Optimizing bus stop locations in Wuhan, China

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by

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Abstract

Public bus is the major transport mode in Wuhan, China. Irrational distribution of existing bus stops leads to a low public bus service quality. For example, redundant distribution of bus stops within short distances in most central areas elongates unnecessary bus stopping and consequently passengers waiting time, thus spending unnecessary public resources. Furthermore, bus stop inadequacy also exists especially in urban outskirts that results in a low walking accessibility, attracting less public traffic demands and causes social inequity as such.

The objective of this research is to optimize locations of bus stops in Wuhan using a GIS based platform to reach a trade-off distribution of bus stops that not only assures appropriate walking accessibility and maintaining adequate service coverage, but also minimize the operating costs for the operator, i.e. reducing bus stop redundancy. Furthermore, improving the bus system efficiency, in terms of selection of key bus stops with high spatial importance, i.e. connectivity and accessibility, is also needed.

Bus stop optimization can be implemented by using service location models, i.e. expansion model and relocation models, in FLOWMAP software. The expansion model is first utilized to distribute minimal number of bus stops that can satisfy the basic transport demand within defined service range. Secondly, the relocation model is applied to improve system efficiency by minimizing average bus stop distance along road networks or to enhance system equity by minimizing longest stop distance.

Meanwhile, a random walking algorithm is utilized to find spatial important places. It can be tested that the random walking values of road nodes are in positive proportion to road connectivity and capacity.

To achieve the number and location of optimized bus stops, candidate bus stops have first been generated using Network Analysis in ArcGIS. Subsequently, key bus stops are selected based on the random walking value of candidate bus stops by utilizing the service location model outcomes. Finally, normal bus stops are selected by again utilizing a service location model in FLOWMAP based on public transport demand.

The evaluation of optimized bus stops indicates that redundant stops in city centers are reduced; service coverage is enlarged by distributing fewer bus stops. Meanwhile, the serviced demand and walking accessibility are maintained at an appropriate level. The operational costs for these reduced bus stops will be saved accordingly, while competition level of the bus system is improved.

Keywords:
Bus stops optimization, GIS, Random walking; Flowmap

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1. Introduction

1.1. Research background

As a consequence of stable economic growth and rapid urbanization over the past 30 years, China is confronted with a series of severe traffic problems. High population density and fast urban growth resulted in a dramatic increase of traffic demand. For example, the number of registered vehicles increased exponentially from around 1 million in 1994 to 5 million in 2001, and jumped to a staggering 16 million in 2004 (Transport Sector Unit Infrastructure Department 2006), as depicted in Figure 1-1. Meanwhile, the suburbanization of large Chinese cities causes longer distances of daily trips which require higher levels of motorized travel and thus more traffic demand (Cervero and Day 2008). Therefore, a series of traffic problems have been generated consequently (Figure 1-2). For instance, China is confronted by some global environmental problems as Green House Gas Effect and Air Pollutions. At the national level, more travelling costs are aroused from high fuel prices and large traffic demands. Furthermore, the mortality of traffic accidents is growing, traffic congestion and motor vehicle pollution have emerged and become common in most large cities in China(Transport Sector Unit Infrastructure Department 2006)

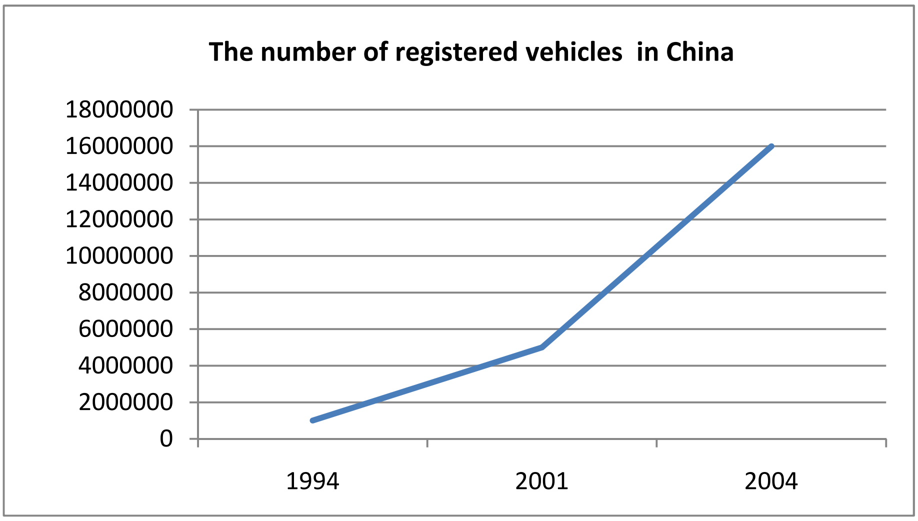


Figure 1-1 The number of registered vehicles in China
(Cited from (Transport Sector Unit Infrastructure Department 2006))

