Agent-Based Modeling of the Formation and Prevention of Residential Diffusion on Urban Edges

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Abstract: This paper presents an exploratory urban dynamics agent-based model (ABM) that simulates the relationship between the introduction of a hub facility open to residents, the interaction promotion around it, and transport policies on the sustainability of urban development through the autonomous actions of individual residents. By contrasting the model results with theoretical and empirical insights from actual cities, the validity of modeling the formation of residential diffusion on urban edges based on individual gain-maximizing daily travel and residential relocation is explained. The major contribution of the model is that it offers a new perspective on the bottom-up control of residential diffusion on urban edges, with benefits for productive human interactions at the microscale. Specifically, the model experimentally suggests the existence of a trade-off between increasing human interactions, through the introduction of an open hub attracting diverse activities and promotion of interaction around it, as well as the progression of residential diffusion. The model also suggests that the direction of urbanization is the result of collective action, and sustainable urbanization may be achieved through concerted efforts.

Keywords: agent-based simulation; urban design; land use; transportation; policy science

1. Introduction

1.1. Urban Expansion Issues

The world population has rapidly grown during the 20th and 21st centuries, and land—a finite resource—has continued to be rapidly urbanized in various places around the globe [1]. The urban area has expanded at a much faster rate than population growth [2]. The proportion of urban area to the Earth’s land surface may not seem large, however, increasing land urbanization affects fertile agricultural land, creates risks for biodiversity, increases the risk of flooding and water scarcity, and contributes to both the causes and effects of global warming [3]. Urbanization, in particular, causes many seriously negative environmental, social, and economic impacts than other land use because it creates problems such as soil-sealing (the covering of soil by impermeable artificial material such as asphalt and concrete), infrastructure development, and increases in traffic (especially automobiles) [4]. Therefore, dealing with the expansion of urbanization has become a global interest.

In Europe, the following three archetypical urbanization scenarios, which are the outcome of different intervention policies, are compared and assessed regarding the three dimensions of sustainability (economic, ecological, and social) in the land-use management guide written by researchers [3]:

- Compact urbanization: often the outcome of containment policies attempting to direct new development inward through regeneration, infill, or redevelopment;
- Polycentric urbanization: often pursued by spatial planning policies such as conjuction between public transportation and urban development;
Diffuse urbanization: often the result of libertarian policies opposed to bureaucratic planning, such as stimulating private automobile use and homeownership.

Of the urban forms derived from these three scenarios, the first and second are generally assessed positively, although some drawbacks, e.g., traffic congestion and exposure to pollution in compact urbanization, and traffic noise pollution in polycentric urbanization, can be noted. Conversely, the third is negatively assessed in all dimensions, e.g., high transportation costs, low energy efficiency, environmental pollution, negative impact on biodiversity, and prominent social segregation, except for the glaring advantages of convenience in the individual life of certain people. This diffuse urban form is one of the major aspects of urban sprawl that we have been facing around the world.

The literature on antisprawl is vast and varied, ranging from the popular to the academic. The reason for this is that sprawl remains ill-defined, although an almost universal consensus exists on its key manifestations and disadvantages. Although there is little rigorous evidence showing that antisprawl urban containment and densification strategies work and that their societal benefits exceed their drawbacks, political support for such strategies is substantial and growing [5,6].

Set against this background, this paper provides a starting point for discussions on sustainable urbanization by focusing on: (i) a change in the specific spatial behavior of residential diffusion on urban edges, which is a part of diffuse urbanization and urban sprawl; (ii) individual residents, who are the most important players among the many stakeholders in this process.

1.2. Countermeasures against Residential Diffusion

What is the preferable approach to address complex issues such as sustainable urbanization? Land use, including urbanization, is the result of the decisions which key stakeholders interact to produce. Stakeholders are not limited to authorities with legal rights or economic or political clout. For example, land use is also the outcome of how stakeholders such as developers anticipate and react to the decisions of such authorities. In particular, urbanization is characterized as an “emergence” from countless collective and individual decisions made by residents every day about where and how they want to stay, work and/or study, and enjoy interacting with each other within the constraints of what they can afford and what they can access [7,8].

One of the conventional methods of urban planning is to present an ideal image and restrict liberal activities by individuals and organizations in the process of its realization. In a democracy, however, it is difficult for standalone initiatives to assert such top-down authority [9]. Thus, multidimensional, multisectoral, and multistakeholder approaches are preferable. In other words, urban planning needs to present a desired direction of development, considering various circumstances, values, and interests and offering a compromise between them. Therefore, we adopted an approach with the aim of achieving the desired development—control of residential diffusion—through the bottom-up emergence of a moderate intervention in the behavior of individual residents from the perspective of policymakers and implementers.

1.3. Purpose of This Study

Set against this background, this paper discusses intervention policies for sustainable urbanization based on simulation experiments, with a focus on changes in the specific spatial behavior of residential diffusion on urban edges, which is the result of the collective action of individual residents. Due to its advantages in discussing the bottom-up emergence of urban forms based on collective action, we used the results of the growing agent-based urban land-use/transport interaction (LUTI) models as the starting point of the simulation. The simulation was then extended by drawing attention to the benefits of productive human interactions at the microscale in urban areas, and then extended by considering transportation policies that also support such face-to-face interactions. This allowed us to evaluate the relative contribution of the factors contributing to the control of residential
diffusion and to discuss an approach to sustainable urbanization based on the promotion of
human interactions. Discussions on the benefits of face-to-face human interactions in urban
space are also crucial for supporting the policymakers who decide on the direction of urban
transportation for sustainable urbanization. As such, our aim was not to directly improve
the urban environment in a particular area, but rather to draw insights into changing
urban forms, which depend on the behaviors of individual residents, by answering the
following questions:

• How could the formation of residential diffusion on urban edges, an obstacle to
  sustainable urbanization, be modeled?
• What kinds of resident behaviors could prevent the formation of urban diffusion?
• Which factors may induce such behaviors?

We also aimed to support the possibility that direction urbanization is the result of
collective action, and, therefore, can be influenced by concerted efforts [3].

1.4. Organization of This Paper

The remainder of this paper is organized as follows: Section 2 provides the intel-
lectual platform underlying the modeling approach by reviewing the related studies in
the literature and positions the urban dynamics agent-based model used in the experi-
ments. Section 3 describes the fundamental building blocks of the model according to
the overview, design concepts, and details (ODD) protocol. Sections 4–6 validate this
model by contrasting the model results with the insights based on actual cities, followed by
simulation experiments assuming some intervention policy scenarios of urban expansion.
A discussion of these results is provided. Section 7 concludes by summarizing key model
outputs and outlining an agenda for the future development of the model.

2. Related Studies and Position of This Study

2.1. Agent-Based Urban Land Use/Transport Interaction Model

Urbanization is the land-use change of building up and paving over undeveloped
areas along a city boundary. Such land-use changes occur due to the land use’s complex
social, economic, political, and physical driving forces and their interactions [10]. Above
all, the fundamental principle that land use impacts transport and vice versa has been
acknowledged by many researchers and supported by empirical findings [11]. Given
this background, over the last half-century, a considerable number of cross-disciplinary
studies have sought to formalize the relationship between land use and transport. In
addition, in urban planning, there has been a strong tendency to respect and inherit the
precedent experiences, because it is impossible to easily experiment in actual cities. As
a method to overcome such challenges and to explore urban growth strategies, many
efforts have been devoted to the development of transportation and land-use change
models and simulations [4,10,12]. These efforts have culminated in the development of
operational urban land-use/transport interaction (LUTI) models for decision support
systems considering the impacts of land use on transport and vice versa by households
and firms.

