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A Framework of Community Pedestrian Network Design Based on Urban Network Analysis

Xiaolin Yang [1], Haigang Sun [2], Yu Huang [3,4,*] and Kailun Fang [2]

[1] College of Architecture and Urban Planning, Guangzhou University, Guangzhou 510006, China; saupyangxiaolin@gzhu.edu.cn
[2] Guangzhou Urban Planning and Design Co., Ltd., Guangzhou 510030, China; sunhaigang@gzscsghsjyxgs.wecom.work (H.S.); helenhoilunfong@gmail.com (K.F.)
[3] College of Civil Engineering, Guangzhou University, Guangzhou 510006, China
[4] State Key Laboratory of Green Building in Western China, Xi'an University of Architecture and Technology, Xi'an 710064, China
* Correspondence: ceyuhuang@gzhu.edu.cn; Tel.: +86-13104872057

Abstract: Community is the foundation of modern cities, where urban residents spend most of their lifetime. Effective and healthy community design plays a vital role in improving residents' living quality. Pedestrian network is an indispensable element in the community. Successful pedestrian network design can help the residents be healthy both physically and mentally, build the awareness of "Go Green" for the society, and finally contribute to low-carbon and green cities. This paper proposes a community pedestrian network design method based on Urban Network Analysis with the help of the Rhino software. A case study of a typical community in Guangzhou, China was implemented, specifying the steps of the proposed method. The findings presented include the features of the citizens and the accessibilities of the neighbors that are obtained from the community pedestrian network simulation. The limitation and scalability of this method was discussed. The proposed method can be essential to designing healthy and sustainable communities.

Keywords: community pedestrian network; simulation-based design; urban network analysis; betweenness

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1. Introduction

A good and healthy community environment is essential to guiding the residents to healthy outdoor activities such as walking [1]. Healthy community is an important foundation for building a healthy city and residents' health. World Health Organization research shows that the influence of personal behavior and lifestyle accounts for about 60% (the highest) of their health [2]. In recent studies, walking has been defined as a healthy physical activity suitable for different ages, different athletic abilities, and different exercise goals, which could promote social communication, avoid obesity, and enhance immunity [3,4]. Relevant data shows that outdoor jogging (78.0%) and walking/hiking (60.6%) are the main daily activities of sports lovers. Linear outdoor activities such as jogging and walking have become daily sports patterns of many city residents; thus, the demand for corresponding outdoor space is increasing accordingly [5,6].

At present, most of the dedicated walkways in cities are built in public landscapes (such as parks). In high-density urban communities, the setting of walkways depends on the delineation or renovation of existing traffic facilities. There also exist problems such as air and noise pollutions due to automobiles nearby, making the sidewalks not suitable for the leisure and recreation activities of the citizens. Compared to sidewalks near motor vehicles, independent trails attract more attentions from residents and become the best selection for healthy walkway design towards high-density built environment [7]. The slow-walk spaces in the densely built old communities, however, are relatively scarce, and the pace of modern people's life is speeding up. It is thus getting more and more difficult for many residents to have long-time outdoor activities. On the other hand, walking and jogging during the fragmented time after dinner have become popular outdoor activities [8]. Therefore, it can be an effective way to improve the high-density environment by building up or improving the pedestrian network, making use of the small-scale, non-motorized vehicle lanes, and scattered open public spaces of old communities. This pedestrian network can be an effective supplement to the traditional old community renewal task [9,10].

Early research involving healthy community mainly focused on environment optimization, community governance, as well as cultural construction, etc., focusing on the community participation and residents' enthusiasm. Recent research started to notice the internal relationship between residents' community activities and the environment [11–13]. For slow-walk traffic, especially, the academia focuses on the characteristics of residents' slow-walk behavior, the influence of the spatial layout on the slow-walk behaviors, and the construction mode of the slow-walk system. With the development of computer technology, the correlations between environmental walkability score and walking behavior are studied quantitatively [14]. Specifically, empirical studies show that the walkability index of a 15-minute walking range imposes a considerable influence on the walking behaviors in the community [15].

The concept of "15-minute community neighborhoods" has been widely recognized and applied in community planning in some high-density cities such as Shanghai and Milan [10,16–18]. However there are still some problems in practice [19]. For example, in Shanghai, the 15-minute community life circle concept is used for building basic living units (3 square kilometers, with a population of about 50,000–100,000 people). The public facilities for a living unit are further specified as those with 5-minute, 10-minute, or 15-minute "walking" distances, as presented in Figure 1 [20,21]. Such thresholds are intuitive, yet arbitrary somehow. The so-called living circle is determined by the Euclidian distance without concerning the walking accessibility of the residents. This means that the residents may have to take long-distance detours due to poor accessibility even if the destination is "not far-away" from the map perspective. In addition, the location of facilities in the living circle should be optimized with a good consideration of the amount of the pedestrian traffic. On the other hand, the public facilities should be set according to the actual situation. It is thus necessary to restudy the methods for walking evaluation and measurement to reconstruct the community life circle based on walkability.

