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A GIS-CA Model for Planning Bikeways upon the Footpath Network

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Abstract: This study proposes a geographic information system (GIS)-based cellular automata (CA) model, which is designed for planning bikeways upon existing footpath networks within an urban area. The CA model was developed based on a GIS platform as a visual interface whereby spatiotemporal characteristics and spatial processing can be combined in a highly effective way. The host value of each CA cell is conditioned upon four indicator variables, namely cycling demand level, land-use nature, social value, and traffic safety. This model gives traffic planners a quick and intuitive framework to develop cycling facilities under limited land resources. A model prototype has been developed in a common desktop GIS and applied to a mid-sized rapidly developing area in Singapore.

Keywords: bikeway network planning; bike-sharing scheme; geographic information system; cellular automata model

Citation: Zhao, X.; Zhang, J.; Zhang, N.; Wong, Y.D.; Zhou, Y.; Meng, M. A GIS-CA Model for Planning Bikeways upon the Footpath Network. *Sustainability* **2021**, *13*, 8926. https://doi.org/10.3390/su13168926

Academic Editor: Ardeshir Faghri

Received: 21 July 2021
Accepted: 8 August 2021
Published: 10 August 2021

1. Introduction

Cycling is one of the main transport modes in an urban transportation system and is being rapidly revitalised for its sustainability and compatibility with a green lifestyle. Singapore, as well as other big cities, is striving to promote extensive cycling usage in urban areas. The long-term aim is to provide all 26 towns with a comprehensive cycling network. Within confined land areas, provision of cycling facilities and bike-sharing schemes shall be an effective way to enhance first-/last-mile connectivity, which has become very popular and advanced in some European countries [1–3]. On the basis of the cycling demand forecast, the ideal network of docking stations upon the footpath network can be determined. Cycling has been a minor mobility mode in Singapore over the 1980s and 1990s, hence, there are few extant on-road cycling lane or off-road bikeways. Given the apparent risk faced by cyclists on the narrow urban roadways in Singapore, utilitarian cyclists have, by and large, come onto the footpaths (typically 1.5 m wide pathways), which has generated conflicts with the pedestrians. Singapore passed the Active Mobility Bill in 2017, which accords cyclists the right to jointly use off-road footpaths amidst pedestrians, with a 15 km/h speed limit [4], which was subsequently amended to 10 km/h [5]. Where demand is high, the footpaths have been widened for shared use by pedestrians and cyclists [6]. Furthermore, docking stations are located along the bikeway network as bike-sharing nodes. How to plan a conjoint walking and cycling facility is an important issue in effectively implementing Singapore's bike-sharing scheme in order to satisfy the cycling demand without excessive uptake of new land space. Some amount of research work has been done in the cycling field in recent years. For instance, cycle route network planning has been highlighted in recent years in order to develop multi-modal sustainable transportation systems [7]. Yet, there exists little research on how to plan a new bikeway network layered upon existing footpath network.

This study fills the gaps of research findings by presenting the development of bikeway network on existing footpaths using a geographic information system (GIS)-based cellular automata (CA) model. The model captures four main factors that influence the prioritisation and location of bikeways juxtaposed onto existing footways. The key factors are land-use nature, cycling demand level, traffic safety, and construction difficulty. The model provides the flexibility to collate relevant data into an easily interpretable graphical format, which has strong practicability. Moreover, with the application of a GIS platform, the results can be shown directly. The selection of off-road bikeways is the most important topic being considered, aimed at providing the maximum benefit for both cyclists and the authorities [8].

The proposed planning framework is well suited for planning a bikeway network for cities with sparse cycling infrastructure, yet where cycling and bike sharing is rapidly growing in demand. The findings are clean-cut and intuitive, which can be effectively used to plan cycling facilities within confined land areas. The proposed model may not be the most accurate tool for planning every kind of bikeway, but can be improved as data for various factors are built up. Moreover, the attribute values shall be adjustable as commensurate with actual conditions.

Section two of the paper reviews the literature on planning cycling facility, and methods used in planning bikeways. The third section introduces the CA modelling theory and the applicability of the CA and GIS combination for planning bikeway networks. Section four describes and explains the proposed methodology used for planning bikeways. The fifth section applies the method in a district in Singapore. The final section provides the conclusions as well as the identification of opportunities for future research in this field.