In the middle of the last century, top-down urban planning processes gradually gained
ground, propelled by the arguments of Jacobs (1961) [13], Alexander (1964) [14], and others.
Recently, many have supported the concept of expressing artificial systems including cities
as a self-organization, generated by the collective interactions and adaptive behaviors of
multiple autonomous agents, such as natural systems [7,15]. Based on this concept of
complexity science, an agent-based model (ABM) is an unique modeling approach that
particularly emphasizes that each autonomous agent learns, modifies, and improves their
own activities through interactions with the environment [16–18]. Then, ABM can be
used to simulate the bottom-up emergence of previously unexpected macroscopic social
phenomena from individual-level behaviors.

Prior to the establishment of this concept, an ABM methodology was applied to
land-use models as a spatially explicit cellular automaton (CA) form. CA is a discrete,
iterative, and dynamic spatial system, where each cell, which uniformly fills in the model space, and changes its state according to a set of transition rules referring its previous state and the state of neighboring cells [19]. Classical CA-based models, represented by Schelling’s segregation model (1971) [20], in which the state of each individual cell indicates a specific land use, and were used as abstract models of urban morphology that describe the emergence of simple patterns. Subsequently, the development of a series of urban ABMs has contributed to the expression of complex macro-level urban land-use patterns including clustering and sprawl as self-organization by the urban agents, e.g., households and firms. These urban ABMs have been applied to study a variety of urban issues, including forecasting land-use changes and urban growth including sprawl [12,21–23], extension of urban sprawl and its environmental impacts [24,25], assessment of residential policy to realize a compact city [26], price changes in the housing market due to household relocations [27–29], slum formations [30], gentrification leading to the displacement of low-income residents [31], and simulation of residential land-use patterns in both population growth and shrinkage processes [32].

2.2. Agent-Based Human Interaction Model

In 1961, Jacobs emphasized the attractiveness and key function of cities as a bustling and lively place for human interaction [13]. Oldenburg (1989) also argued that “third places”, such as streets, plazas, and public facilities, where people can easily gather and interact, are necessary to revitalize cities [33]. Recently, it was argued that, in a city with population aggregation, diversity of residents, and social tolerance, the creativity that is enhanced by increased human interaction drives economic growth through improvements in productivity and innovation [34]. When cities become gathering locations for creative artists, thinkers, and planners, the benefits of such interactions exceed economics and bring people richer cultural and recreational experiences [35]. Against this background, many cities are increasingly embracing policies such as mixed land use, walkability, and population aggregation for smart growth [36].

Due to these aspects, based on human interactions, the socioeconomic behavior of the city as a whole is greater than the sum of its components: the activities of individuals and organizations. ABM is also adept at exploring the behaviors of an urban system due to its advantages in simulating complex social phenomena, as mentioned in the previous subsection. Therefore, a growing amount of the ABM literature has focused on the relationship between urban morphology and the benefits of human interactions. Spencer (2012) examined the effects of location on the evolution of social networks through human interaction, using a social dynamics agent-based model based on evolutionary economic geography. The model then demonstrated how large and diverse places can lead to individuals’ productive activities flourishing [37]. Liu and Silva (2013) spatially and explicitly modeled the market dynamics of firm and household locations to evaluate industrial policies for sustainable development. The simulation results were examined from the perspective of spatial density distribution and the clustering pattern of firms and workers, representing the intensity of human interactions in urban space [38]. The Creative City Model by Malik et al. (2015), designed with agents with multiple attributes, can capture the nuances of dynamic urban environments and explore the formation of “creative clusters”, defined by De Propris and Hypponen (2008) [39], in greater detail. The model suggested that knowledge spillovers through human interactions, the dynamic socioeconomic processes underlying urban economic growth, could emerge from the bottom-up through the desire for social equity [40].

2.3. Position of This Study

By integrating the conceptual frameworks of the above two ABM studies, we attempted to construct an urban dynamics ABM that can simulate bottom-up sustainable urbanization scenarios. Therefore, the contribution of this study is that our urban dynamics ABM spatially and explicitly represents all daily travel and associated face-to-face human
interactions, and the relocation of individual residents in the simulation space. Then, it allows for a discussion on the formation and dissolution of residential diffusion on urban edges, which is a macroscale change in urban areas based on the microscale collective action of these individual residents. In other words, our model attempts to simultaneously incorporate the social complexity of human behavior and the complexity of urban morphology in a stylized manner, using integration and input–output linkages of the submodel components of daily travel, residential relocation, and human interaction.

3. Simulation Model

To simulate real phenomena, a model should be tailored to the research question and abstracted as much as possible, rather than incorporating too many aspects of the real world [41], since abstraction enables us to capture the essential factors that generate complex phenomena in their reproduction process [16].

Based on this concept, we focused on the daily travel and residential relocation of residents, as well as the resulting change in urban land-use patterns. However, we did not consider the irregular fluctuations in land rent and the influence of direct urban policies on the real estate market. To enable application to various regions, we also did not consider geographical conditions such as topography and climate or the heterogeneity of households in income, generation, preference for specific behaviors, etc.

The model was designed and run in NetLogo [42] which is free software. Its source code is available at https://www.comses.net/codebases/20a1e7dc-0ab9-4e41-bb53-14a1da86e088/releases/1.0.0/, accessed on 10 October 2021. The overview of the experimental model is described below according to the overview, design concepts, and details protocol [18].

3.1. Purpose

The purpose of this abstract urban dynamics ABM is to simulate the effects of the relationship between the introduction of a hub facility open to residents with pedestrian-friendly interaction promotion and two transport policies on residential diffusion on urban edges through the autonomous actions of individual residents. The simulation also aims to provide insights into the micro–macro linkage in an urban system under different scenarios.

3.2. Entities and Scales

The entities represent a highly abstracted planar urban schematic and the household agents. Both are expressed spatially and explicitly. The planar size of the model space corresponds to 20 km² in the real world. Figure 1 shows the urban schematic. This is the abstraction of a part of a typical regional city that has a central business district (CBD) and suburban towns connected by a railway. The city was planned according to the zoning, with a separation between residences and job locations. Therefore, despite the polycentric and rational land use, a clear hierarchy exists between the districts. In modern Japan, many towns with this schematic were developed in the suburbs of large cities, along the railway routes centering on such cities. This was partly due to the lack of suitable land for urbanization due to the mountainous landscape [43,44].

With such a simple urban form and well-developed public transportation, the potential for and threat of urban diffusion may seem rather modest. However, in reality, the urban area in Japan has consistently been expanding [6,44], while the share of railways in passenger transport has declined from nearly 80% in 1960 to less than 30% today (the share of private automobiles has increased from less than 5% to over 60%). As a result, the business conditions of railway operations, especially in rural areas, have deteriorated; in the last 20 years, more than 1100 kilometers of railway lines have been discontinued on 45 routes [45]. This situation shows that cities, although clearly planned, as assumed above, can easily diffuse.
In the urban schematic, the two primary domains are the residence district and the CBD. The residence district is the aggregation of residences, which are the starting point and final destination of each household agent’s daily travel, which corresponds to commuting. The CBD is the aggregation of job locations, which are also the halfway point of commuting travel. The distance between the centers of each district is 4 km at the same latitude. Two railway stations, the suburban station and the central station, are located at the centers, and connected by a railway. Additionally, a highway is located 500 m north of the railway. To simplify the simulation, there are no traffic flow controls, such as traffic lights, roundabouts, or one-way streets, etc., and uniform and high-density roads and sidewalks are located throughout this entire urban schematic.