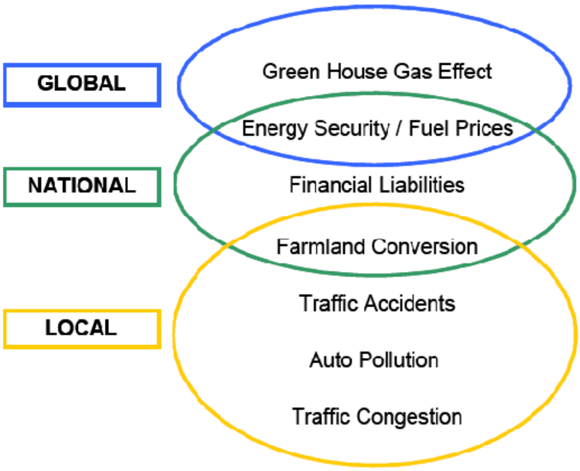


Figure 1-2 The urban transport problems in China
(Cited from (Transport Sector Unit Infrastructure Department 2006))

To counter this problem, public transport systems provide effective and efficient solutions. The major function of urban public transport is to facilitate inhabitants' commuting (Feng Shumin and Chen Hongren 2005), i.e. to provide accessibility. Although, more public transport facilities can assure adequate walking distances thus high accessibility, the operating costs are increased accordingly. Furthermore, redundant facilities can impact system efficiency. For instance, redundant bus stops cause more bus stopping time and hampering bus travel speed that elongates the total travel time. Therefore, an essential problem has emerged that is how to improve urban public transport systems, by enhancing the public transit capacity and optimize the distribution of public transport facilities, such as bus stops. Chien and Zhaoqiong Qin claimed that the performance of a transit system can be significantly improved if the spacing of bus stops are optimized (Chien and Zhaoqiong Qin 2004).

1.2. Research problem

The study area is Wuhan, a typical metropolis in central China characterized by its high population density and large urban scale. Although, public bus service is the major urban passenger transit mode in Wuhan (Figure 1-3), inhabitants are still suffering a set of serious transport problems such as air pollution, traffic congestion and low quality of public transport services.

The public bus service is operating at a low quality, i.e. characterized by unpunctual bus dispatching, insufficient capacities of public buses that is causing very crowded buses, long waiting and long travel times, as well as a low proportion of public bus utilization.

One of the reasons might be bus stop redundancy, which leads to low bus service quality. From the viewpoint of users, bus stop redundancy may supply high accessibility by shortening walking distances. However, superabundant bus stops require more operating cost. Furthermore, given the fact that buses halt at each stop waiting for passengers boarding, redundant bus stops will aggregate the total bus travel time thus declining the system efficiency.

Another reason is that, although the stop redundancy exists, there are some other urban areas, especially in urban skirts, that are distributed with inadequate bus stops. Although, less number of bus stops can be cut off the maintaining cost for the operators, insufficient bus stop locations result in small bus service coverage and low walking accessibility that fails in attracting more potential bus users and impairs social equity.

Rational locations of bus stops would provide a trade-off that not only assures appropriate walking accessibility and maintaining adequate service coverage, but also minimize the operating costs for the operator, i.e. reducing bus stop redundancy.

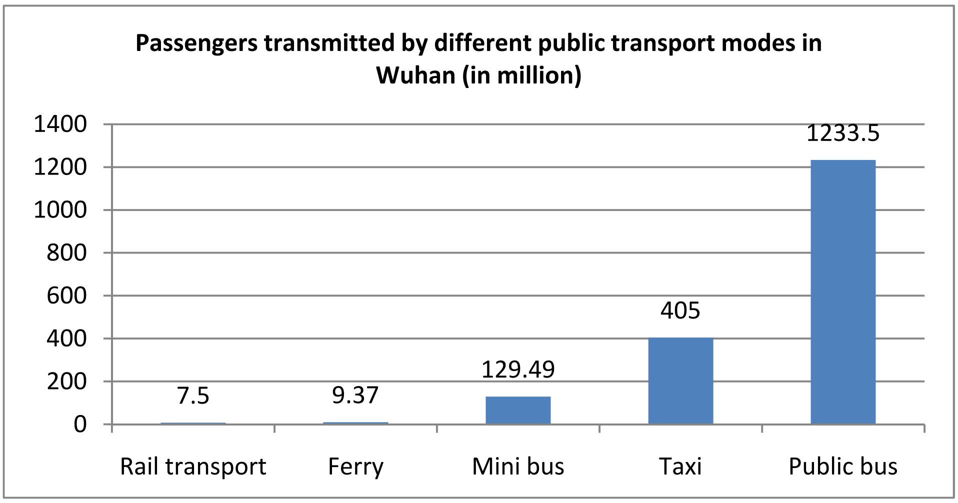


Figure 1-3 Passengers transmitted by different public transport modes in Wuhan (Cited from(WTPI 2007))

1. Bus stop redundancy leads to low bus service quality.

Bus stop distances, according with the national standards (MOHURD 1995), should be more than 400 meters and less than 600 meters to cater for reasonable walking accessibility. Meanwhile, Murray suggested that the stop distance should range from 200 to 600 meters (Murray 2003). Therefore, bus stop redundancy can be defined as those stops of which the distance to a nearest other stop (on the same line) is less than 200 meters. Unfortunately, a quick analysis indicates that for Wuhan less than 30% stops (red bars in Figure 1-4) are located appropriately fitting in with national standards. Furthermore, in Wuhan's central areas, the bus stop distribution appears to show a Poisson distribution, meaning that the bus stops in central areas are clustered within even smaller distances. For example, the nearest neighbor distance function $G(r)$ which is the distribution function of the distance from a point to its nearest neighbor, is utilized to test the stop distribution. The function $G(r)$ can be interpreted as the conditional distribution of the remainder of X given a point at location a (Baddeley 2008). It can be inferred that the smallest internal distance between each stop is nearly 80 meters (Figure 1-5(G function)). Bus stop redundancy leads to unnecessary waiting and travel time for passengers (Murray 2003), and less competitive routes for operators.