2. Literature Review

Cycling facility planning models have drawn attention among transportation academic research circles since the mid-1990s. The models generally fall into three groups: supply-based models, demand-based models, and supply/demand-based models.

Supply-based models rely on two overarching theories: (a) all major attractors should have cycling facilities and (b) a mathematical method, such as hazard score analysis, bicycle compatibility index (BCI), and level of service acceptability matrix (LOSAM) for cyclists and pedestrians, should be calculated to prioritise the relevant issues for the cycling facility [6]. That is, cycling facility planning is either specialised or can be improved based on the current condition of the level of service for cyclists. The bicycle compatibility index (BCI) is a typical supply-based model, which was developed for U.S. metropolitan areas. A level of service acceptability matrix was proposed based on Singapore's local travel characteristics, which is easy to develop and can be quickly applied to assess the current cycling situation and to propose necessary countermeasures. Although these supply-based models consider various important factors, such as traffic safety and interaction, there is still a lack of the foresight on the most "desired" path for cyclist.

Demand-based models focus on the cycling travel data relevant to travel from one zone to another. Therefore, this kind of model does not indicate site-specific facility improvements or represent the actual increase in usage if a cycling facility is implemented [9]. Demand-based models put a greater emphasis on cycling travel predictions, including market analysis, facility demand potential models, discrete choice models, and aggregate behaviour studies. One of the most popular demand-based models is the latent demand score (LDS) model, which was proposed by [10]. This model estimates the probability of cycling travel on individual street segments based on their proximity, frequency, and magnitude of adjacent bicycle trip generators and/or attractors. However, the LDS model may result in overestimation as it does not consider existing nearby high-LDS alternative routes.

Supply/demand-based models have been regarded as a reasonable method for cycling facility planning due to the balanced consideration of both supply and demand sides. Although this concept has been accepted by many scholars, there has been little research on how to combine both the supply and demand sides to decide how to prioritise and plan the cycling facility [11,12]. Recently, a data science framework was proposed that considers both potential demand and path prioritisation [13]. The case study results showed that the data science framework can inform interventions and improvements to an urban cycling infrastructure. A heuristic and data-mining-based method was developed by [14] to weigh both demand and/or equity (DARE) in the station distribution and allocation process of planning bike sharing. DARE provides transparent decision-making support for supply distribution and presents an alternative where the benefits of the bike-sharing system (BSS) are extended beyond privileged populations.

This study proposes a GIS-based CA bikeway planning method to address the gap in research into how to systematically plan a new cycling network layered upon an existing footpath or roadway network. The CA bikeway planning model has been explored in detail by researchers in the past two decades with the aim to find an optimal path within the minimum possible time. However, besides the incomplete consideration of influence factors, the traditional CA path planning method based on a part-to-whole approach suffers the shortcomings of easy-to-premature convergence. An improved CA bikeway planning method is developed using whole-to-part technique based on a GIS platform. Path planning on a GIS platform does not come out of the blue and has been successfully applied in other planning problems. As such, this paper adds a CA model on a GIS platform to fill a gap in existing bikeway planning methods.

3. Cellular Automata Model

The cellular automata (CA) method was first proposed by [15] to simulate the self-reproducing function in a living system. Following this, [16] applied it widely by introducing a system dynamics method, computer theory, and formal language to CA research. CA is not determined by a strictly defined equation or formulation, but is formed by a series of rules. Any model that satisfies these rules can be regarded as a CA model. A CA model usually includes five components: cell space, cell state, neighbour, transfer function, and temporal state, as shown in Figure 1.