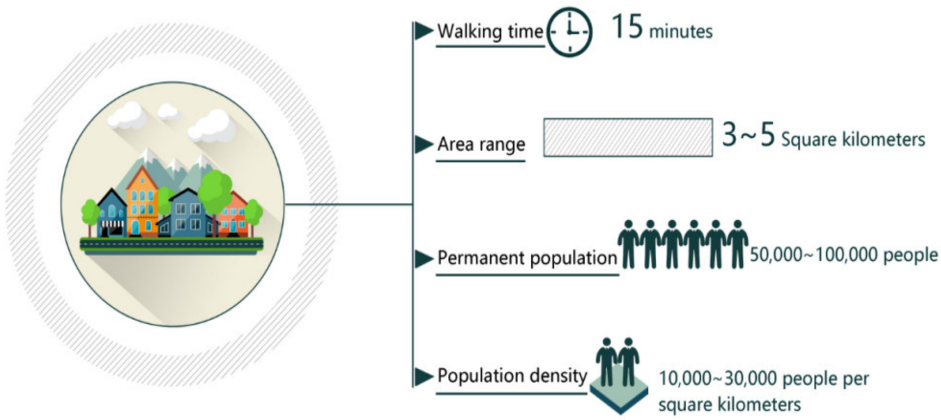


Figure 1. Basic living unit setting in Shanghai.

Successful planning of the community life circle relies on the investigations and analysis of the walking behavior of the residents and the walkability of the community. This is usually associated with (i) the availability of useful and diverse destinations within walking distance; (ii) the safe routes, (iii) physical and environmental comfort of the routes, (iv) interesting routes with businesses, green space, and vistas [22]. However, despite a rich literature on qualities of built environments for the walkability, the current measuring, analyzing, and modeling methods remain insufficient for engineering tasks [23].

Early explorations of residents' walking behaviors are crudely described as community vibrancy that are determined by population density, block size, land-use mix, etc. [22]. These parameters are usually acquired from open-access sources [24] such as the number of mobile phone users [25], activity intensity based on social media data [26], and government planning targets. These parameters, though accessible from open data source, can be very limited in spatial resolutions (e.g., >1 km^2/ha grid), in which case the urban vibrancies on the street level are rarely studied. As for the influence of the surrounding environments to the walking behaviors, it can be difficult and unattainable to study the environment-oriented behaviors person by person, though the residents' activities are generally determined by themselves [23]. Therefore, it is necessary to adopt new methods to explore the street vibrancy objectively and accurately.

Currently, several walkability and traveling indices are being used in representing the street vibrancy in urban research. These indices are usually derived by mathematical models including Pedestrian Environment Review System (PERS) and Walk Score [27–30], exploring the influence of the environment on walkability via walking experiments and establishing relationship between people and environmental factors by mathematical models. The above evaluation systems have their own advantages and disadvantages. PERS focuses on sidewalks, public transportation, and public spaces, but ignores pedestrians' access to amenities. Walk Score, on the other hand, measures walkability based on public transportation and amenities, yet is not considering the practical conditions of the sidewalks in the area of interest [31]. Other approaches available for walking evaluation are list in Table 1. Given the different focuses and accessibilities of the current approaches, there is a need to simulate the residents' walking behavior in detail in the street scale, distinguishing the walkability features between the age groups and time periods, which are essential to the detailed design of the community walking system.

Table 1. Summary of quantitative methods for walking evaluation (walkability).

Measurement Method	Research Objectives	Cited
Origin-destination surveys	Measure the walkability based on proximal access to nearby amenities and public transportation offerings	Manaugh and El-Geneidy, 2011 [32]
Pedestrian Environment Review System (PERS)	Focus on walkways, public transportation, and public spaces	Buchanan et al., 2007 [27]
Walk Score (population density, dwelling density, land-use diversity, access to stores and urban services, connectivity, intersection density)	Focus on public transportation and local amenities to evaluate the walkability	Lwin and Murayama, 2011 [28], Mayne et al., 2012 [29], Taleai and Sabzali Yameqani, 2018 [30]
The HEI model and previous research outcomes	Explore the relation between perceived neighborhood qualities and walking	Inês A. Ferreira et al., 2016 [33]
The Street Walkability and Thermal Comfort Index (SWTCI)	Focus on comfort facilities and Physiological Equivalent Temperature (PET) at street scale	Kahina Labdaoui et al., 2021 [34]
Several artificial neural network (ANN)configurations	Predict subjective walkability index from objective measures	Ali Sabzali Yameqani, Ali Asghar Alesheikh, 2019 [35]
Semantic segmentation and statistical modeling on Google Street View images	Assess streetscape walkability (SW)	Shohei Nagata et al., 2020 [36]; Wang et al., 2019 [37]; Rzotkiewicz et al., 2018 [38]; Villeneuve et al., 2018 [39]
Space syntax models	Estimated associations SSW and neighborhood-specific leisure (LW) and transportation (TW) walking	Gavin R. McCormack, 2019 [40]

The above algorithms of walkability analysis established through mature mathematical models are mainly used retrospectively to study existing urban developments. Impact on design and planning can only be achieved if spatial analytic methods are applied in a normative way to synthetic, open-ended future design scenarios; therefore, prediction methods are also significant [23], such as Spatial Syntax and Urban Network Analysis (UNA) [41,42], which simulate and predict the pedestrian traffic with a toolbox. Spatial syntax belongs to traditional graph theory, while UNA builds up spatial connections based on traffic network, which is closer to people's perception of a real living environment.

Urban Network Analysis (UNA) measures accessibility at the accuracy level of the individual, which is dedicated to predicting non-motor vehicle traffic flow. UNA could quantitatively analyze how environmental design affects accessibility of space and facilities, and how environmental design affects public space vitality and pedestrian flow on sidewalks. The advantage of UNA is that it could calculate different types of network models, such as topology, Euclidean distance, etc., and simulate the distance that pedestrians pass through in the real situation. It is possible to use the parameters of nodes (accommodating population, total building area, floor to area ratio, land use property, etc.) to give weights to nodes, which effectively improve the accuracy of micro-spatial quantitative calculation [23]. For example, the parameters of building nodes represent the number of residents (which can be regarded as proportional to the travel volume), and the parameters of activity space and public facilities represent the attraction level towards residents, which is converted to pedestrian volume per area.