Based on the statistical data of railway transport, the suburban station covers 10,000 real-world households. However, considering the processing capacity of the computer, 1000 household agents were set in the residence district. That is, one household agent corresponds to 10 households in the real world. In the residence district, as in the initial location, the same number of residences as household agents is randomly located based on normal distribution centering on the suburban station. Similarly, in the CBD, the same number of job locations are also located randomly based on normal distribution centering on the central station. The suburban station is also equipped with bicycle parking that can hold enough bicycles. Each job location is equipped with car and bicycle parking. Additionally, one hub facility that is open to people, and plays a role in attracting diverse activities to city center, is located in the CBD. This is assumed to provide complex facilities such as the library-centered complexes that have been introduced in recent years, e.g., Idea Stores in London, U.K. [46]; and the new Seattle public library in Washington, USA [47]. However, the operator may be public, private, or a combination of the two. The hub is also equipped with car and bicycle parking. Within a 500 m radius centering on the hub, which was set as an influential area, the interaction promotion policy was considered (see below).

### 3.3. State Variables of Household Agents

The state variables of the household agents are as follows:

- Position of the residence;
- Position of the job location;
- Type of current linked trip;
Value list of linked trips.

To focus on the change in land-use patterns through the residential relocation of household agents, we adopted the classical exogenous job location assumption. In other words, the position of a job location corresponding to a certain household agent is always fixed, and one-worker households are included. A linked trip indicates the series of travel of each household agent from the starting point to the destination. An unlinked trip indicates each travel mode that is a component of a linked trip.

### 3.4. Process Overview and Scheduling

Figure 2 shows the scheduling of household agents. Each household agent commutes daily based on the value list of linked trips, and after the learning period of repeating this daily travel 30 times, fixes travel modes in one way. After, a portion of the household agents relocate their residences to the candidate residences based on the total living cost. The change in land-use pattern is produced through these residential relocations. In this study, after the loop process of residential relocation was repeated 20 times, the simulation stopped processing. This model assumes that 30 repetitions of daily travel (a single loop process of residential relocation) represent 2 years in the real world. Therefore, 20 loop processes of the residential relocation correspond to a simulation of 40 years in the real world, and, in the 40 years, a household agent relocates twice on average. Households actually tend to relocate with changes in a family structure, such as birth, separation, etc. [48,49] Based on the above, this scheduling can be considered valid.

![Figure 2. Scheduling of household agents.](image)

### 3.5. Sub-Model of Daily Travel

The daily travel of household agents is spatially explicitly processed on the urban schematic. This reflects the empirical findings of traffic studies regarding the impact of urban structural variables, e.g., density, accessibility, and travel distance, on travel behaviors [50,51].

Each household agent repeats daily travel according to the selected linked trip. In this study, six types of linked trips were assumed, as shown in Figure 3. The representative travel mode is one of the following: on foot, by bicycle, by railway, or by private automobile. The initial representative travel mode of all household agents is railway (linked trip no. 2 or 3), according to the original planning philosophy.
Prior to departure, each household agent forecasts total travel time to each job location according to the selected linked trip. It was empirically shown that a commuter shifts the arrival time to avoid traffic congestion [52]. Reflecting these findings, each household agent leaves the residence while adjusting the departure time to shift the arrival time from the average starting time of work based on a normal distribution. After household agents arrive at each job location, they leave for the hub. After arriving and staying there, finally, they leave for their respective residence (The co-location of tenants offering different services in the same facility was shown to be mutually beneficial in terms of attracting people with different lifestyles [53]. Therefore, the hub is assumed to equally attract household agents, regardless of its location, by providing multiple services, such as the above-mentioned complex facilities. Thirty daily travel times in the model are assumed to represent two years in the real world, rather than 30 consecutive days. Therefore, the household agent does not visit the hub for 30 consecutive days.). The time flow in the model is discrete, and each time step corresponds to one minute in the real world.

When the household agents return to the residence, the total travel cost $C$ is calculated according to:

$$C = w_tC_t + w_cC_c + w_fC_f - w_P P$$

where $C_t$, $C_c$, $C_f$, and $P$ indicate time cost, charge cost, fatigue cost, and interaction value, respectively, and $w_t$, $w_c$, $w_f$, and $w_P$ indicate each preference bias, respectively. In this study, the preference biases of all agents were assumed to be equal. According to this cost, the household agent updates the value $V_i$ of the selected $i$th linked trip according to:

$$V_i \leftarrow \alpha (-C) + (1 - \alpha) V_i$$

The following this, the household agent travels according to the linked trip selected by the $\varepsilon$-greedy method based on this value. With the $\varepsilon$-greedy method, the action is randomly chosen from all options with the probability of $\varepsilon$, and the action with the highest value is selected, with a probability of $1 - \varepsilon$. The previous total travel time is applied to forecast the total travel time. Based on this, each household agent adjusts the departure time to shift the arrival time. $\varepsilon$ is gradually attenuated according to the equation below and approaches zero as the trials are repeated.

$$\varepsilon \leftarrow \gamma \varepsilon$$

As such, each household agent fixes the travel mode in one way throughout the learning period, repeating their daily travel 30 times. This setting is based on the findings that individuals choose travel modes and routes through habits and bounded rationality, rather than rationally complete based on the complete information [54].
3.5.1. Time Cost

Many traffic simulation models assume that travel time is the only or most important criterion when choosing travel mode and route [55]. In this study, to consider travel time along with other factors when making decisions regarding daily travel, travel time is converted to monetary cost according to:

\[ C_t = \eta_t t \]

\[ t = t_w + t_b + t_t + t_c \]

where \( t \) indicates the total travel time of each resident; \( \eta_t \) is the conversion coefficient time to monetary cost; and \( t_w, t_b, t_t, \) and \( t_c \) indicate the travel time of each household agent on foot, by bicycle, by railway, and by private automobile, respectively. Time cost coefficient \( \eta_t \) was set by dividing the average annual income by the average annual working time based on statistical data [52, 56].

3.5.2. Charge Cost

The charge cost \( C_c \) associated with daily travel is calculated according to:

\[ C_c = m_{bp} + m_{cp} + m_t + m_g t_c \]

where \( m_{bp}, m_{cp}, \) and \( m_t \) indicate bicycle parking fare, automobile parking fare, and railway fare, respectively; \( m_g t_c \) indicates gas price; and total gas price is proportional to travel time by private automobile \( t_c \). These were determined as reasonable values for the model conditions based on statistical data [57].

3.5.3. Fatigue Cost

Previous studies have reported that the duration of commuting time of residents may also cause health problems [58, 59]. Based on these findings, the fatigue cost \( C_f \) associated with daily travel is calculated according to:

\[ C_f = (f_w t_w + f_b t_b + f_t t_t + f_c t_c) + f_{cong} \]

where \( f_w, f_b, f_t, \) and \( f_c \) indicate the conversion coefficient travel time on foot, by bicycle, railway, and private automobile to monetary cost, respectively; \( f_{cong} \) indicates the additional fatigue cost due to traffic congestion. Each fatigue cost coefficient was set by multiplying the caloric consumption of each travel mode per unit time and the average price of calorie acquisition, based on statistical data [56].