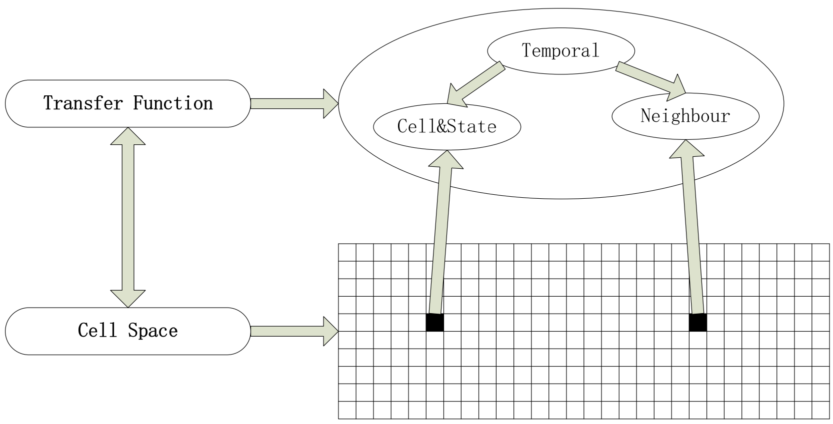

Figure 1. Components of CA.

The applicability of a CA model used in bikeway planning is based on three aspects: (1) CA's bottom up modelling mechanism, starting from the state of the cell, can easily describe the behavioural regularity for determining the position of the cell; (2) the computational completeness of a CA model is suitable for simulating the complex spatial cycling system, as CA has no defined set of formulation laws; and (3) a CA model can be easily achieved by a computer program. A CA model possesses the spatial and temporal characteristics that can describe bikeway's spatial distribution and changes in its development over time.

GIS-based techniques have received more and more attention in recent decades as they can effectively manage, express, analyse, and process static space information [17]. The advantages of using GIS in infrastructure planning have been widely discussed. It has also been applied in bikeway network planning in many countries, such as New Zealand, USA, Singapore, and Greece [7,18–20]. Both studies and practices have shown that GIS techniques can effectively support in bikeway network planning decision making. However, it has so far failed to describe and simulate spatiotemporal behaviour in a geographical framework. CA has a strong ability to simulate spatiotemporal behaviour, but the geospatial processing is relatively weak. Therefore, the combination of CA and GIS models can take full advantages of each other.

4. Method

4.1. Influence Factor

A cell is set as a square with a side of length 30 metres. Each cell *ci,j*(*x*,*y*) has a host variable *wij*(*x*,*y*) to determine the cell state, where (*i*, *j*) is the grid coordinate and (*x*, *y*) is the actual coordinate. A host variable is defined as one that has 3 kinds of value, including: "0", which means the cell is not ideal for the planning path; "1", which means the cell is a possible option; "2", which means the cell is an ideal section along the planning path. The host variable is influenced by four indicator variables based on Singapore's conditions: land-use nature ("0" means unavailable land, e.g., building, expressway, river etc., if x1 = 0, then *wij*(*x*,*y*) = 0, other variables will be unavailable to be valued; "1" means green space, which can be developed for widening adjoining footpath for shared use; "2" means available space, which can be used for constructing shared-use pathways; "3" means existing footpath, which can be shared by cyclists); cycling demand level ("0" means low demand area with low priority, "1" means medium demand to be a shared-used pathway, "2" means high demand); traffic safety ("0" means a safe place, "1" means low hazard place, "2" means medium hazard place, "3" means high hazard place); construction difficulty, which is related to the soil conditions, construction cost, etc. ("0" means no difficulty, "1" means low difficulty, "2" means medium difficulty, "2" means high difficulty).

After generating the spatial distribution grid map, the data table can be organised based on the cells' attributes. According to the actual conditions, the required information for a GIS platform includes hydrological features, land-use nature, and construction difficulty. After inputting these data into GIS, the corresponding grid map is generated onto the GIS platform with a corresponding data table. Each row represents a cell, which includes four fields: UserID (cell code), Pos (real location in geographic coordinate), Hos (host value), Ind (Indicator value).

4.2. Cell Transfer Rule

Based on the state of each cell in the planning area, the cell on the planning path shall be determined by three parameters: host value, $w_{ij}(x,y)$; transfer rate parameters, α; and transfer probability, $P_{ij}(x,y)$.

4.2.1. Host Value $w_{ij}(x,y)$

The host value can be calculated based on the four indicator variables as follow:

$$w_{ij}(x,y) \;=\; b_1x_1 + b_2x_2 - b_3x_3 - b_4x_4 \tag{1}$$

where b_1, b_2, b_3, b_4 are the weight coefficients of each indicator variable x_1, x_2, x_3, x_4, and $b_1 + b_2 + b_3 + b_4 \;=\; 1$.