2. Inadequate bus stop locations result in small bus service coverage and low walking accessibility.

It is recommended that an appropriate walking distance from original location to the nearest bus stop should be around 400 meters (Murray 2003). Therefore, F function is applied to evaluate walking accessibility of existing bus stops in Wuhan. For each $a \in A$, let $\rho(a, X)$ be the distance from a to the nearest point. Then the empty space function (F function) of X for $r \geq 0$ equals the probability of observing at least one point closer than r to the arbitrary point a (Baddeley 2008). By calculating point patterns of bus stop locations in central areas, the F function (Figure 1-5(F function)) indicates that one inhabitant living in central areas has to walk at least 600 meters in linear distance to reach one bus stop. It is necessary to optimize the bus stop locations in Wuhan to enlarge the bus service coverage and enhance the walking accessibility.

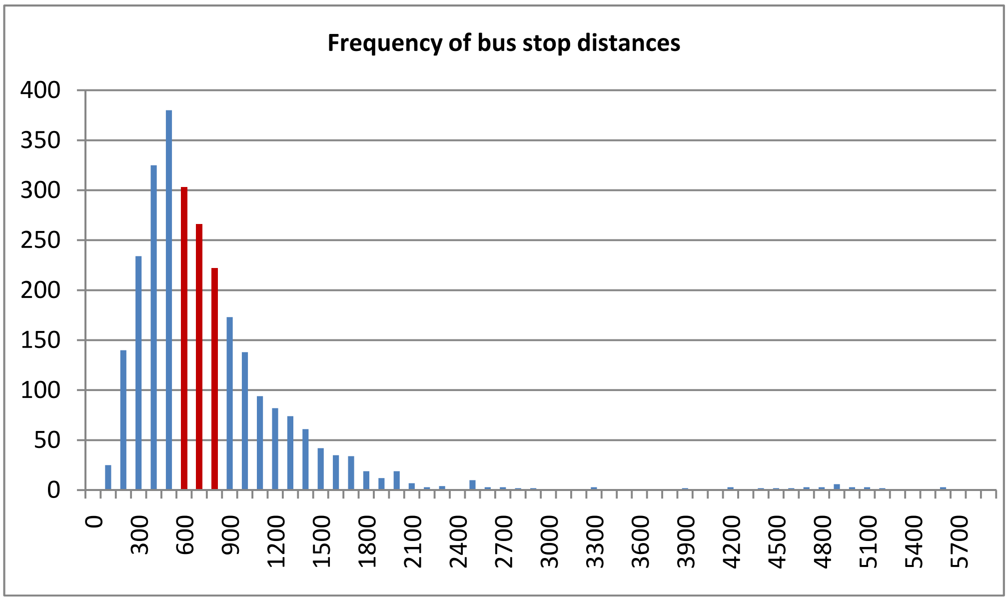
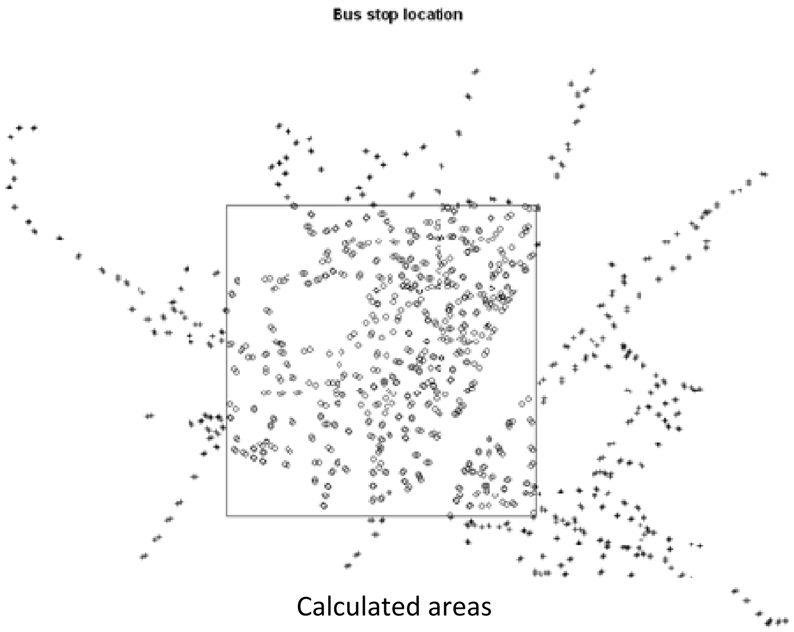
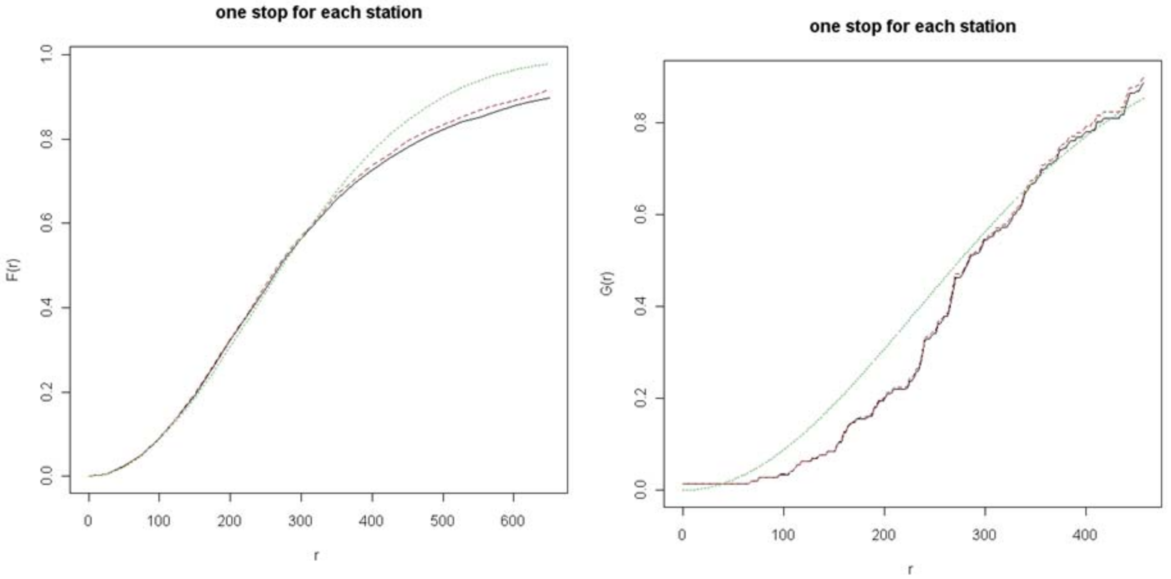