Traffic congestion in the morning and evening rush hours has become a serious issue in many urban areas around the globe. In this study, because of the simplified representation of the road traffic network, we assumed that traffic congestion occurs as a simple local interaction between household agents. In other words, on each ordinary road and highway, traffic congestion occurs when a certain household agent and other household agents travel by private automobile at the same time. The velocity of the private automobile (standard velocity \( V_N \) on ordinary road or \( V_H \) on highway) during traffic congestion \( V_{CN} \) (on an ordinary road) or \( V_{CH} \) (on a highway) is calculated according to:

\[ V_{CN} = (1 - \eta_v D_{CN}) V_N \quad \text{or} \quad V_{CH} = (1 - \eta_v D_{CH}) V_H \]

where \( D_{CN} \) and \( D_{CH} \) indicate the number of household agents traveling by private automobile within a \( r_{cong} \)-meter radius centering on an ordinary road or highway, respectively; \( \eta_v \) indicates the conversion coefficient. These were set based on the previous studies on traffic congestion and transport-related statistical data [57]. This deceleration by traffic congestion results in increases in the time and charge costs.

Additionally, not only travel time duration, but also its reliability, are important variables in travel-related decisions [60]. Traffic congestion considerably reduces the
reliability of travel time and causes wide variances. Based on these findings, during caught-in-traffic congestion, congestion fatigue cost $F_{\text{cong}}$ is added every minute according to [61]:

$$F_{\text{cong}} = \eta_{\text{cong}} D_{CN} + \eta_{\text{cong}} D_{CH}$$

3.5.4. Interaction Value

Within a 500 m radius around the hub, which is regarded as a sphere of influence for its diverse activities that are unique in the business district, the interaction promotion policy was considered. This distance was set based on the concept of “Ped Shed”, which is defined as the town area encompassed by the walking distance from a center or other location [62]. We assumed that when household agents who travel within this range on foot or bicycle interact face-to-face (i.e., agglomerate geographically on the model plane), they acquire use or efficiency benefits as well as the creatively, culturally, and recreationally rich experiences created by such interactions, denoted “interaction value”.

It has been suggested that the diversity of land-uses and the resulting higher density of human interactions within cities have positive impacts (innovation, entrepreneurship, their economic productivities, etc.) on urban environments [40,63]. We particularly emphasized the positive feedback that a higher number of people staying in a certain place attracts more people and reinforces the intensity of activity in that place [64]. Based on these findings, interaction value $P$ is calculated according to:

$$P = \eta_{ir} D_{ir}$$

where $D_{ir}$ indicates the number of other household agents traveling on foot or by bicycle within an $r_{ir}$-meter radius centering on the relevant household agent, and $\eta_{ir}$ is the interaction promotion coefficient. The total travel cost is reduced by the amount, multiplied by the interaction value $P$ and preference bias $w_P$.

The interaction promotion coefficient can be regarded as the degree of concerted effort to create further interactions within the relevant range according to the agglomeration of pedestrians. Empirical studies have suggested that the features required for urban environments that are rich in valuable human interactions include the following, which are interrelated [35,40,63,65–68]:

- Affordable mobility/walkability;
- Mixed land/building use;
- Social diversity;
- Societal tolerance.

Based on the above, this interaction promotion coefficient is enhanced by the concerted efforts of the whole area to provide walkability, mixture, diversity, and tolerance, e.g., arranging comfortable sidewalks and cycleways, arranging various attractive stores/spots, and organizing open events. An increase in this coefficient enhances the benefits of travelling on foot or by bicycle, which generates interactions, reducing the total travel cost. Therefore, this coefficient can be regarded as a coefficient of gain. Hereafter, the policy that corresponds to improvements in this interaction promotion coefficient is referred to as interaction promotion.

3.6. Submodel of Residential Relocation

The residential relocation of household agents is also spatially and explicitly processed in the urban schematic. After all household agents fix their travel mode in one way after the learning period, one-tenth of all household agents are randomly chosen to relocate their residence. Ten residence candidates are randomly presented to each relevant household agent within a predetermined nearby range. This setting is based on the findings showing that residences and households cannot be completely isolated for reasons such as accessibility to the existing infrastructure and desire for social connection [69,70].
In residential (re)location, households attempt to fulfill as many of their location preferences as possible. At the same time, they face constraints [71]. Among them, the following two factors are particularly emphasized:

- Travel cost (or time) and [11, 61, 72, 73]
- Land rent. [11, 61, 74]

Based on these findings, the total living cost $C_l$ of each candidate is calculated according to:

$$C_l = C + R$$

where $C$ is the estimated total travel cost and $R$ is the land rent. Each household agent relocates to the candidate residence, of which the total living cost $C_l$ is the lowest of the 10 candidates.

### 3.6.1. Estimated Total Travel Cost

Households prioritize higher accessibility to shopping and other recreational activities as well as employment [73]. Additionally, related studies empirically demonstrated that daily travel before relocation becomes habitual and impacts the destination and the daily travel there [54]. Based on these findings, the estimated total travel cost $C$ is calculated by virtual daily travel from a candidate residence based on the travel mode fixed by the relevant household agent through learning.

### 3.6.2. Land Rent

Previous studies empirically demonstrated a positive correlation between the agglomeration of development and rent. The reason for this relation is explained by the aggregation, which leads to improvements in efficiency and productivity [65, 75–77]. Based on these findings, the land rent $R$ at each residence candidate is calculated according to:

$$R = \eta_R \left( \frac{A'}{A} \right) + \eta_J \left( \frac{A_j}{A} \right)$$

where $l_r'$ and $l_j'$ indicate the number of residences and job locations within an $r_R$-meter radius centering on the relevant residence candidate, respectively; $A$ indicates the area of the relevant range; $A'$ and $A_j'$ indicate the consumption areas by the unit of residence and job location, respectively; $\eta_R$ and $\eta_J$ indicate the conversion coefficients for residence and job location, respectively. Therefore, the land rent at each residence candidate increases, corresponding to the agglomeration of neighboring residences and job locations. This means that the local interactions between households and an environment also impact the change in land-use pattern through the change in land rent.

### 3.7. Initialization and Input Data

Table 1 shows the setting values of the parameters of the urban schematic (left) and household agent (right). These values must be carefully set, especially the monetary conversion coefficients for, for example, the value of time, since the evaluation of profits automatically changes depending on how these coefficients are set. Therefore, we carefully set these values mainly based on empirical materials, including the socio-demographic and other statistical data published by public authorities [52, 56, 57, 78, 79], and previous studies, while assuming a regional city in Japan. However, different values may be set for applications to other cities. Then, the validity of these values and the whole model were verified by the simulation results, based on the concept of Patterns-Oriented Modeling [18] (refer to the next section).
Table 1. Parameters of the urban schematic and household agents.