4.2.2. Transfer Rate Parameter α

The planning process for a bike-sharing path should consider the high cycling demand, available land-use sections, and safe and low hazard places. Based on the Moore neighbourhood model with a radius of 1 m, find an eligible cell ($w_{ij}(x,y) \geq 1$) from the 8 surrounding neighbourhoods. The transfer rate is given by:

$$\alpha = \begin{cases} 0, \ the\ number\ of\ eligible\ cells > \eta_1 \\ \beta_1, \ \eta_2 < the\ number\ of\ eligible\ cells < \eta_1 \\ \beta_2, \ the\ number\ of\ eligible\ cells < \eta_2 \end{cases} \tag{2}$$

where β_1 and β_2 are the piecewise function value of α, $0 < \beta_2 < \beta_1$; η_1 and η_2 are the threshold value, $0 \leq \eta_2 \leq \eta_1 \leq 8$.

4.2.3. Transfer Probability $P_{ij}(x,y)$

The transfer probability is calculated from:

$$P_{ij}(x,y) = \frac{(e^{\gamma})^{\lambda}}{1 + e^{[-\alpha * w_{ij}(x,y)]}} \tag{3}$$

where γ and λ are random values in a range of values from 0 to 1, and λ is a control parameter. During each iteration, $P_{ij}(x,y)$ shall be compared with the threshold value δ; if $P_{ij}(x,y) > \delta$, the cell $c_{ij}(x,y)$ shall be on the planning path (bikeway).

4.3. Path Generation

An improved CA path planning method is developed to determine the final bikeway by avoiding unsuitable cells in the network. All the unsuitable cells are obstacles that cannot be selected, while suitable cells obtained based on cell transfer rule shall be the optional cell in the algorithm. Traditional CA method starts from the origin node and proceeds to the destination node following the designed transition rules, which leads to easy-to-premature convergence. An improved CA method shall focus on filling in dead-end paths in the whole bikeway network. Docking stations shall be the origin and destination nodes in the improved CA method. Detailed steps are listed as follows:

Step 1: Initialisation.

Set the status value for the optional cells as 0, for the obstacle cells as χ; set origin node and destination nodes as O and D with status value.

Step 2: Contraction.

If the Moore neighbour in the positive direction of the central cell *ci,j* (neighbour in the direction of north, south, east, and west) has more than 2 non-origin and non-destination cells with equal status value at time *t*, this cell c shall be an obstacle cell at the time *t* + 1 as follows:

Step 1: Initialisation.

Set the status value for the optional cells as 0, for the obstacle cells as χ; set origin node and destination nodes as O and D with status value η.

Step 2: Contraction.

If the Moore neighbour in the positive direction of the central cell $c_{i,j}$ (neighbour in the direction of north, south, east, and west) has more than 2 non-origin and non-destination cells with status value equal to χ at time *t*, this cell *c* shall be an obstacle cell at the time *t* + 1 as follow:

$$\Psi_c^{t+1} = \begin{cases} \chi, \ K_t > 2, c \neq \eta \\ 0, \ K_t \leq 2, c \neq \eta \\ \eta, c = \eta \end{cases} \tag{4}$$

where $\Psi_{c_{i,j}}^{t+1}$ is the status value of central cell $c_{i,j}$ at time *t* + 1; K_t is the cell number of Moore neighbour in the positive direction, whose status value is χ.

Moreover, if the optional central cell *c* is located at an angle among four continuous obstacle neighbour cells, and the neighbour cell against this angle is an optional cell, this cell *c* shall be an obstacle cell at the time *t* + 1. Take the upper left angle as an example, this rule can be expressed as follow:

$$\Psi_{c_{i,j}}^{t+1} = \chi,\ if\ \Psi_{c_{i,j}}^{t} + \Psi_{c_{i+1,j+1}}^{t} = 0,\ and\ \Psi_{c_{i-1,j-1}}^{t} + \Psi_{c_{i-1,j}}^{t} + \Psi_{c_{i,j-1}}^{t} = 3\chi,\ and\ \Psi_{c_{i-1,j+1}}^{t} + \Psi_{c_{i+1,j-1}}^{t} > 0 \quad (5)$$

Step 3: Optimisation.