Figure 1-4 Frequency of bus stop distances



Calculated areas



F function

G function

Figure 1-5 Point pattern calculation of existing bus stops

3. There is not a specific GIS based method for optimizing bus stop locations in Wuhan public transport planning.

In accordance with Chinese government policy (MOHURD 2004), local authorities must make specific public transport plans before the implementation of any urban planning. A series of national standards (MOHURD 1995) have been published to regulate the public bus system with respect to route length, route density, average transfer coefficient and net transit capacity. In conventional planning, planners analyze the existing data and only make adjustment based on political requirements and subjective experiences (Deng Ailong and Wang Qiupin 2004). Without precise calculation of traffic demand and service coverage, such methods lack practical utility. It is sensible to make a specific GIS based method for optimizing bus stop locations in Wuhan. Lao also indicated that the ability of geographic information systems (GIS) to integrate digital maps and spatial analytical methods has made it a powerful tool for transportation planning (Lao Yong and Liu Lin 2009), thus also for transit planning purposes.

In sum, irrational distribution of existing bus stops leads to a low public bus service quality. On the one hand, bus stop redundancy is aroused from superabundant distribution of bus stops within small distances in most central areas. It elongates unnecessary buses stopping and passengers waiting time, and costs unnecessary public resources. On the other hand, bus stop inadequacy also exists especially in urban outskirts. Insufficient bus stop locations results in a low walking accessibility, attracts less public traffic demands and may cause social inequity. It is reasonable to optimize bus stop locations to reduce stop redundancy and enlarge its service coverage.

1.3. Research objectives

The objective of this research is to optimize bus stop locations in Wuhan, China. Four sub-objectives have been arranged subsequently to achieve the main goal step by step.

Main objective:

- **To optimize bus stop locations using a GIS based platform for bus users in Wuhan.**

The objective of this research is to optimize the locations of bus stop in Wuhan to reach a trade-off that reduce redundant bus stops in central areas and enlarge service coverage in urban skirts by maintaining sufficient served traffic demand, rational walking accessibility and adequate stop number.

Sub-objectives:

- **To investigate problems of current bus stop locations.**

By investigating the problem of current bus stop locations from a customer (bus user) point of view and based on a literature review, the associated factors for candidate stops selection can be determined and data collection requirement can be made explicit.

- **To generate candidate bus stops.**

Based on previous associated factors, a method will be developed to propose candidate stops that will be prepared for further classification.

- **To select and implement a GIS based computational method for classifying candidate bus stops**

The candidate stops will be classified depending on their spatial importance which can be computed through a random walking algorithm(Li Zhuoran, Zhao Shichen et al. 2009). The values calculated in random walking algorithm may indicate the position potential values that reflect importance of spatial positions considering the road capacity and lengths of daily trips. The candidate bus stops with high spatial importance will be firstly obtained in the belief that the bus system comprised with high connective and accessible stops will perform more efficiently.

- **To select an optimization method for spatial location optimization.**

The classified candidate stops will be further optimized to finally reach the goals that can reduce the bus stop redundancy and enlarge its service areas. The FLOWMAP software devised by Utrecht University supplies an efficiency model for performing this analysis (J.Breukelman, G.Brink et al. 2009). The output will be evaluated subsequently.

1.4. Research questions

For each sub-objective, several questions have been put forward to guide the research. These questions will be answered accordingly in this thesis. Consequently, a conceptual framework is introduced to illustrate how those questions have been organized to achieve the specific research objectives.