Traditionally, the research on existing environment problems relies on subjective evaluation methods such as survey, which are restricted by actual conditions. For instance, the residents choose to take a detour from a certain road because of a noisy environment or chaotic traffic, not because this road lacks attractive public space or facilities. In these kind of cases, objective evaluation could not be achieved. However, a comparison between UNA-based pedestrian flow simulation and actual situation can make it easier and more intuitive to explore various environmental factors that affect residents' travel behavior. This idea could be summarized as "fault diagnosis", which is of great significance to the environment analysis.

UNA has a high requirement for raw data, and thus is relatively more suitable for small-scale space. Some existing studies applied UNA tools to simulate the best location and scale of retail centers by predicting the passenger flow of planned retail centers in cities [43], or to predict the location and layout of stations around communities by simulating residents' walking activities [44,45].

To explore the street vibrancy more accurately and simulate the residents' walking behavior in detail with a prediction method, UNA is adopted for community pedestrian network design in this paper. Detailed design steps are described through a case study involving a typical community in Guangzhou, China. It is believed that the method presented could serve as a framework for computer-aided healthy community design.

2. Methodology

In this study, Urban Network Analysis (UNA) is used to analyze the community pedestrian network. With the idea of quantitative calculation, it is possible to use UNA to study the street vibrancy of the community objectively and accurately and to predict the residents' walking behavior in age groups.

The basic idea of UNA is a model with characteristics describing residents' pedestrian activities. The model is applied on a spatial network so that all distances are routed along networks and network-based distance accounts for asymmetrical densities in blocks or street scale [43]. Instead of considering the residents as a whole population with the same behavior mode, UNA uses individual demand as buildings or residents, which is reliable for producing a more accurate estimation.

There are three steps in the UNA-based analysis, as shown in Figure 2. The first step is to input the Origins and Destinations to build the network model. Buildings and facilities are simplified as nodes, which are then connected through roads, forming a pedestrian network. All analysis performed by UNA requires three key inputs: a network, along which movement is analyzed, trip Origins, and trip Destinations. The Origins and Destinations can optionally carry numeric attributes to give weight to the analysis [23]. Numeric attributes that indicate the number of residents in each building, which can be used to weigh accessibility or patronage estimates. Take the following community case, for instance: residential buildings were defined as the origins (starting points) with the number of the residents as the origin weight; public space or facilities were defined as the destinations (ending points) with the area or visitors' number as the destination weight. The second step is simulation by the key tool-Patronage Betweenness, which is the integration of Find Patronage and Betweenness. The result shows the pedestrian flows of the routes in the community. The pedestrian flows could be classified by different age groups and various destinations, such as outdoor space, service points, and commercials. The last step is improving the walking systems of the community on design by the above analysis.

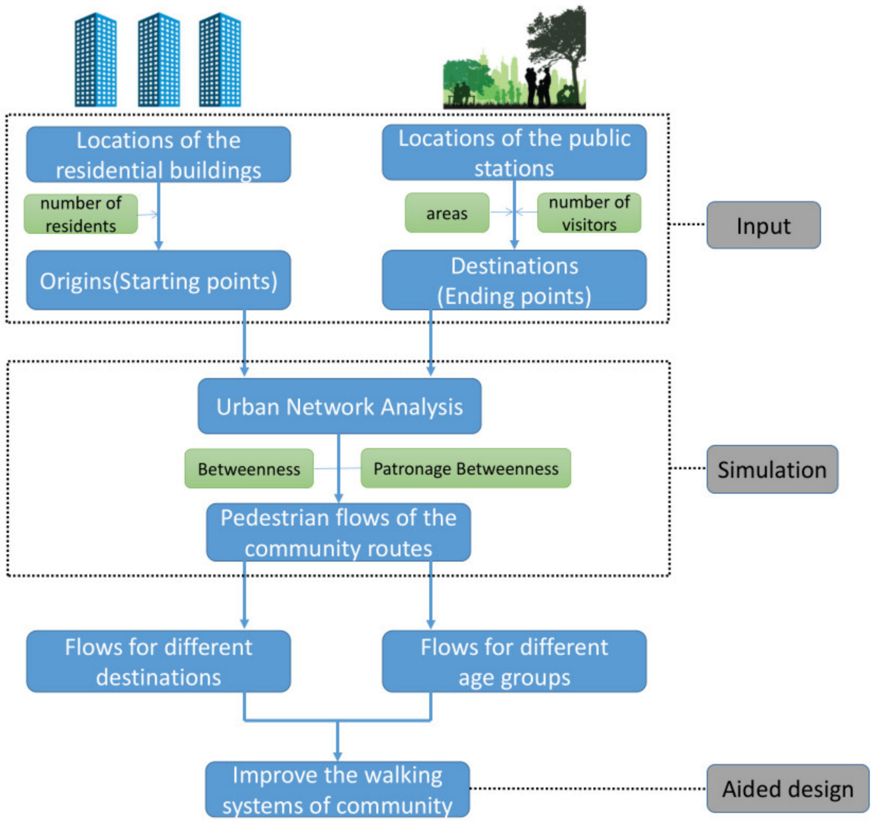


Figure 2. The flow chart of the methodology.