| Parameters of Urban Schematic | Setting Values |
|-------------------------------|----------------|
| standard deviation of residences $L_r$ | 800 (m) |
| standard deviation of job locations $L_j$ | 800 (m) |
| radius for calculating land rent $r_R$ | 100 (m) |
| land rent coefficient of residence $\eta^r_r$ | 150 (yen) |
| land rent coefficient of job location $\eta^r_j$ | 1500 (yen) |
| area size of residence $A^r$ | 140 ($m^2$) |
| area size of job location $A^j$ | 140 ($m^2$) |
| bicycle parking fare $m_{bp}$ | 150 (yen) |
| automobile parking fare $m_{cp}$ | 800 (yen) |
| railway fare (one way) $m_{tr}$ | 160 (yen) |
| gas price $m_g$ | 0.015 (yen/min) |

| Parameters of Household Agent | Setting Values |
|-------------------------------|----------------|
| walk velocity $V_w$ | 4 (km/h) |
| bicycle velocity $V_b$ | 12 (km/h) |
| railway velocity $V_t$ | 55 (km/h) |
| automobile velocity $V_H$ | 24 (km/h) |
| automobile velocity in highway $V_{HI}$ | 60 (km/h) |
| time cost coefficient $\eta_{t}$ | 50 (yen/min) |
| fatigue cost coefficient for walk $f_w$ | 180 (yen/min) |
| fatigue cost coefficient for bicycle $f_b$ | 420 (yen/min) |
| fatigue cost coefficient for railway $f_t$ | 60 (yen/min) |
| fatigue cost coefficient for automobile $f_c$ | 60 (yen/min) |
| radius for calculating congestion $r_{cong}$ | 150 (m) |
| congestion velocity coefficient $\eta_{v}$ | 0.1 |
| congestion cost coefficient $\eta_{cong}$ | 100 (yen/min) |
| radius for calculating interaction value $r_{ir}$ | 100 (m) |
| greedy rate $\epsilon$ | 0.5 |
| learning rate $\alpha$ | 0.5 |
| attenuate rate $\gamma$ | 0.94 |

3.8. Indicators Used to Estimate Experimental Results

By observing the result of each experimental scenario according to the indicators shown below, changes in the urban form were evaluated.

- Percentage of each representative travel mode;
- Total CO$_2$ emission (expressed as percentage relative to scenario A) (Calculated by multiplying CO$_2$ emission per travel distance of one passenger in each travel mode and the total travel distances of all household agents by private automobile and railway);
- Average travel time;
- Standard deviation of the distribution of residences (x and y coordinates; both initial values are 8);
- Distribution map of residences (color-coded by representative travel modes).

Each scenario was run eight times under the same experimental conditions. The percentage of representative travel mode, total CO$_2$ emissions, the standard deviation of the distribution of residences, and the average travel time are presented as the averages of the results of the trials. The presented distribution map of residences is one of the trial results.
4. Experiment 1: Open Hub for Residents and Human Interaction

4.1. Conditions of Experiment 1

The top left of Figure 4 shows the initial distributions of residences and job locations in all the experiments in this study. The residence district and the CBD are completely separately located, and each forms a cluster. Setting the above as an initial state, the experiments were conducted where the hub was introduced and the interaction promotion around it was implemented.

The experiments were conducted under the conditions of the following five types of hub location as shown in Figure 5:

- **A**: not introduced (and no interaction promotion);
- **B**: suburb along highway, 0.5 km north and 2 km east from the central station;
- **C**: suburb away from highway, 2 km south and 0.5 km east from central the station;
- **D**: urban central area, same place as the central station;
- **E**: urban central area, 0.5 km south and 0.5 km east from the central station.

Four interaction promotion coefficients were used: 0, 10, 20, and 30. Hereafter, each of these experiments is expressed by combining the symbols from A to E, indicating the location of the hub and the interaction promotion coefficient, for example, scenario A and E20.

![Figure 4. Residences' initial distribution (top left) and final distribution of experiment 1.](image-url)
4.2. Results of Experiment 1

Table 2 shows the quantitative result of scenario A, B0 to 30, C0 to 30, D0 to 30, and E0 to 30. Figure 4 shows the initial distributions of residences and job locations (top left) and the final distributions of each scenario (others).

Table 2. Result of experiment 1.

| Scenario | Representative Travel Modes | CO₂ Emission | Travel Time | Standard Deviation |
|----------|-----------------------------|--------------|-------------|--------------------|
|          | Walk | Bike | Rail | Car |                  |              | x-cor | y-cor |
| A        | 1.3% | 2.4% | 7.3% | 89.0% | 100%              | 9.3 min     | 22.9  | 9.8   |
| B0       | 1.2% | 1.4% | 3.9% | 93.5% | 159.7%            | 29.8 min    | 26.2  | 11.1  |
| B10      | 1.4% | 1.4% | 4.0% | 93.3% | 161.5%            | 30.0 min    | 25.9  | 10.9  |
| B20      | 1.2% | 1.5% | 4.1% | 93.3% | 175.3%            | 30.7 min    | 22.1  | 10.2  |
| B30      | 2.6% | 1.3% | 47.7% | 48.4% | 102.3%            | 55.1 min    | 16.1  | 8.8   |
| C0       | 1.1% | 1.7% | 3.9% | 93.3% | 158.7%            | 36.3 min    | 25.6  | 13.1  |
| C10      | 0.9% | 1.4% | 4.2% | 93.5% | 163.8%            | 36.7 min    | 24.7  | 12.8  |
| C20      | 1.2% | 1.4% | 5.1% | 92.3% | 177.9%            | 39.8 min    | 22.0  | 11.5  |
| C30      | 2.7% | 1.1% | 48.9% | 47.3% | 98.1%             | 60.6 min    | 17.2  | 9.9   |
| D0       | 1.2% | 1.6% | 9.8% | 87.5% | 120.5%            | 19.0 min    | 21.0  | 10.3  |
| D10      | 1.1% | 1.5% | 10.3% | 87.1% | 119.5%            | 18.8 min    | 21.2  | 10.6  |
| D20      | 1.2% | 1.6% | 10.4% | 86.8% | 119.5%            | 19.0 min    | 20.8  | 10.5  |
| D30      | 1.3% | 1.7% | 12.2% | 84.8% | 117.8%            | 19.2 min    | 20.7  | 10.2  |
| E0       | 1.0% | 1.6% | 5.6% | 91.8% | 129.4%            | 23.0 min    | 23.4  | 11.2  |
| E10      | 1.1% | 1.5% | 9.3% | 88.1% | 133.7%            | 24.4 min    | 21.4  | 10.4  |
| E20      | 1.7% | 1.5% | 47.6% | 49.2% | 84.9%             | 33.2 min    | 15.4  | 8.8   |
| E30      | 2.3% | 1.5% | 66.8% | 29.4% | 58.3%             | 40.7 min    | 12.4  | 8.0   |

The result of scenario A shows that private automobile users reached about 90%, with most residences diffused on the periphery of the CBD.

The results of scenario B0, C0, D0, and E0, changing the location of the hub while not promoting interactions, show that private automobile users reached about 90%, most with residences that diffused, as in scenario A. In both scenario B0 and C0, the hub was in the suburb; however, in the former, the private automobile users on highways were almost equal to the rest of the private automobile users, and in the latter, the ones using the highway were about half of the total. Along with this, the following features of residential diffusion were observed: There is no difference in the standard deviation in the east–west direction, but scenario C0 had a larger standard deviation in the north–south direction than B0, with many residences distributed around the hub. Scenario B0 had many residences distributed along highways.

The results of scenarios from B0 to 30 show that there was almost no observable change observed in scenarios from B0 to 20. However, when the scenario reached B30,
by further increasing the interaction promotion, private automobile users decreased by half and railway users were considerably increased, reaching values close to 50%. Along with this, residential diffusion on the periphery of the CBD improved, and the cluster of residences of railway users around the suburban station was maintained. The total CO₂ emissions were also considerably reduced.

The results of scenario C0 to 30 show that private automobile users decreased and railway users increased when the scenario reached C30, similar to the B series of experiments. The same changes were observed in the distribution of residences and total CO₂ emissions.

The results of scenario D0 to 30 show that a decrease in private automobile users and subsequent improvements in residential diffusion were not observed when the scenario reached D30, unlike the B and C series of experiments.