1.4.1. Research questions

- To investigate problems of current bus stop locations.

Question1: What factors should be considered when selecting bus stops?

- To collect data for this research.

Question2: What data is required for candidate bus stops generation?

- To generate candidate bus stops.

Question3: How to perform the spatial selection with respect to the determined factors?

- To select and implement a computation method for classifying candidate bus stops

Question4: How to operationalize the random walking model?

- To determine the goals and constraints of spatial optimization.

Question5: What indicators can be set as goal for optimization?

- To select and implement a computation method for spatial location optimization

Question6: How to utilize the location models in FLOWMAP?

- To testify whether the improvements are achieved by stop optimization?

Question7: How to evaluate the optimized bus stop locations?

1.4.2. Conceptual framework

According to the research questions, six research procedures have been constructed (Figure 1-6). The content of each procedure is described as follows:

- **Investigation of current problem**

Data requirement for field work can be obtained in this procedure. Associated factors can be determined by literature review and analysis on existing data. Such required factors will be useful for deciding the content field work.

- **Field work and data integration**

Considering the influence of new subway construction, existing data needed to be updated for candidate stops generation. Latest obtained data will be integrated with existing data.

- **Candidate stops generation**

Methodology for selecting candidate stops will be derived from literature review. Locations that are potentially to be bus stops will be selected as candidates. After data operation, the candidate stops will be obtained for further classification.

- **Candidate stops classification**

Candidate stops classification is done based on random walking algorithm. They will be classified according to their spatial importance. The places with high spatial importance will be firstly obtained in the belief that the bus system comprised with high connective and accessible stops will perform more efficiently.

- **Stops optimization**

Optimization goal and constraints will be determined from a literature review. The position potential value calculated by random walking and public traffic demand are set as the weight for optimization. Classified candidate stops will be optimized using the location allocation optimization model in FLOWMAP. A set of bus stops with adequate stop distances, appropriate walking accessibility and sufficient service coverage will be obtained finally.

- **Evaluation**

Evaluation criteria and a method will be obtained from literature review as well. The comparison will be performed between optimized bus stops and existing bus stops by evaluating the output with respect to service coverage, served demand and walking accessibility.