The UNA model is calculated as follows. The index of Betweenness is applied to visualize how many pedestrians may pass through certain network nodes so as to estimate the possible pedestrian traffic of the whole network. The Betweenness of a node in a network is defined as the share of the shortest path between several groups of start points and end points passing through a certain node, which is first defined by Freeman [46], and its mathematical definition is shown in Equation (1).

$$\text{Betweenness}[i]^{r,dr} = \sum\nolimits_{j,k\in G-\{i\},d[j,k]\,\le\, r.dr} \frac{n_{j,k[i]}}{n_{j,k}} \times W[j] \times \frac{1}{e^{\rho\times d[j,k]}} \quad (1)$$

In Equation (1), Betweenness $[i]^{r,dr}$ refers to the Betweenness value of the observation point i under search radius r and detour ratio dr; $n_{j,k[i]}$ refers to the number of shortest paths passing through point j between the starting point j and the ending point k; $n_{j,k}$ refers to the total number of shortest paths from *j* to *k*. While the measure of Betweenness is weighted, the starting point *j* will be attached with its own weight $W[j]$, that is, the starting point will release a weighted number of trips to its corresponding destination.

To calculate the traffic distribution from a specific starting point to an end point (weighting the starting point and the end point), it is possible to use the Patronage Betweenness analysis, which is the integration of Find Patronage and Betweenness. Through discrete selection method, it is feasible to simulate how pedestrians choose among multiple end points [47] so as to predict the passenger flow of space facilities (parks, shops, amusement places) on the network. The calculation principle is originated from David Huff's passenger flow model and the follow-up work of Eppli and Shilling. Sevtsuk and Kalvo improved the original Huff model to make it specific for urban design and planning practice [48]. The calculation theorem of Find Patronage is as follows:

$$C[J]\text{Patronage} = \sum_{i}^{\#DP} DP[i]Weight \times DP[i]Probability[j] \times \frac{1}{e^{\beta \times [i,j]}} \quad (2)$$

$$DP[i]Probability[j] = \frac{DP[i]Gravity[j]}{DP[i]Gravities} \quad (3)$$

$$DP[i]Gravities = \sum_{j}^{\#c} DP[i]Gravity[j] \quad (4)$$

$$DP[i]Gravity[j] = \frac{C[j]weight^{\alpha}}{e^{\beta \times dist[i,j]}} \quad (5)$$

In the above equations, *DP* stands for Demand Point (representing the starting point I), *C* stands for Center (representing the end point *j*), and $dist[i,j]$ refers to the distance from the starting point *i* to the end point j on the network.

$DP[i]Probability[j]$ in Equation (3) indicates the probability that a person at the starting point *i* will visit the end point *j*, which is the ratio of the Gravity accessibility from point *i* to the end point *j* and the sum of the Gravity accessibility from *i* to all end points (including *j*). The last item $\frac{1}{e^{\beta \times [i,j]}}$ in Equation (2) represents the "distance attenuation effect", which is used to estimate the actual passenger flow to each facilities. The purpose of this item is to make the passenger flow calculation closer to the reality, because not all the demand weights of the starting point can be assigned to the terminal facilities [47].

Since the principle and algorithms of UNA is a bit difficult to understand, a case study is introduced below to describe the detailed steps and possible output of the proposed UNA-based design method.

3. Case Study

3.1. Case Introduction and Simulation Settings

3.1.1. Case Introduction

This paper takes the communities around Dadong Street, Guangzhou, China as an example for displaying the UNA-based design procedure. The community researched is marked with a red circle in Figure 3. Via on-site investigation, the basic information of the community is listed as follows. This community covers an area of about 209,266 square meters, including 536 buildings (520 houses, four schools, five food markets, two pieces of land to be built, and a number of shops along the street). The residential housing area is about 754,450 square meters, with a population of 22,556. The community covers a relatively small area with a dense population (the plot ratio is 3.61), which has relatively good vitality and obvious stratification of population structure, as shown in Table 2. This case is suitable for adopting UNA analysis with an accurate result and for simulating the walking behaviors of the residents in age groups objectively.

Figure 3. 3D model of the studied community.

Table 2. Residential buildings and population distribution in the community.

Residential Building Area (m^2)	Number of Buildings	Population Groups	Proportion	Persons
≥10,000	11	0–14 years old	13.64%	2932
5000~10,000	34	15–59 years old	64.11%	13,796
1000~5000	154	≥60 years old	22.25%	4807
0~1000	321	Total	100%	22,556