The results of scenario E0 to 30 show that private automobile users decreased considerably when the interaction promotion coefficient reached 20 (scenario E20), unlike the B and C series. Furthermore, when the scenario reached E30, private automobile users further decreased and railway users reached about 65%. Along with this, in scenario E30, the cluster of railway user residences around the suburban station became more remarkable, and total CO₂ emissions reduced to less than 60% of the value for scenario A.

4.3. Validation of the Simulation Model

Prior to discussing the effects of intervention policies, the validity of the simulation model was verified. Due to the properties of the emerging complex self-organizing systems, ABMs should be assessed based on validity rather than one-to-one correspondence or correlation measures. This requires the model to be validated in terms of whether the ABM can capture the basic features of the system in the real world; for example, the structural similarity between simulated and actual phenomena [32]. Patters-Oriented Modeling (POM) is an effective validation procedure. In the POM procedure, after identifying the observed patterns in the real world that characterize the system to be modeled, the ABM is evaluated according to whether the observed patterns are reproduced [18]. We validated the simulation model according to the POM concept.

Figure 6 shows the history of urban areas (densely inhabited district (DID) areas) in Japan over 40 years, starting in 1970 (yellow) and the history of residential areas in scenario A (blue). These are similar, so this scenario can be regarded as an accurate reproduction of the urban areas of many cities in Japan, which have consistently been expanding since the high economic growth period [80]. In this scenario, the residence distribution significantly changes from separation between residences and job locations (“initial state” in the top row in Figure 4) to residential diffusion, where most of the residences are on the periphery of a CBD (“A” in the second row). This can also be regarded as the reproduction of the growth process of concentric low-density suburban residences based on the monocentric urban model, which was proposed by Alonso (1964) [81] and subsequently supported by many related studies. Figure 7 shows the history of the percentage of private automobile users in scenario A over the 40 year span: It increases, drawing a sigmoid growth curve, so that this scenario can also be regarded as reproducing the trend where the main commuting travel mode switches from railway to private automobiles, and that road traffic has reached saturation in Japanese regional cities since the high-economic-growth period [78].
The purpose of the model is not to precisely reproduce the real world but to analyze the mechanism of highly abstracted urban dynamics using a small number of elements and simple rules. Nevertheless, the simulation model reproduced the multiple social phenomena shown above (the observed patterns in the real world), which were not directly incorporated into the model. Therefore, these reproductions demonstrate that the simulation model, the setting values, and the experimental results of this study are valid and explain the real world to the required level.

4.4. Discussion of Experiment 1

In any case, by introducing a hub without promoting interactions around it, regardless of its location, private automobile users increase, and their residences diffuse, similar to the case when a hub is not introduced. As a result, there are few pedestrians in the central urban area, and only private automobiles pass through. Particularly, in the cases where a hub is introduced in the suburbs, the residential diffusion considerably increases. This may be because private automobile use is more convenient, since the hub is far from the central station. However, in the real world, the introduction of a facility attracting many people (e.g., a large commercial building), either of alone in a suburb, often worsens residential diffusion. These experimental scenarios clarify the mechanism of this phenomenon.

In any cases, except when introducing a hub in the same place as the central station, by increasing the interaction promotion so that it reaches a certain size, private automobile users decrease, total CO₂ emissions reduce, and residential diffusion is drastically improved, as if a phase transition had occurred. These experimental scenarios suggest that the combination of the proper location of a hub facility that is open to people and promotes interaction is generally effective in maintaining rational land use. These findings also suggest that such a policy is not effective unless implemented at a certain large scale.

Among these cases, for those introducing a hub near the central station, phase transition occurs even though the interaction promotion was implemented at a smaller scale. This may be because interaction promotion, which creates incentive to stroll downtown, was more effective in increasing railway users, since the hub was within walking distance of the central station. However, in the cases introducing a hub in the same place as the central station, this phase transition does not occur. This also may be because the interaction promotion was not effective, since walking was not necessary between the hub and the central station. In the real world, the development of a large-scale commercial building integrated with the station and equipped with parking often does not contribute to improving the urban environment (e.g., shifting the travel mode or vitalizing the surrounding area). These experimental scenarios clarified the mechanism of this phenomenon and suggest the possibility that a slight difference in the location of such a facility may produce a significant difference in the future urban environment. These findings also suggest that a concerted area-wide effort to induce interactions between urban residents may be effective in improving the urban environment.

The abovementioned notable complex facilities based on a library, which were assumed to be a hub in this study, tend to focus on their content and disregard their location. Although such facilities are still being introduced in various places, they are often built in front of a station or in an available lot away from the central area. However, these experi-
mental scenarios also suggest that their location and accessibility should be thoroughly considered in view of their impact on the future urban form.

The application of interaction promotion can be expensive and a controversial budget item for a local government. Therefore, we suggest an operation system such as the Town Centre Management in the United Kingdom or the Business Improvement District in the United States. In these systems, private sector entities such as local landowners, business firms, etc., play public roles by revitalizing public spaces through profit-making businesses such as sales promotion and events, in addition to nonprofit endeavors such as cleaning and beautification activities, public security services, etc. [82] Both residents and local businesses can enjoy the benefits produced by street activity. With this in mind, this suggestion would not be unrealistic.

5. Experiment 2: Promotion of Bicycle Use

5.1. Conditions of Experiment 2

The promotion of bicycle use is one of the policies used to prevent the deterioration of an urban environment by excessive automobile traffic. The Netherlands is one of the countries in which bicycles are actively used. There, each local government supports bicycle use by providing bicycle lanes, installing traffic signs for bicycles, requiring stores and public facilities to be equipped with bicycle parking, and organizing a bicycle-sharing system. In recent years, bicycles have widely been used in The Netherlands to travel between cities [83]. As such, the momentum for promoting bicycle use has increased in many cities suffering from excessive automobile traffic: many local governments have attempted solutions such as bicycle-sharing systems, bicycle-carrying trains, and a subsidy to purchase power-assisted bicycles.

In this scenario, we assumed that the bicycle-related changes to travel after the above-mentioned promotion of bicycle use are as follows:

- The velocity of traveling by bicycle increases by 120%;
- The fatigue cost of traveling by bicycle reduces by 50%;
- Bicycle and railway in combination users (linked trip no. 3) could travel by bicycle after disembarking from the train.

The initial conditions were the same as in experiment 1. To consider the difference in the distance between the central station and the hub, the experiments were conducted under the conditions of the four scenarios, A, C, D, and E, for the location of the hub and the four different interaction promotion coefficients. Below, each of these experiments is expressed by combining the symbols A–E, indicating the location of the hub, the initial letter b for the word bicycle, and the interaction promotion coefficient, for example, scenario Ab and Cb30.

5.2. Results of Experiment 2

Table 3 shows the quantitative results of scenario Ab, Cb0 to 30, Db0 to 30, and Eb0 to 30. Figure 8 shows the final distributions of the residences of each scenario.

The results of scenario Ab, compared with scenario A, show that private automobile users decrease by close to 20 points, whereas bicycle users and railway and bicycle combination users increase accordingly. Similarly, total CO$_2$ emissions reduce by about 15%.

The results of scenarios Cb0, Db0, and Eb0, which do not promote interactions, show that private automobile users do not reach 60%. When compared with scenarios C0, D0, and E0, residential diffusion on the periphery of the CBD improves, and the clusters of railway user residences are maintained around the suburban station.