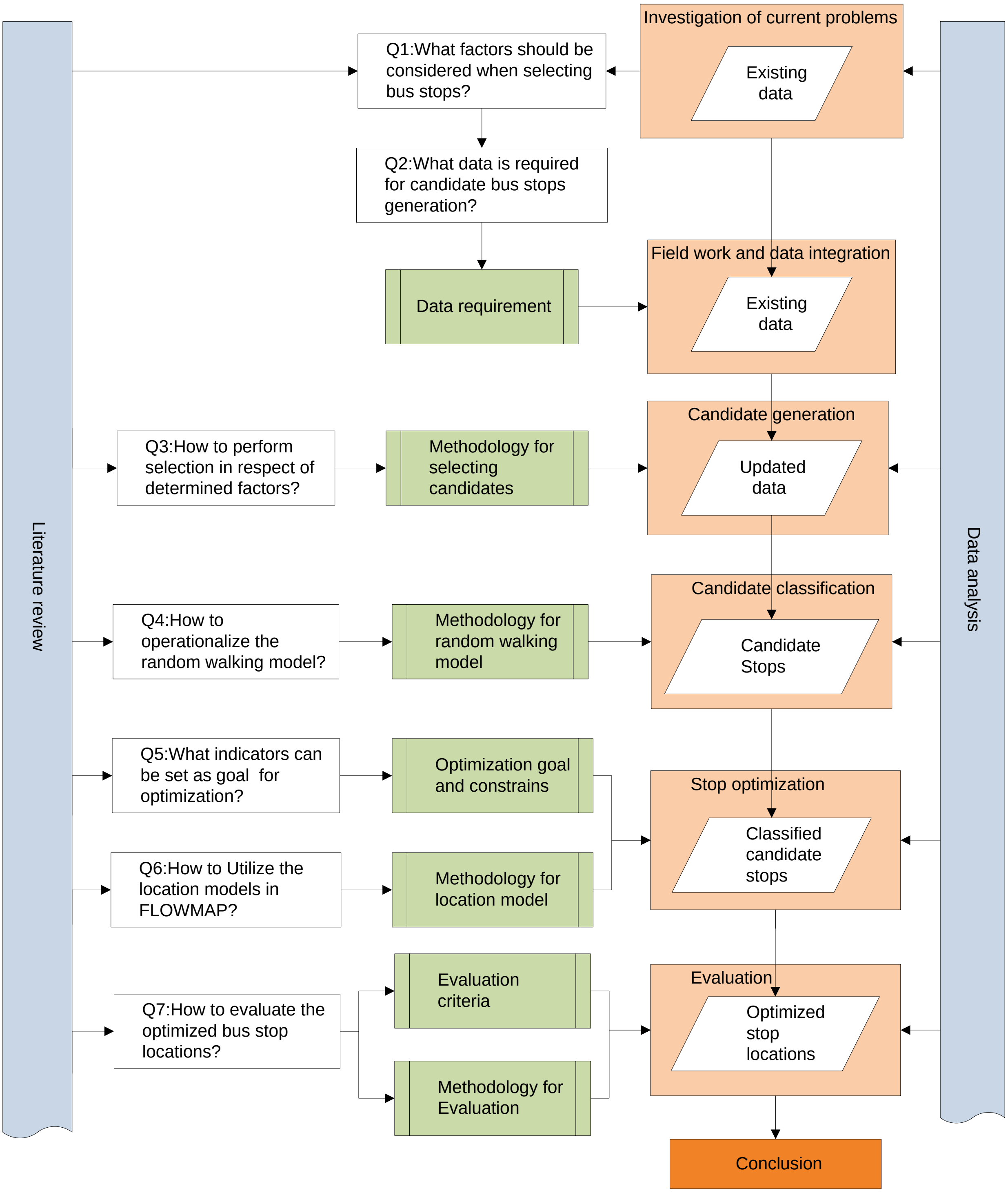


Figure 1-6 Conceptual framework

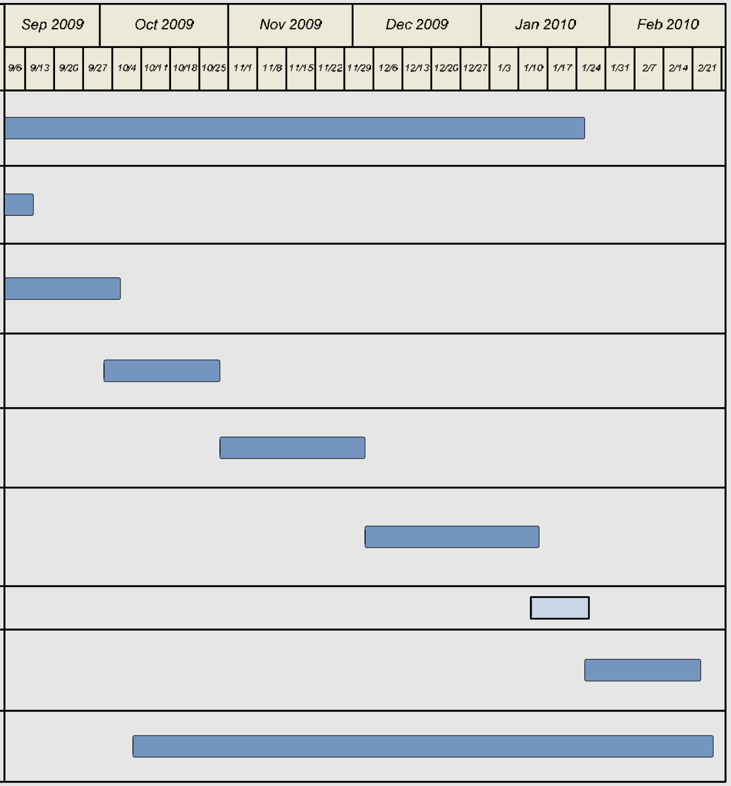
1.5. Research design

1.5.1. Research schedule

Research schedule is presented in Table 1-1.

Table 1-1 Research schedule

ID	*Task Name*	*Description*	*Start*	*Finish*	*Duration*
1	Literature Review	To review and classify existing optimization methods Determining the required data	2009-9-8	2010-1-25	20w
2	Investigation of current problems	To generate associated facts for stop locating To specific data requirement	2009-9-1	2009-9-14	2w
3	Field work and data integration	To update current data set including bus stop locations, road network and subway stations.	2009-9-1	2009-10-5	5w
4	Candidate generation	To design methodology for selecting candidates To generate stop candidate	2009-10-2	2009-10-29	4w
5	Candidate classification	To design methodology for random walking calculation To generate classified candidate	2009-10-30	2009-12-3	5w
6	Stop optimization	To define optimization goal and constrains To utilize location models in FLOWMAP To generate optimized stop location	2009-12-4	2010-1-14	6w
7	Spring festival	Chinese holiday	2010-1-13	2010-1-26	2w
8	Evaluation	To identify evaluation criteria To design methodology for evaluation To evaluate optimized bus stop	2010-1-26	2010-2-22	4w
9	Writing thesis	To document all important progress and results. To summarize the optimization and make discussion	2009-10-9	2010-2-25	20w



1.5.2. Field work plan

Current data sets available contain data on the road network, bus stop locations, population distribution and land use patterns. To improve urban traffic efficiency, the local government is constructing a series of new transport facilities in terms of overpasses and subways. Those transport constructions have changed some spatial locations of bus stop and road levels. Therefore, the field work is needed to update the current data set including bus stop locations, the road network attribution and subway stations. According to the official construction plan and combining field observation, the information of location change will be recorded in the existing data set. The time schedule is arranged as Table 1-2.

Table 1-2 Field work schedule

Objective	Date type	District	Start Day	End Day
update bus stop location	point	Wuchang	01-09-2009	04-09-2009
update bus stop location	point	Hanyang	05-09-2009	08-09-2009
update bus stop location	point	Hankou	09-09-2009	12-09-2009
subway station distribution	point	Wuchang, Hanyang	13-09-2009	16-09-2009
subway station distribution	point	Hankou	17-09-2009	20-09-2009
update road network	polyline	Wuchang, Hanyang	21-09-2009	24-09-2009
update road network	polyline	Hankou	25-09-2009	28-09-2009
data integration.			29-09-2009	05-10-2009

1.6. Structure of this thesis

This thesis is structured into 8 chapters as following:

Chapter 1: Introduction

This chapter addresses the research objective that a set of appropriate bus stop locations will be achieved to reduce stop redundancy and enlarge service coverage. The research problems, questions and designs have also been described accordingly.