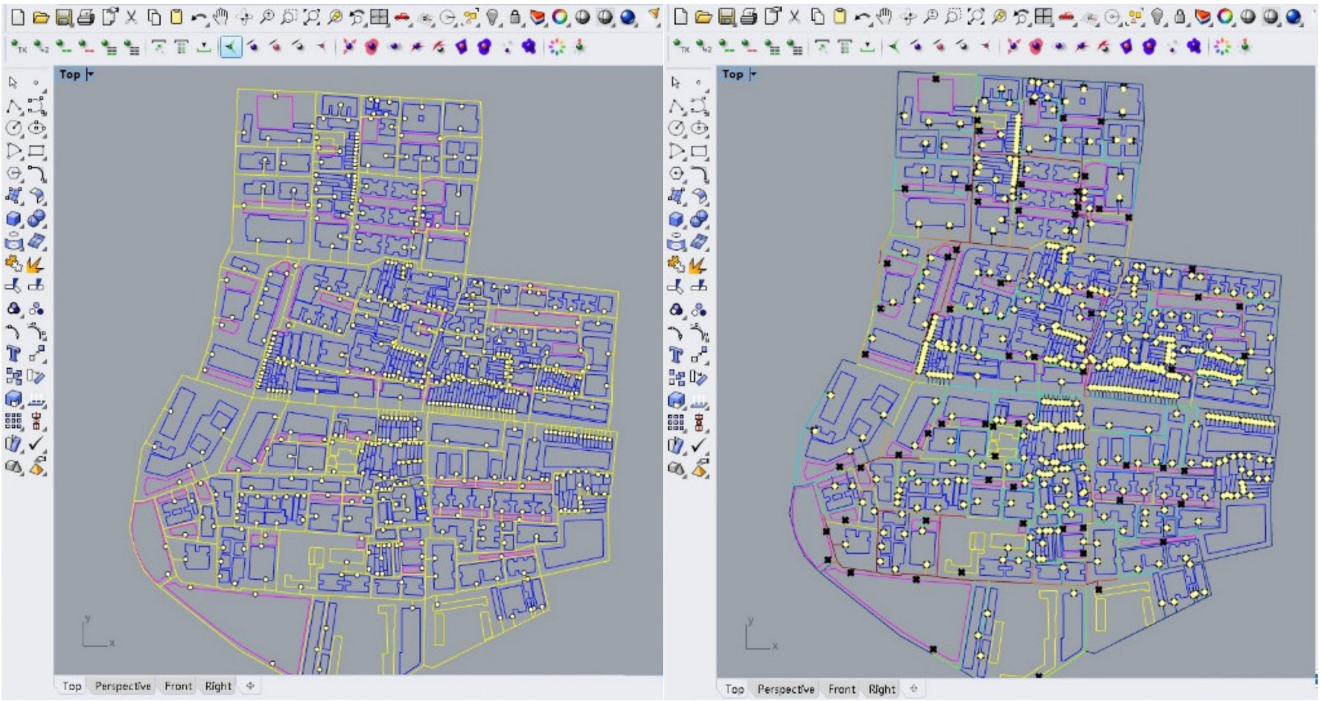
The detailed CAD drawings of the community were obtained from the urban planning department, including information such as the size and types of buildings and roads. The CAD drawings were first recognized and analyzed, roads that were not suitable for walking (such as elevated roads) were deleted, roads inside residential quarters were added, and 51 potential public activity areas were identified and located, as presented in Figure 4. The POI (Point of Interest) data of the community was collected via on-site survey and a total of 407 facilities related to residents' daily life were identified, including 160 commercial buildings, 99 living services, 109 restaurants, as well as 39 education and medical facilities. The detailed distribution of the facilities is presented in Figure 5. During the on-site survey, the actual pedestrian flow rates on the main routes were collected, which could be used to verify the simulation results.

Figure 4. The distribution of buildings and public areas.

Figure 5. The distribution of POI within the community.

3.1.2. Simulation Settings

The popular modeling software tool Rhino was applied for the pedestrian network simulation and analysis. The first step of pedestrian flow simulation in a community is to establish a pedestrian network model, which is to define the starting point and ending point of every possible pedestrian route and assign weight values to each point. Taking the pedestrian flow calculation of residential buildings to outdoor public activity area as an example. Each residential building was set as the starting point, to which a weight value was assigned. The public activity areas were set as the ending points. The residential building to public activity area network was then input into Rhino. A UNA-based Patronage Betweenness calculation was then conducted, aiming at a distribution map of the community's pedestrian flow rates, as presented in Figure 6.



(**a**) (**b**)

Figure 6. (**a**) UNA network model diagram of residents' walking route (yellow line indicates the path), (**b**) UNA network model diagram of residents' walking starting points (yellow dot indicates the starting point).

The determination of the parameters during the Patronage Betweenness calculation was shown as follows:

The weight value of the starting points (Origins Weight) could be calculated as the number of residents in specific buildings, representing the possible pedestrian flow rate, considering each resident would only go for a leisure walk once each day (actually some residents come out more than once each day, while some residents rarely do leisure walks: once each day is a widely accepted average number for a daily leisure walk) [49]. The weight value of the ending points (Destination Weight) is the size of the public activity area, representing the possible capacity of the area. α and β in Equation (2) represents the "distance attenuation effect", which is used to estimate the actual passenger flow to each facility as mentioned above, α is used to control the attraction effect of Destination Weight, and β is used to estimate the possibility of a specific destination. In this study, α was set to "1", indicating that during the simulation a specific destination would not be preset to any residents. The value of β is determined by the travel mode and destination type, In tropical areas such as Singapore, researchers have concluded that the β value is about

0.004 (in meters) [50]. Since the climate of Guangzhou is close to that in Singapore; thus, the 0.004 value is applied in this study.

The Detour Ratio indicates the ratio of the total length of a specific travel route to the shortest travel route. According to previous survey of walking route selection, people usually walk 15–20% more than the shortest route [51]. The purpose of residents' leisure activities is generally weaker than that of shopping or taking public transportation; thus, the detour ratio is determined as 1.2. Search radius is determined by the 5-minute walking range (which is widely used for evaluation of the accessibility of community) [51]. The walking speed of ordinary adults is calculated at 80 m/min [52], and the search radius is determined as 400 m.

3.2. Results and Discussion

According to different design and evaluation requirements, the UNA-based simulation could output different visualization results for discussion. Some of the most referred results were displayed as follows. It should be noted that the data presented below is just an example of some possible applications of the UNA-assisted design procedure.

3.2.1. The Pedestrian Flow from Residential Building to Public Activity Area

The simulation results for the pedestrian flows from residential buildings to public activity areas within the studied community are shown in Figure 7. The pedestrian flow rates difference is expressed in color. From Figure 7, it is clear that walking routes with high pedestrian flow rates are mostly public municipal roads that lead to certain public activity area, while the lanes inside residential quarters and alleys account for a relatively small proportion. The crowded routes appear to be connected to each other, with barely any buffer zones between, which means once a traffic congestion occurs, the scope of the impact will expand rapidly. The pedestrian flow rates of the routes located at intersections are significantly higher than those of the terminal paths.