Many feasible paths may be obtained after Step 2 in the network. In order to select the only optimal path in the network, the host value is extended to calculate the path utility. The final path shall be the path with the maximum host value.

The overall planning framework is shown in Figure 2.

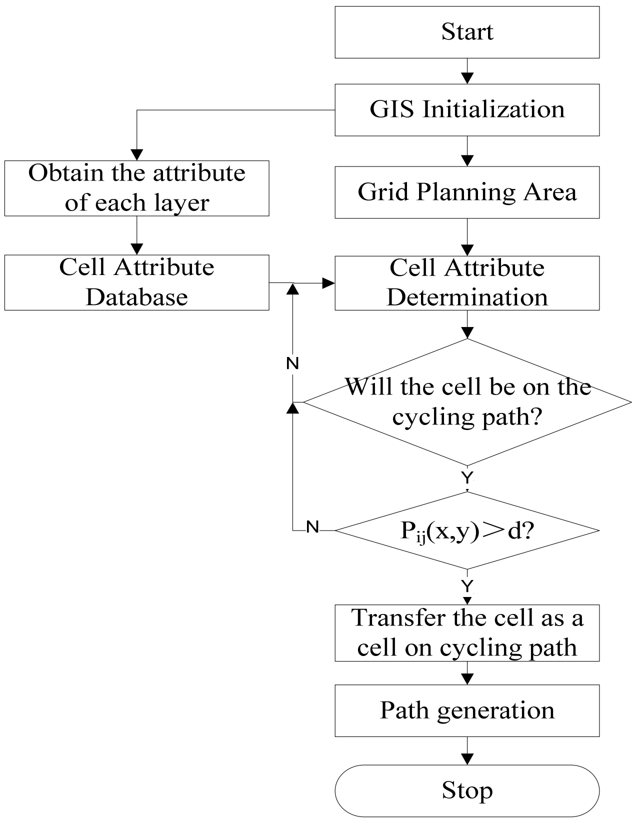

Figure 2. GIS-based CA cycling path planning framework.

5. Application

5.1. Study Area

In order to demonstrate the effectiveness of the proposed method, a real network (boundaries with expressways) located in the west of Singapore was selected as a study area, as shown in Figure 3. Three mass rapid transit (MRT) stations are located within this area, namely Lakeside, Chinese Garden, and Jurong East. At present, there are footpaths with varying width alongside all roads, linking most of the areas within the town centres, and there are no segregated bikeways.

After forecasting bike-sharing demand, 10 bike-sharing (docking) stations were determined, as shown in Figure 3, where three docking stations were located nearby the three MRT stations and the other seven docking stations were located in the vicinity of residential or industrial buildings.