Chapter 2: Literature review

General reviews of previous researches on public transport optimization are summarized in this chapter. Among those, FLOWMAP software which can obtain the optimization objective easily is introduced. Considering the importance of realizing the spatial structure property in transport network planning, two methods of investigation the spatial importance of a given road networks, i.e. Space syntax and Random Walking Algorithm, are described as well.

Chapter 3: Background of study area

A brief description of Wuhan city is given in this chapter. Subsequently, the characteristics of Wuhan traffic operation are also discussed. In addition, some problems of utilization of public transport system are concluded.

Chapter 4: Methodology and data collection

This chapter mainly illustrates the content of collected data. Road networks, population distribution, land use pattern and key transport facilities in Wuhan are collected and integrated completely. After that, the methodology of optimizing bus stop locations are described in four specific steps, namely candidate stops generation, candidate stops classification, stop optimization and evaluation.

Chapter 5: Random walking calculation

Random walking calculation is described in this chapter. The algorithm is displayed in details, and some consequent assumptions are also addressed. The random walking values of candidate bus stops can indicate the importance of connectivity and capacity of road networks, and will be set as weight for further optimization to select key bus stops.

Chapter 6: Optimization of bus stop locations in FLOWMAP

This chapter focuses on bus stop optimization processes in FLOWMAP. Three kinds of model combinations with two kinds of services ranges are operated to obtain an optimized bus stop distribution. In addition, the comparisons of nearest distances of optimized results in all cases are performed. It can be concluded that more bus stops are required in Expansion model when the service range becomes smaller. Relocation models can concentrate the stop distances to expected values. Finally, the outputs which are optimized by Expansion model with 800 meters range combining with Relocation model of minimal average distances are selected for further evaluation.

Chapter 7: Evaluation and discussion

To testify whether the improvements are achieved by above optimization, the valid service coverage, walking accessibility and served demands are assessed in this chapter. It can be concluded that after stop location optimization, redundant stops in city canters are reduced; service coverage in urban skirts is enlarged. In addition, the serviced demands and walking accessibility are maintained at an adequate level by distributing fewer bus stops. The operation costs can be saved accordingly. However, due to the limited research time and parts of unavailable data, some deficiencies of this research exist and have been discussed.

Chapter 8: Conclusion

The research questions are answered according with the achievements of this research in chapter 8. Moreover, some recommendations are also addressed.

2. Literature review

2.1. Advanteges of utilizing public bus system

Public bus system plays a significant role in urban traffic system and offers economical and social advantages. First of all, compared with private vehicles, fewer resources like motor vehicles, road capacities and monetary investments are required to serve same amount of passengers by utilizing public bus (Figure 2-1). Furthermore, as fewer vehicles are driving on roads in public bus system, severe environmental problems can be avoided and traffic congestions can be alleviated. Finally, unlike other kinds of public transport modes, i.e. subway, public bus can offer a more flexible services and cost relative lower social resources that can benefit the masses and enhance social equity.

Figure 2-1 Required vehicles for transmitting same amount of passengers
(Cited from (Wright and Fjellstrom 2003))

2.2. General review of optimization of public bus system

Since public bus system can offer such economical and social advantages, optimization of public bus system is essential for bus users and public bus operators. Murray concluded that public bus system can be improved by applying more effective price structures; enhancing travel comfort; offering suitable and convenience service quality; reducing in travel time efficiency; and increasing service access (Murray 2001). Expanding service coverage and increased efficiency of routes should be addressed in bus-oriented transit management and planning (Murray 2003).

The main purpose of optimization of public bus focus on offering high service quality, serving more passengers and minimizing operating costs (Guihaire and Hao 2008). For example, the transit route configuration should be designed that passengers can reach their destinations as directly as possible to reduce the transfers or travel time. The percentage of served demand is set as a measurement to evaluate public bus system in respect of route length, stop spacing and stop density. Moreover, the demand will be considered as unsatisfied if the distances from bus stop to destination or origin of travelers are too far to attract people traveling. In addition, trip directness is another measurement because the insufficient directness will cause more transfers. Finally, for some social or political reasons, it is sensible to utilize the existing transit networks as much as possible without disturbing current services. Minimized bus lines or total route lengths will decisively reduce the operators' cost in terms of vehicle amount or crew resources (Guihaire and Hao 2008).

2.2.1. Previous works of optimization of public bus

The previous optimizations of public bus system can be classified into three perspectives: 1) locating bus stops based on simplified demand distribution in terms of social, spatial and environment facts; 2) joint optimization of bus route, stop spacing and spatial coverage of bus system; 3) concerning on temporal demand while optimizing a bus system (Yao Xiaobai 2007; Ziari, Keymanesh et al. 2007).