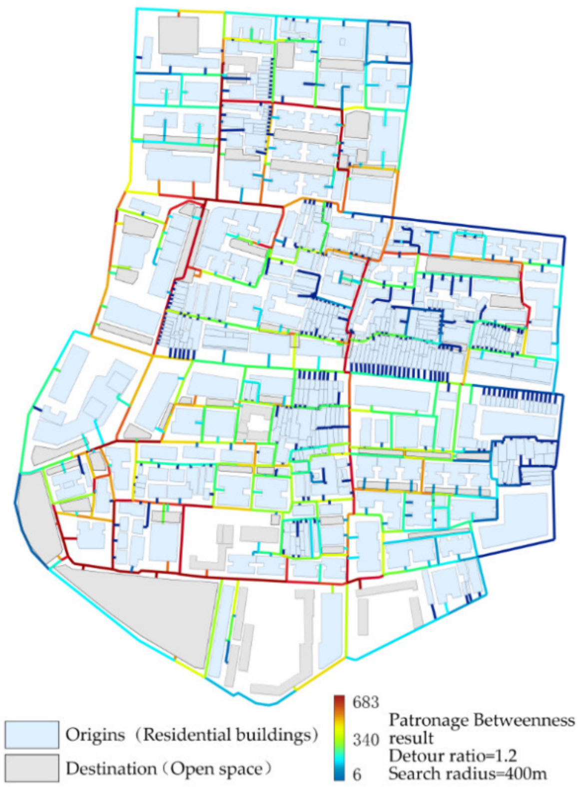


Figure 7. Simulation results of pedestrian flow distribution from residential buildings to public activity areas.

3.2.2. The Pedestrian Flow from Residential Buildings to Commercial Facilities

The simulation results for the pedestrian flows from residential buildings to commercial facilities within the studied community are shown in Figure 8. During the simulation, the Detour Ratio was set at 1.15, while the β value was set at 0.001. The pedestrian flow rates difference is expressed in color. Routes with a pedestrian flow rate of higher than 876 person/day (exactly 50% of the highest pedestrian flow rate within the community) were extracted, which could be defined as crowded routes [53], as shown in Figure 9. Comparing the simulation result in Figures 7 and 9, it is clear that several crowded routes to the public activity area and to commercial facilities overlapped, as shown in Figure 10.

Overlapping routes mean higher pedestrian flow rates, which is good news from the perspective of business prosperity, which could be an important reference for commercial site selection and property pricing. However, it should also be noticed that the daily user population of public activity area (mainly elderly and children) is different from the target population of commercial facilities (mainly young people). Overcrowded routes would affect the leisure experience of pedestrians, which reduces the walkability to destinations. During the urban planning of a healthy community, the distribution of public area and commercial facilities should be slightly differentiated. While forming a community center, different needs from different resident groups should also be taken into consideration.

Figure 8. Simulation result of pedestrian flow distribution from residential buildings to commercial facilities.

Figure 9. Distribution map of crowded routes from residential buildings to commercial facilities.

Figure 10. Distribution map of overlapping crowed routes from residential buildings to public activity area and to commercial facilities.

3.2.3. Pedestrian Flow Simulation against Different Age Groups

Residents' walking speed and common destination are significantly affected by the age groups. It is possible for UNA-based pedestrian network simulation to analyze the difference in pedestrian choice caused by living habits and age difference. The studied community in this paper includes a total population of 21,556, of which the population aged 0–14 accounts for 13.64%, about 2932 people, the population aged 15–59 accounts for 64.11%, about 13,796 people, while the population aged 60 and above accounts for 22.25%, about 4807 people. According to the literature [54], the average walking speed of children aged 9 and below is 37.8 m/min. The average walking speed of people aged 20 to 60 is about 84 m/min, and the average walking speed of people aged 60 and above is around 64 m/min. Based on the analysis of the walking distance sensitivity evaluation data, the walking state is "comfortable and accessible" within 5 min, which is chosen as the search radius of residents' leisure walking in this case [55,56] (they arrive at a public space or POI within 5 min, and then go to the next place after completing the activity), that is, the search radius of residents aged 0–14 is 189 m, that of residents aged 15–59 is 420 m, and that of residents aged 60 and above is 320 m, as shown in Table 3.

Table 3. UNA simulation parameters and destination settings of different age groups.

Age Groups	Detour Ratio	Search Radius	Destination Type
0–14 years old	1.5	189 m	Culture, science, and education facilities
15–59 years old	1.2	320 m	Catering, shopping, and life service facilities
≥60 years old	1.2	420 m	Health care, life service facilities

(Note: Detour Ratio indicates the ratio of the total length of a specific travel route to the shortest travel route).

Separate simulation cases were conducted to analyze the pedestrian route choices of different age groups. The population of children (0–14 years old), young and middle-aged people (15–59 years old), as well as elderly people (60 years old and above) were set as the starting point weight value, while the corresponding commercial facilities and public activity areas were set as the ending point. Among them, the common destination for children includes culture, science, and education facilities, while those for young and middle-aged people include catering, shopping, and life service facilities, and those for elderly people include health care and life service facilities. The pedestrian network models of three groups of people were constructed, respectively, and the results are presented as follows:

- Simulation of pedestrian route choice of children (0–14 years old).
- Simulation parameters: Detroit ratio = 1.5; Search radius = 189 m; β = 0.004 [45,50].

Characteristics: The crowded routes are concentrated near large public activity area.