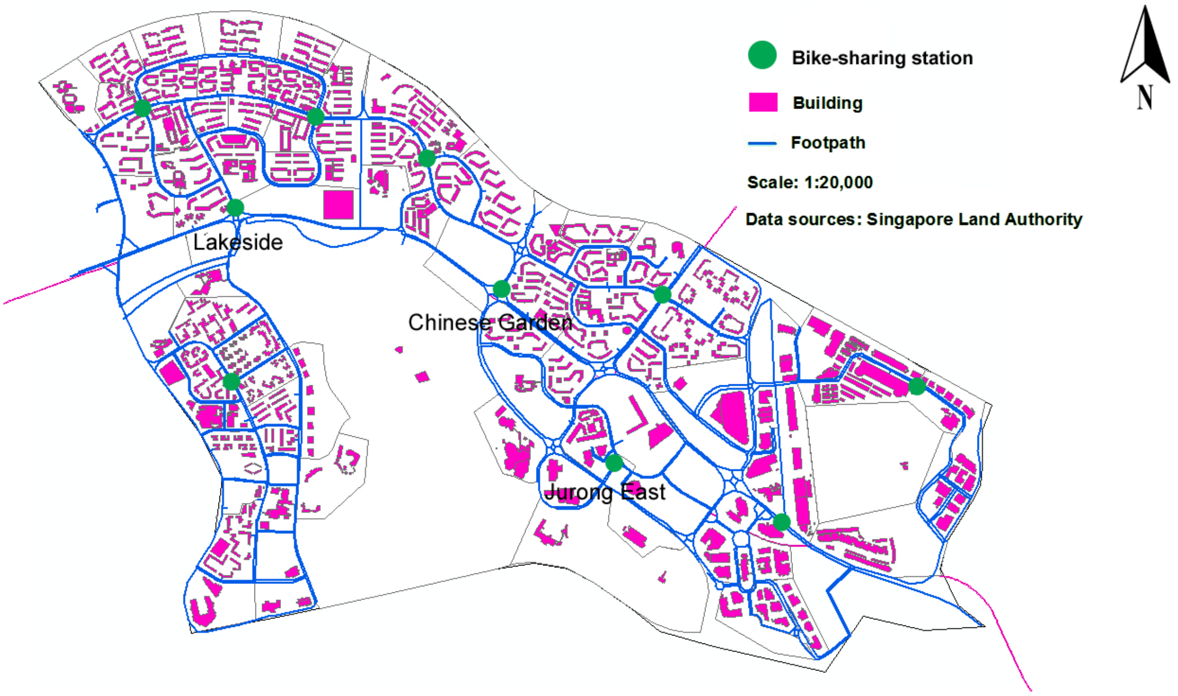

Figure 3. Map of the study area.

5.2. Data Source

The data used in this analysis came from three sources. The first source was the home interview travel survey (HITS), which tends to under-report short-range non-motorised trips, hence a field transportation stated preference (SP) survey of non-motorised travellers was administered within the study area during three months from April 2014 to June 2014. Respondents were briefed about what "bike-sharing" is before answering the questions. The SP questions included likely usage frequency, trip purpose and destination, hazardous spot(s) along cycling route, preferred cycling parking location, how different conditions (weather, AM/PM peaks) would affect the respondent's decision to use bike-sharing, etc. Ultimately, the survey was completed by nearly 450 respondents. This survey served to predict the bike-sharing demand and also investigated potential unsafe or difficult to construct pathway segments.

The second source of data came from the Onemap [21], which is an integrated map system for government agencies. Three types of maps were considered in this study. One was the Urban Redevelopment Authority (URA) Master Plan 2019, which is the statutory land-use plan for the next 10 to 15 years. Another was "street map", which contains roadside footpath, building, and hydrology information. The other was a geological map of Singapore, which was obtained from Singapore Geology Office. These data provided the detailed GIS layers for determining the land-use nature and construction difficulty.

The third source was the traffic accident database, which was provided by the Singapore Police Force. The relevant cyclist and pedestrian collision data in the study area were extracted to build the current safety level layer in this study.

5.3. Results

Once the data for all the indicators were prepared, they could be displayed on the grid cells. Based on land-use planning and field observations, the first variable of land-use nature could be valued, as show in Figure 4a. The cycling demand was extracted from the SP survey, whereby the original zones of a cycling trip were distributed onto the nearest road segments, as shown in Figure 4b. Traffic accident data are summed in Figure 4c. The terrain in the study area is relatively flat with firm solid ground. Construction technology is not difficult. Therefore, the variable value of construction difficulty in the study area is mostly related with construction cost, which was evaluated by field observation according to its social impact, as shown in Figure 4d. The value of the host variable $wij(x,y)$ for each cell was calculated based on Equation (1), where $b_1 = 0.4$, $b_2 = 0.4$, $b_3 = 0.1$, $b_4 = 0.1$. Set $\beta_1 = 5$, $\beta_2 = 0.5$, $\eta_1 = 6$, $\eta_2 = 3$, $\delta = 0.5$, and the suitable cells for path generation were obtained based on cell transfer rule.