The results of from Cb0 to 30 show that with increases in interaction promotion, private automobile users gradually decrease. For scenario Cb30, private automobile users decrease to less than 40%, and total CO$_2$ emissions reduce to about 70%. These are, compared with scenario C30, about 10- and 25-point reductions, respectively. Along with this, the cluster of railway users residences around the suburban station become more remarkable.
Table 3. Result of experiment 2.

| Scenario | Representative Travel Modes | CO₂ Emission | Travel Time | Standard Deviation |
|----------|-----------------------------|--------------|-------------|--------------------|
|          | Walk | Bike | Rail | Car |                  |              |              |                    |
| Ab       | 1.3% | 4.7% | 22.6% | 71.5% | 85.3% | 8.1 min | 21.5 | 9.1 |
| Cb0      | 1.3% | 3.9% | 35.7% | 59.2% | 104.1% | 30.3 min | 22.8 | 11.3 |
| Cb10     | 1.0% | 3.9% | 43.8% | 51.3% | 93.4% | 29.7 min | 21.4 | 10.8 |
| Cb20     | 1.4% | 4.6% | 49.9% | 44.1% | 82.0% | 29.7 min | 20.3 | 10.5 |
| Cb30     | 1.3% | 5.7% | 56.5% | 36.5% | 73.5% | 29.9 min | 17.3 | 9.9 |
| Db0      | 1.1% | 3.1% | 40.7% | 55.1% | 80.3% | 15.0 min | 18.3 | 9.2 |
| Db10     | 1.2% | 2.9% | 39.7% | 56.3% | 80.5% | 14.9 min | 18.6 | 9.2 |
| Db20     | 1.3% | 3.2% | 40.8% | 54.7% | 79.5% | 15.2 min | 18.4 | 9.0 |
| Db30     | 1.3% | 3.0% | 41.0% | 54.6% | 78.8% | 15.3 min | 18.5 | 9.0 |
| Eb0      | 1.2% | 3.2% | 42.9% | 52.8% | 79.1% | 18.2 min | 19.7 | 9.6 |
| Eb10     | 1.1% | 3.0% | 48.3% | 47.5% | 73.7% | 17.8 min | 18.6 | 9.1 |
| Eb20     | 1.5% | 3.1% | 55.8% | 39.6% | 65.8% | 18.0 min | 16.4 | 8.5 |
| Eb30     | 1.4% | 3.2% | 65.6% | 29.8% | 54.5% | 22.8 min | 13.9 | 8.2 |

The results of from Db0 to 30 show that despite increasing interaction promotion, a further decrease in private automobile users is not observed, nor is a further improvement in residential diffusion, as with the D series. A further reduction in total CO₂ emission is also not observed.

The results of Eb0 to 30 show that with increasing interaction promotion, private automobile users gradually decrease, similar to the Cb series. However, for scenario Eb30, neither private automobile users, residential diffusion, nor total CO₂ emissions differ from scenario E30.

5.3. Discussion of Experiment 2

By combining the promotion of bicycle use with introducing the hub and promoting interactions around it, private automobile users decrease compared with the cases when not combining policy, and bicycle users and combined railway and bicycle users increase accordingly. Total CO₂ emissions also reduce, and residential diffusion improve. Additionally, average travel time decreases.
In many cities around the globe, automobile-oriented traffic infrastructure and systems have already been developed through expansions in low-density suburban areas where residents use a private automobile. Therefore, in practice, the implementation of such promotions of bicycle use would be challenging. However, these experimental scenarios suggest that the synergistic effects of the promotion of bicycle use, the proper location of facilities for residents, and interaction promotion could positively impact urban environments.

In all scenarios, the growth in the positive impact on the urban environment with increasing interaction promotion was rather flat. This may be because interaction promotion is less beneficial for travel by bicycle than on foot due to its speed.

6. Experiment 3: Control of Private Automobile Use

6.1. Conditions of Experiment 3

Recently, to improve urban environments, the idea of controlling road development by reducing or rationalizing the increase in traffic demand was introduced. This idea is called traffic demand management (TDM) \[44,84\]. The “park-and-ride” (or bus-based park-and-ride) method, which is common in the United States and European cities, is representative of a TDM policy. It restricts the use of private automobiles to suburban railway stations or bus stops and encourages people to use the public transport network such as railways, buses, etc., to access urban central areas.

As such, we assumed that 10 parking lots were located within a 1.5 km radius centering on the central station, including most of the job locations, as shown in Figure 9. Within this radius, private automobile users must travel on foot from the nearest parking lot to their job locations. Namely, a “park-and-walk” policy was implemented. Additionally, to eliminate through traffic from this area, a highway was placed 1.5 km north of the railway, and private automobile users should only relocate to the residences outside this radius. The linked trip of private automobile users is replaced by linked trip number 4 or 5, shown in upper (when the hub is outside this radius) Figure 10 or linked trip number 4′ or 5′ on the bottom (when the hub is inside this radius).

![Figure 9. Schematic of parking lots.](image_url)

![Figure 10. Additional linked trip in experiment 3.](image_url)
The experiments were conducted under the four conditions, A, C, D, and E, for the location of the hub and the four interaction promotion coefficients, as described in the previous section. Hereafter, each of these experiments is expressed by combining the symbols from A to E indicating the location of the hub, the initial letter p for the word parking, and the interaction promotion coefficient, for example, scenario Ap and Dp20.

6.2. Results of Experiment 3

Table 4 shows the quantitative results of scenarios Ab, Cb0 to 30, Db0 to 30, and Eb0 to 30. Figure 11 shows the final distributions of the residences in each scenario.

The results of scenario Ap, compared with scenario A, show that private automobile users decrease by close to 40 points, while bicycle users and combination railway and bicycle users increase accordingly. Total CO₂ emissions decrease by about 30 points. Automobile users are eliminated from the CBD area. However, beyond parking lots, automobile users’ residences diffuse.

Table 4. Result of experiment 3.

| Scenario | Representative Travel Modes | CO₂ Emission | Travel Time | Standard Deviation |
|----------|-----------------------------|--------------|-------------|--------------------|
|          | Walk | Bike | Rail | Car |                  |               |                     |
| Ap       | 1.9% | 10.8% | 37.5% | 49.8% | 72.9% | 26.3 min | 16.0 | 10.3 |
| Cp0      | 1.1% | 8.5% | 10.8% | 79.5% | 151.2% | 63.3 min | 23.5 | 14.3 |
| Cp10     | 1.5% | 4.2% | 33.1% | 61.2% | 127.1% | 66.9 min | 18.8 | 12.0 |
| Cp20     | 2.7% | 2.3% | 58.1% | 36.9% | 86.7% | 73.5 min | 13.6 | 9.6 |
| Cp30     | 3.3% | 1.8% | 70.1% | 24.7% | 64.7% | 79.0 min | 12.1 | 8.7 |
| Dp0      | 1.5% | 12.3% | 64.9% | 21.3% | 42.7% | 36.6 min | 12.9 | 8.0 |
| Dp10     | 1.6% | 9.5% | 60.0% | 28.9% | 52.5% | 37.9 min | 12.9 | 8.3 |
| Dp20     | 2.0% | 6.2% | 56.4% | 35.5% | 61.6% | 39.9 min | 12.4 | 8.4 |
| Dp30     | 3.3% | 4.3% | 48.4% | 44.1% | 74.0% | 43.2 min | 12.5 | 8.8 |
| Ep0      | 1.4% | 14.7% | 53.8% | 30.2% | 55.0% | 45.3 min | 15.3 | 9.3 |
| Ep10     | 2.1% | 5.7% | 71.9% | 20.3% | 42.6% | 48.2 min | 10.7 | 7.4 |
| Ep20     | 2.3% | 4.2% | 79.5% | 14.0% | 34.7% | 50.4 min | 10.0 | 7.2 |
| Ep30     | 2.7% | 2.9% | 82.4% | 12.0% | 31.9% | 52.8 min | 9.8  | 7.3 |

Figure 11. Residences’ final distribution in experiment 3.
The results of Cp0 to 30 show that in scenario Cp0, private automobile users decrease by about 10 points compared with scenario C0, and a reduction in residential diffusion is not observed. However, with increasing interaction promotion, private automobile users remarkably decrease. For scenario Cp30, private automobile users decrease to less than 25%, and total CO$_2$ emissions are decreased to less than 65%. These are, compared with scenario C30, more than 20- and 30-point reductions, respectively. Notably, the cluster of railway user residences around the suburban station become more obvious.