The simulation result for the route choice for children are displayed in Figure 11. Previous research indicated that pedestrian space, pedestrian flow rate, as well as pedestrian speed could be considered as the main parameters for the evaluation of route performance. While the pedestrian area for each individual is larger than 3.7 m^2, pedestrians have enough space to freely adjust walking speed, bypass, and avoid conflicts with other pedestrians [57]. In this study, it is assumed that each resident would only go for a leisure walk once each day, mostly in the morning or evening after dinner. It is necessary to calculate the instantaneous flow rate during these periods (if the pedestrian area meets the requirement during peak period, it would naturally meet the requirement during other periods). According to on-site survey, most of the roads within the community are people–vehicle mixed; an instantaneous pedestrian flow rate of 0.67 people was selected as a comfortable pedestrian flow rate [58]. If the pedestrian flow rate exceeds this value, it is considered crowded. Potential crowded routes for children were marked in Figure 11b. Obviously, most children tend to gather at the large public activity area. Children's daily schedules are relatively consistent in particular, which further increases the possibility of congestion during some specific periods. While designing public activity area, it is a better choice to distribute public activity areas evenly across the community. Planning main roads with high traffic around public area should be avoided.

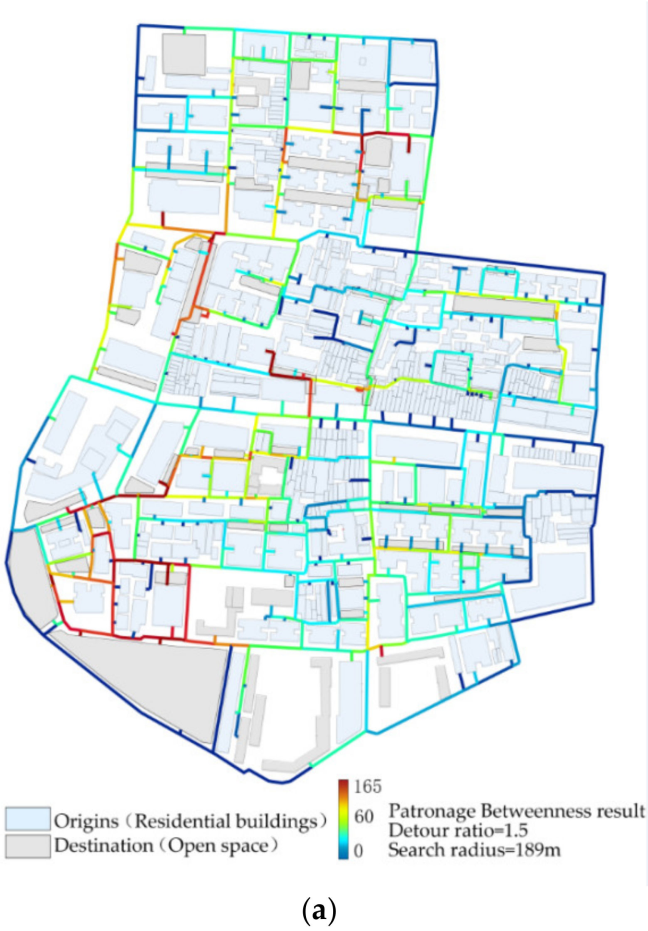


Figure 11. (**a**) Pedestrian flow rates of the children; (**b**) crowded pedestrian route for the children.

- Simulation of pedestrian route choice of the young and middle-aged people (15–59 years old).
- Simulation parameters: Detroit ratio = 1.2; Search radius = 420 m; β = 0.004 [45,50].

Characteristics: The pedestrian flow rate distribution among different routes is relatively uniform.

Similar to the calculation method of children's path flow, calculation on the instantaneous pedestrian flow was conducted. The routes with an instantaneous pedestrian flow rate of higher than 0.67 people were extracted, as shown in Figure 12. The marked routes in Figure 12b could be considered as a potential crowded area for young and middle-aged people. It is clear from the simulation result that a relatively uniform pedestrian flow distribution could be observed, while only a few of the routes appear concentrated, which are directly connected to a large public area. From the simulation result, it can be concluded that due to the relatively higher athletic ability, the search radius of this age group is significantly wider, which leads to a greater flexibility while choosing the routes. For commercial and life service facilities focus on this age group, such as catering and shopping facilities, the scope of location choice could be appropriately enlarged. It is even possible to design facilities attractive to this group of people along routes with a low pedestrian flow rate so as to enhance the prosperity of the whole community.

Figure 12. (**a**) Pedestrian flow rates of the young and middle-aged people; (**b**) crowded pedestrian routes for the young and middle-aged people.

- Simulation of pedestrian route choice of the elderly people (≥60 years old).
- Simulation parameters: Detroit ratio = 1.2; Search radius = 320 m; β = 0.004.

Characteristics: The crowded routes are distributed near the public space.

The simulation result for the route choice for elderly people are displayed in Figure 13a. The routes with an instantaneous pedestrian flow rate of higher than 0.67 people were extracted, as shown in Figure 13b. Compared to the simulation result displayed in Figures 11 and 12, the pedestrian flow rate among the whole network for this age group is more uniform than that for children. However, in terms of the scope of activities, most elderly people prefer large public spaces and main roads, community centers especially. From the simulation result, it is clear that, while planning living and public service facilities towards elderly people, the location should be selected at the fringe of the community center and directly connected to the main roads.

