent county-level built-up areas. For built-up areas such as Ruqiang County, which are characterized by nodal and corridor-based spatial organization, evacuation efficiency is not determined simply by the number of shelters or road distance. Rather, it is jointly shaped by destination recognition, road-network utilization, and the spatial conditions of origins. The contribution of this study lies in extending the mechanism from overall evacuation-curve comparison to the differentiated responses of different origin types, thereby demonstrating that evacuation governance in county-level built-up areas should address both organizational capacity improvement and the identification of spatial weaknesses.

5.2. Theoretical Implications

The theoretical significance of this study is reflected in three aspects. First, the findings show that evacuation in built-up areas of corridor-dependent counties cannot be simplified as a static shortest-path or service-radius problem. In regions such as Ruqiang, where settlements are organized around oasis nodes and transport corridors, evacuation performance is not determined by road geometric distance or the number of shelters alone, but by the combined effects of destination cognition, route organization, and spatial constraints. Second, this study extends the two boundary scenarios of ordered and disordered evacuation into a continuous set of mixed scenarios, enabling the model to describe evacuation processes under different organizational levels in greater detail. Compared with only contrasting fully ordered and fully disordered scenarios, the 25%, 50%, and 75% ordered scenarios reveal staged changes in evacuation efficiency as the level of organization increases. This helps avoid reducing the evacuation system to a binary state of “effective” or “ineffective” and instead frames it as a dynamic process that changes continuously with destination cognition and route organization. Third, by analyzing origin-type success rates, this study further decomposes overall evacuation efficiency to the spatial-origin level and reveals the moderating role of different spatial conditions in evacuation outcomes. This analysis shows that evacuation in county-level built-up areas cannot be fully explained by a

single aggregate curve. Rather, it is a spatially differentiated process shaped by different origin types, road-connectivity conditions, and shelter accessibility. This understanding helps advance evacuation ABM from overall efficiency comparison toward spatial diagnosis and mechanism identification.

5.3. Planning Implications

Based on the scenario results, the planning implications of this study should be interpreted as possible applications derived from model-based mechanism identification, rather than as directly tested intervention effects. The model does not explicitly simulate signage installation, staff guidance, emergency broadcasting, drill frequency, or real-time behavioral adaptation. Therefore, the following implications are proposed cautiously and are linked to the observed differences in evacuation curves and origin-type success rates.

First, origin–shelter correspondence may be strengthened for origins with different accessibility conditions. The origin-type results show that origins near shelters and directly connected to the road network perform better, while origins far from shelters or with discontinuous paths show lower success rates. For this reason, local planning may consider clarifying a “primary shelter–backup shelter–recommended route” relationship around major population origins, especially for distant origins and origins with weak road continuity.

Second, greater attention may be given to origins with strong spatial constraints. The results show that boundary-adjacent origins, low-connectivity origins, distant origins, and bottleneck-adjacent origins are more likely to generate late-stage retention. These findings suggest that subsequent planning may prioritize the inspection of dead-end roads, wall barriers, excessive detour distances, and unclear corridor directions in these areas. Measures such as improving local micro-circulation, reserving emergency access points, and strengthening route guidance can be considered as possible planning responses.

Third, signage, drills, and local guidance may be organized according to origin types, but their quantitative effects are not directly tested in this model. The ordered scenario represents an idealized information and route-organization condition that may be partially approached through such measures. Highly accessible origins may focus on rapid assembly and orderly entry; low-connectivity or distant origins may require clearer detour routes and backup destinations; and bottleneck-adjacent origins may require staggered departure and directional guidance. These suggestions should therefore be understood as planning hypotheses derived from the scenario results, rather than as confirmed intervention effects.

5.4. Limitations and Future Directions

This study is a scenario-based simulation aimed at mechanism identification and still has several limitations. First, the model simplifies real-world crowd behavior and does not incorporate group heterogeneity factors such as age structure, physical condition, household co-movement, herding behavior, or panic diffusion. Second, the model is positioned as a general evacuation-capacity experiment rather than a predictive simulation of specific hazard processes; therefore, it does not explicitly simulate hazard diffusion, road damage, visibility reduction, heat exposure, or facility failure. Third, systematic parameter sensitivity testing has not yet been conducted. Key parameters such as movement speed, visual range, and shelter-recognition radius may affect evacuation curves and threshold times. Therefore, the reported numerical results should be interpreted as scenario-specific outcomes under the current parameter settings, rather than as robust policy estimates.

Future research should further calibrate behavioral parameters with measured data, introduce dynamic hazard processes, and conduct parameter sensitivity and spatial-optimization analyses. In addition, the fully ordered and fully disordered scenarios should

be understood as idealized upper- and lower-bound assumptions. The results are intended for mechanism identification under specific model settings, rather than direct prediction of real evacuation performance.

6. Conclusions

This study takes a typical built-up area within Ruoqiang County as the simulation unit and constructs an agent-based evacuation simulation framework for a corridor-dependent county context. The model is positioned as a general evacuation-capacity experiment rather than a predictive simulation of a specific hazard process. Under unified spatial environment, movement speed, release mechanism, and shelter-capacity conditions, five scenarios are compared: fully disordered, 25% ordered, 50% ordered, 75% ordered, and fully ordered evacuation. The analysis further examines spatial differences in evacuation success rates across six origin types.

First, destination cognition and route organization affect simulated evacuation efficiency within the selected built-up area under the specified model assumptions. Under the ideal ordered-information assumption, the simulated system reaches complete evacuation within 9.25 min, whereas the fully disordered scenario enters a low-level plateau after approximately 4.88 min, with a final evacuation ratio of about 13%. The GIS-based shortest-path distances from origins to the nearest shelters range from approximately 0.03 km to 0.64 km, with an average value of approximately 0.12 km. These values confirm that the time results correspond to the local built-up-area scale rather than to county-wide evacuation.

Second, differences among scenarios emerge clearly within the early evacuation window. The fully ordered scenario forms a rapid and continuous simulated evacuation flow within 0–3 min under ideal information assumptions, while the 25% ordered and fully disordered scenarios remain in a low-level growth stage. This suggests that evacuation efficiency is shaped not only by the final evacuation ratio, but also by whether destination-oriented movement can be established early.

Third, evacuation outcomes show clear spatial heterogeneity. Origins near shelters, directly connected to shelters, or embedded in continuous road networks respond more strongly to increases in the ordered proportion. In contrast, origins near boundaries, in low-connectivity areas, far from shelters, or close to bottleneck nodes are more likely to generate late-stage retention. These findings indicate that possible evacuation-capacity improvement in typical built-up areas within corridor-dependent counties should pay attention to spatially constrained origins, route continuity, and origin–shelter correspondence.

Overall, this study reveals how destination cognition, route organization, and origin spatial conditions jointly shape simulated pedestrian evacuation efficiency in a typical built-up area within a corridor-dependent county. The results should be interpreted as conditional scenario-based insights for mechanism identification, rather than direct empirical predictions of real evacuation performance. They provide methodological support for local shelter-space organization, evacuation-route guidance, and spatially differentiated evacuation planning.

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