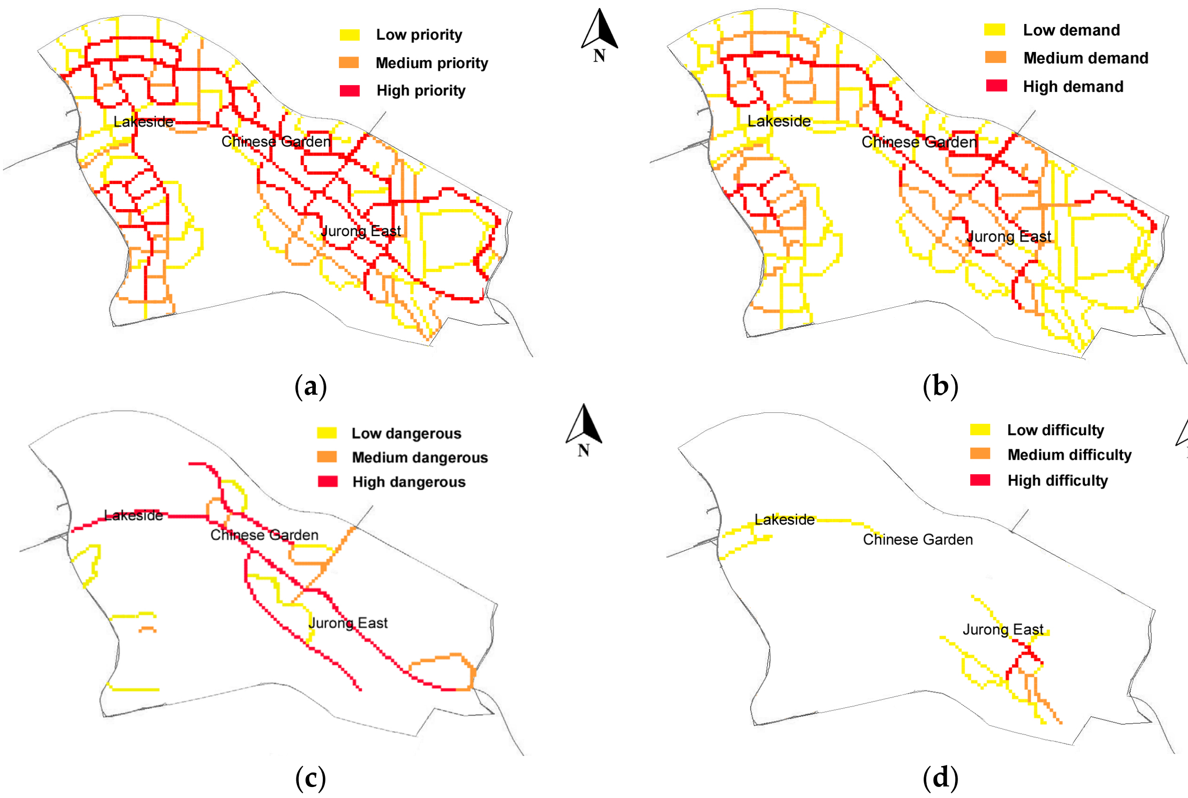

Figure 4. Initial values of four indicator variables. (**a**) Land-use nature. (**b**) Cycling demand level. (**c**) Traffic safety. (**d**) Construction difficulty.

After the path generation process, the final planned bikeway paths for the study area are shown in Figure 5. In this map, all the bike-sharing stations are well connected within the planned bikeways. Combining the land-use characteristics in Master Plan 2019, both the residential areas and industry areas are covered in Figure 5. The selected cells ensure that the planned bikeways with bike-sharing nodes can better supply the cycling demand with available land sources, while avoiding unsafe and difficult-to-construct areas.