The results of Dp0 to 30 show that, in scenario Dp0, private automobile users decrease by more than 65 points compared with scenario D0, while bicycle and railway users increase accordingly. Residential diffusion remarkably improves, and total CO$_2$ emissions considerably reduce However, with increasing interaction promotion, private automobile users gradually decrease, residential diffusion advances, and total CO$_2$ emissions increase.

The results of Ep0 to 30 show that in scenario Ep0, private automobile users decrease by more than 60 points compared with scenario E0 while bicycle and railway users increase accordingly. Residential diffusion remarkably improves, and total CO$_2$ emissions considerably decrease. Additionally, with increasing interaction promotion, private automobile users gradually decrease. For scenario Ep30, private automobile users decrease to close to 10%, and total CO$_2$ emissions to close to 30%. Residential diffusion is hardly observed, and the cluster of residences of railway users around the suburban station is maintained at almost the initial state.

Additionally, in some scenarios with less promotion of interaction, bicycle users significantly increase, and they live in the CBD.

6.3. Discussion of Experiment 3

By combining the control of private automobile use in an urban central area with the introduction of a hub and promotion of interactions around it, private automobile users decrease, total CO$_2$ emissions reduce, and residential diffusion significantly improves compared with the cases that do not combine these policies. These results are more positive compared with the cases combining the promotion of bicycle use. Particularly, in the cases introducing a hub to the urban central area, eliminating private automobile traffic within its range, this positive tendency is remarkable. This also may be because interaction promotion, which is an incentive to stroll about downtown, is more effective at increasing railway users.

We observed slight differences based on whether the location of the hub is in the same place as the central station or near the station; however, with increasing interaction promotion, the urban environment gradually worsens in the former and gradually improves in the latter. This also may be because interaction promotion promotes the residents to travel on foot from the hub to parking lots rather than accessing the central station. These experimental scenarios suggest that the synergistic effects of the control of private automobile use, the proper location of facilities for residents and interaction promotion, could more negatively impact urban environments.

The increase in bicycle users and their residence in the CBD seem to be induced by the uselessness of private automobiles in the area. This plan deviates from the initial zoning with the separation between residences and job locations. However, these can be evaluated as follows: First, the residents can live close to their job location, preventing wastes of time and monetary cost, reducing risk of traffic accidents and air pollution, etc. Second, further mixed land-use revitalizes the central urban area by providing a broad range of social activities. Agglomeration of the heterogeneous activities enables people to enjoy the benefits of urbanization economies, which provide a mutually complementary revitalization of an economy [85].

7. Conclusions

This paper presented an exploratory urban dynamics ABM to simulate the relationship between the introduction of a hub facility that is open to residents, promotion of interaction
Sustainability 2021, 13, 12500

around it, and transport policies on the sustainability of urban development through the autonomous actions of individual residents. First, by contrasting the model results with the theoretical and empirical insights from actual cities, the validity of modeling the formation of residential diffusion on urban edges based on individual gain-maximizing daily travel and residential relocation was demonstrated. Then, this stylized abstract urban model with autonomous agents was used to gain insights into the micro–macro linkage in the urban system under different scenarios.

The major contribution of the model is that it offers a new perspective on the bottom-up control of residential diffusion on urban edges through the benefits of productive human interactions at the microscale. Specifically, the model experimentally suggests the existence of a trade-off between increasing human interactions, through an introduction of an open hub attracting diverse activities and interaction promotion around it, and the expansion of residential diffusion. The model also suggests that the direction of urbanization is the result of collective action, and sustainable urbanization may be achieved by concerted effort. In particular, we observed that increasing interaction promotion could considerably reduce residential diffusion when the hub is within a moderate walking distance of the central station. However, if the hub is too close to the central station, increasing interaction promotion has no effect. In other words, throughout the experiments, we observed that these small differences in policy implementation may result in significant differences in the future, in both the static and dynamic urban environments.

The experimental results showed that pedestrian- and/or cyclist-friendly transport policies, in combination with the above policies, could further reduce residential diffusion by increasing human interactions. This trend remains consistent irrespective of the location of the hub and the level of interaction promotion. We observed that improvements in bicycle transportation could counteract residential diffusion associated with the shift to the private automobile use of resident agents. Likewise, the physical exclusion of automobile travel from the urban central area further fostered densification of the range of residents’ activities. This suggests a trend toward a favorable urban transformation with residents enjoying the convenience of living close to work and experiencing various activities in close quarters, i.e., compact urbanization.

Based on the dynamics presented here, it is expected that human interaction promotion will significantly impact future urbanization through the benefits it provides to individuals. Thus, this approach provides some anchor points for more fruitful discussions supported by multiple grounds, which are required for policies aiming towards sustainable urbanization. It should, therefore, be seen as a starting point and an initial effort to argue for a differentiated view of the density of human interaction and its impact on complex urban environments. In other words, rather than solutions oriented towards specific urban issues, this modeling approach describes a combination of lessons from the past and emerging theoretical and empirical insights, with the intention of developing a new theory of urban morphology. In this respect, in its current stage, the model is exploratory in nature, further analyzing such theories. However, in presenting the experiments, the model was calibrated based on actual cities, and, as such, we think that this paper could contribute to the growing literature generatively exploring the dynamic social processes underlying the expansion of urbanization, and our simulations lay the foundation for further work.

One direction of model extension is to incorporate more realistic and complex transport systems. The model assumes a city with a simple structure and well-developed public transportation. In practice, the threat of residential diffusion is greater in cities that do not have such conditions. However, this extension would involve developing more complicated algorithms of residents’ daily travel than are currently implemented in the model. Next, we set a constant number of households throughout the model’s running; however, in reality, population dynamics vary from city to city. For example, in Europe, urban expansion has generally been associated with population growth. Conversely, recent depopulation due to low birthrates and an ageing population have become serious issues in regional cities in Japan. It was emphasized that population dynamics fluctuate far
more than changes in the physical shape of an urban area [86]. How population dynamics affect policies that reorganize urban space is an open question, which is worthy of further investigation.

Regarding concerns about the validity of model and its results in the application of ABMs in social science [32], this model might be no exception. Although the interaction value and interaction promotion of the model were carefully defined based on previous interdisciplinary theoretical and empirical insights, reliable empirical data that directly describe the benefits of human interaction would reinforce the interpretability of the model. At later stages of development, the model would benefit from a more sophisticated human interaction component to incorporate the negative benefits of this local interaction: congestion between pedestrians and between pedestrians and automobiles.

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