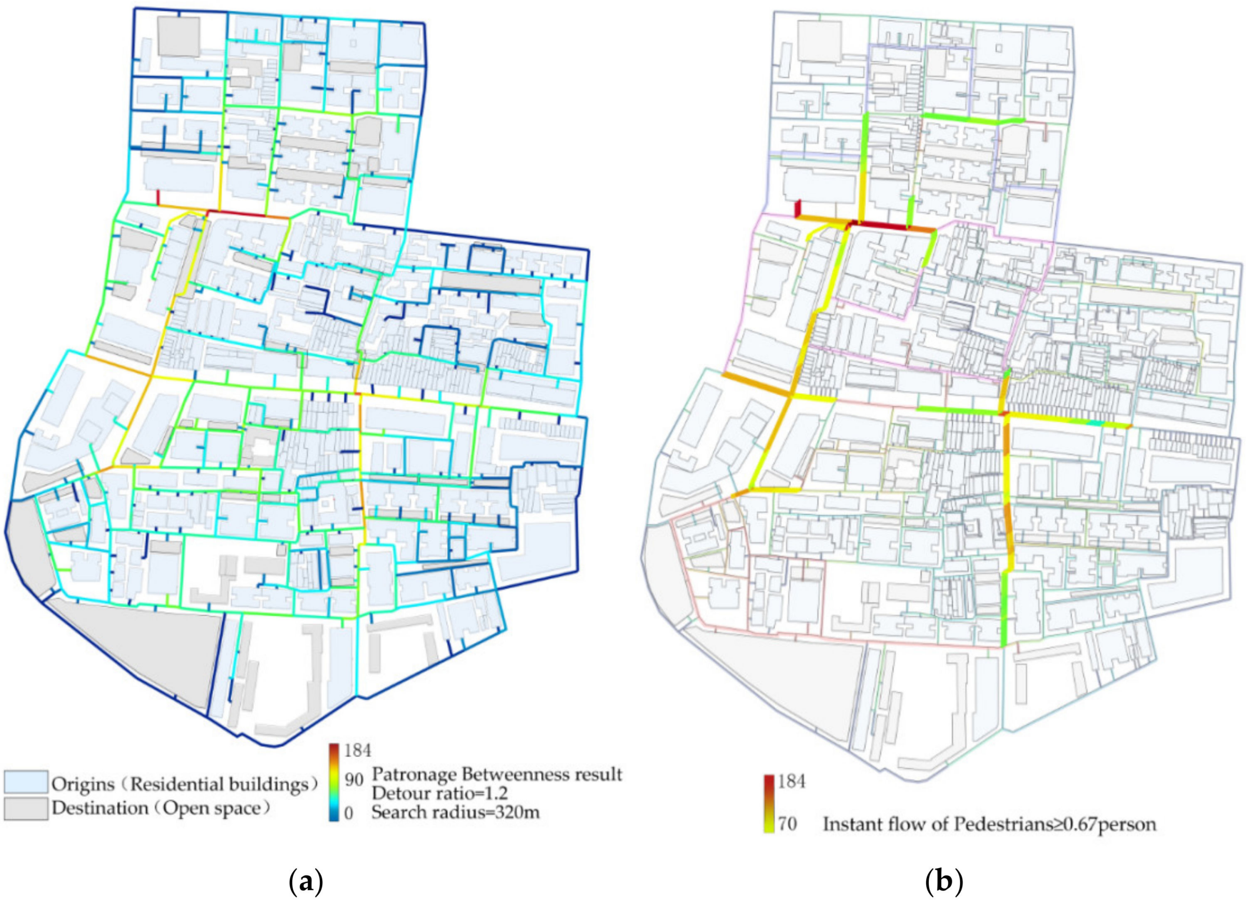


Figure 13. (**a**) Pedestrian flow rates of the elderly people; (**b**) crowded pedestrian route for the elderly people.

4. Conclusions and Future Work

This paper puts forward a community-scale pedestrian network design method based on UNA, which is able to build up pedestrian network based on residents' destination and residents' age, and simulates the corresponding pedestrian flows. The proposed method combines quantitative and visualization analysis, which is able to objectively reflect the travel characteristics of community residents and predicts residents' walking activities within a community based on the community living density and road and public space distribution. Compared with existing research, the proposed method could achieve more detailed results, which could serve as a solid reference for the retrofitting and renovation design of old communities and endows the quantitative analysis method of urban space with practical significance. The optimal design conclusion of the community around Donghua West Road in Guangzhou is as follows:

Based on the distribution of resident, roads, and public spaces, the leisure pedestrian network connecting public spaces in the community could be constructed. The maximum flow path selected by a quantitative method as well as the obtained pedestrian flow path can be used as the reference for long-term urban planning and design, such as optimizing the surrounding public facilities according to the path, making the public space and service facilities better match with the resident density, optimizing the configuration of community public service system, and providing efficient strategies for the planning of the 15-minute life circle in the community. For convenience facilities serving special groups, such as canteens for the elderly, childcare institutions, etc., it is more favorable to combine them with walking paths.

It can be seen from the simulation results of walking distance by different ages that the distribution uniformity of the overall pedestrian flow in the community is ranked as follows:

young people > old people > children. The space for activities for the elderly and children as well as for public facilities can be relatively concentrated, close to the densely populated areas, so as to shorten the walking distance of the elderly and children. Youth activity facilities can be distributed relatively decentralized so as to improve the utilization rate of facilities. During the optimization of the pedestrian network, the densely populated areas of the elderly and children should be focused. Figure 14 shows the pedestrian-gathered routes of the elderly, young, and middle-aged people and children; these routes should be given priority to be planned and constructed when funds are short. It provides quantitative support for the renewal planning of the case community.

Figure 14. Pedestrian flow gathered routes of the elderly, young, and middle-aged people and children.

There exist some limitations for the proposed method, which would be improved in future work. Due to the limitation of data collection, the community scope of the case study is quite small, which affects the accuracy of the result to some extent, especially for the marginal area. Urban network analysis is based on residential density and road network connection, while in this paper the grades of community roads are not rated. Some pedestrian-intensive paths measured may not be optimized due to objective factors such as too-narrow road width, etc., which need to be further evaluated according to on-site measurement.

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