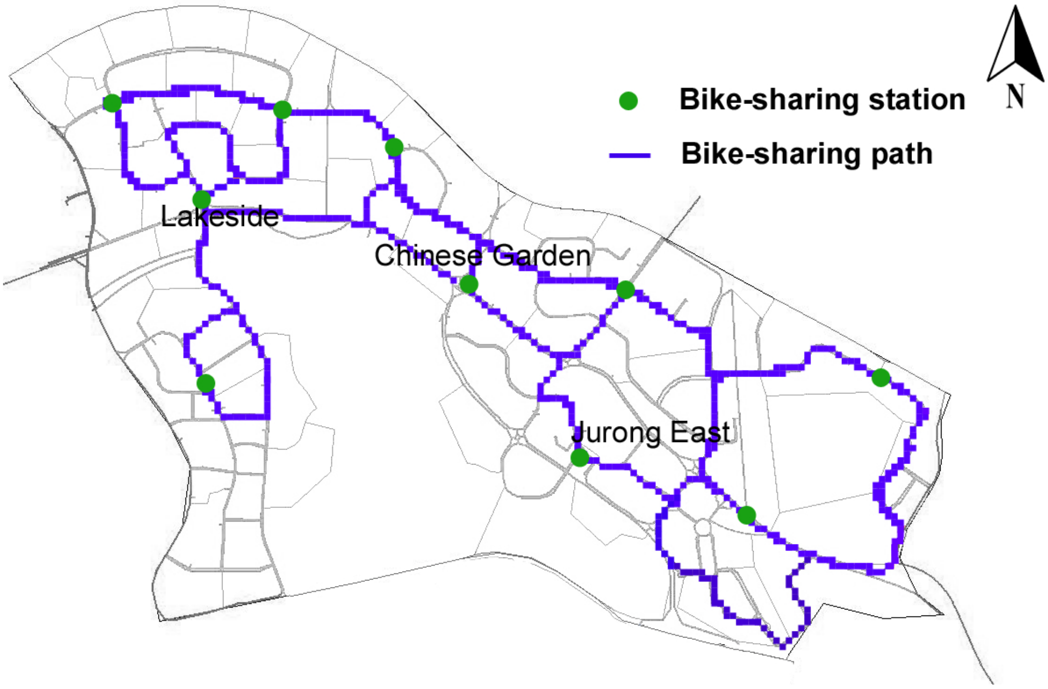

Figure 5. Final planned bike-sharing paths for the study area.

6. Conclusions

Singapore is aiming to be the world's first "smart nation" by using high-tech services in transport, eldercare, and other public domains. This study proposes a CA bikeway planning model, fully operational in a GIS environment, to overcome the limitations of the four-step approach for bikeway modelling. The model uses a 30 × 30-square-metre grid cell mesh in the vector GIS data format with consideration of four indicator variables to determine the optional cells. An improved CA method is proposed, filling in dead-end paths in the whole network, where non-optional cells are regarded as obstacles. The final bikeway network shall be obtained by connecting all the bike-sharing stations.

The contributions of the proposed method are threefold: (1) This proposed method can capture both the spatiotemporal behaviour and the geospatial processing at the same time, which meets the demand and supply requirements in bikeway network planning. (2) The definition of the host variable in the CA model can be flexibly extended to other cases by combining various influence factors. The paper has used Singapore as a case study to illustrate the application of the proposed method. This method can be applied in various countries and can incorporate localised factors, e.g., accessibility to other public transport services, competition from other first-/last-mile mobility services. (3) The algorithm can be repeated to map the priorities for the development of cycling facilities. The final path is the output with the maximum host value. The threshold can be adjusted to generate the best path.

However, the proposed method has the limitation of its large cell size setting. To ensure the computation performance on the GIS platform, the cell size in the CA model in this method was larger than the normal setting in other transportation scenarios, e.g., intersection scenarios and platform scenarios. The definition can be adjusted in small-sized networks to ensure an efficient calculation performance. Also, there was a minor gap between these two datasets (HIST and vehicle accident data) in the temporal dimension. Considering that cycling network planning is a long-term project, the influence on the results can be neglected. The practicability of the proposed method has been verified by a study area in Singapore.

The techniques of determining the bikeway network with bike-sharing nodes serve as a useful tool in planning non-motorised transport facilities. It provides an idea of how to combine various influence factors into complex planning of bikeways on the GIS platform. Future studies can focus on the design and implementation of sub-modules, such as computer-aided survey modules, historical data analysis modules, and so on.

Author Contributions: Conceptualization, X.Z. and J.Z.; methodology, M.M.; software, X.Z.; validation, J.Z., N.Z. and M.M.; formal analysis, X.Z.; investigation, J.Z.; resources, Y.D.W.; data curation, Y.Z.; writing—original draft preparation, N.Z.; writing—review and editing, Y.D.W.; visualization, X.Z.; supervision, Y.D.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank Singapore Police Force for their support by providing the accident data, and the student helps who participated in the field surveys and data analyse. All the interpretations and conclusions in this paper are the responsibility of the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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