Considering the factors which affect bus system performance, Lao concluded that local population, transportation network and commuting patterns largely determine passenger demand, and geographic setting within which a transit system operates can strongly affect its performance and effectiveness (Lao Yong and Liu Lin 2009).Yao applied Need Index method and data mining approach to predict public transmit demand (Yao Xiaobai 2007). Abbas-Turki and Kaakai use Petri net model to evaluate and optimize bus system based on maximizing number of travelers (Abbas-Turki, Bouyekhf et al. 2004; Kaakai, Hayat et al. 2005).

Different optimization goals, like minimum total cost (Chien and Zhaoqiong Qin 2004), using limited bus stops to obtain adequate bus service (Schwarcz and Stacey 2004) and increasing bus system accessibility (Ziari, Keymanesh et al. 2007) have been put forth for bus system optimization. Alterkawi analyzes field-collected data based on a computer FORTRAN program to simulate the optimum bus stop spacing (Alterkawi 2006). A tabu search algorithm has been introduced by Bai Zijian to optimize transit network (Alterkawi 2006). A Heuristic Algorithm has been developed by Ceder to maximize the number of simultaneous bus arrivals at the connection nodes of the network that obtains the minimum waiting time for passengers' transfers (Ceder, Golany et al. 2001).

2.2.2. Methods of bus stop selection and locating

Since proper spacing of stops can significantly enhance the quality of transit services and reduce travel time(Alterkawi 2006), selection of bus stop locations is also an important objective of optimization of public bus system. Meanwhile, the optimal amount and locations of the stops will be affected by users' value of time, access speed and demand (Chien and Zhaoqiong Qin 2004).

The covering model, addressed by Klose, itself is a location model which determines a minimal subset of facilities that every customer can be reached within a given maximal distance from one of the given depots(Klose and Drexl 2005).Schöbel set the goal of bus stop optimization as achieving a maximal covering of given demand points with a minimal number of stops (Schöbel and Anita 2005). Matisziw optimized bus stop locations based on maximizing potential demand coverage and minimizing route length extension (Matisziw, Murray et al. 2006). Murray has addressed the so called LSCP (location set covering problem) model and MCLP (maximal covering location problem) model to optimize bus stop locations to minimize the number of transport stops needed in the bus system to reduce the stop redundancy(Murray 2001) or to maximize the total passengers to be covered by a continues service coverage(Murray 2003). Chien has formulated a mathematical model to optimize the number and locations of bus stops that achieve the minimum total cost. Ibeas developed a bi-level optimization model to locate bus locations for minimize the social cost of transport system(Ibeas, dell'Olio et al.).A combined Mode Choice Assignment Model was used to represent the traffic congestion and the effect of bus location changing initially, and the equilibrium between passengers, number of bus stops and fleet size and social cost had been reached finally.

Moreover, in public bus system planning, School Bus Routing Problems (SBRP) has been addressed to reach such goals that related to efficiency (capital cost and incremental cost), effectiveness (traffic demand and service quality) and equity (equality or fairness of bus service for each student). To solve that Vehicle Routing Problems (VPR), a set of bus stop locations must be distributed firstly. Bodin and Berman manually assigned the students to the nearest potential bus stop locations. Meanwhile, another method has been introduced by Dulac Ferland and Fogues that the students were located on the road segments and then were subsequently assigned to an incident road intersection that was selected as a potential stop location. Those potential locations assigned with largest students within walking distance are selected as bus stops. Chapleau and Bowerman addressed an improved method that grouped the road nodes into clusters as potential stop locations and then allocated the students into clusters which can be serviced by a single bus route generated consequently(Bowerman, Hall et al. 1995).

In sum, it can be concluded that bus stop optimization mainly aims at distributing a set of bus stop locations that can mostly satisfy public transport demand, maintain adequate walking accessibility and cover sufficient service areas with minimal number of stops.

2.2.3. Service locations models in FLOWMAP

As the objective of bus stop optimization is to obtain rational spatial locations that offering public bus services, service location models in FLOWMAP can solve this problem but avoid the mathematical complexity. FLOWMAP devised by Faculty of Geographical Sciences of Utrecht University, is a program for spatial analysis such as Accessibility Analysis, Gravity Modeling and Service Location Modeling(J.Breukelman, G.Brink et al. 2009). It can simultaneously interrogate the threshold/ supply of a range of facilities in relation to the demand in order to evaluate access to the facilities using a selected mode of transport on a specified road network (Green, Breetzke et al. 2009).

Four different models have been served for locating or relocating public services:

- **Coverage model:**

This model intends to resolve the question that how many different locations are adequate to meet a minimum level of service. Spatial Pareto method is provided to solve such problems. Maximal travel time or reach distance are required to assure that only those locations within the required range can be selected (J.Breukelman, G.Brink et al. 2009).

- **Expansion model:**

This model intends to resolve the same question mentioned in coverage model, but differs on expensing locations based on existing facilities. Meanwhile, four alternative solutions are provided such as:

Maximize customer coverage: to add additional service centers at locations where the highest market share will be realized based on an assumption in that people will make use of their nearest possible service(Sahr 2006; J.Breukelman, G.Brink et al. 2009).

Minimize overall average distance: to minimize the total (thus average) distance traveled by population to the services to enhance the system efficiency. If a number of services is located to reach the minimum objective in an area without any pre-existing services, the resulting pattern is called a p-median (Jong, Maritz et al.).

Minimize overall worst case distance: to minimize the largest distance travelled by anyone to a service to ensure the system equity. If it is applied to an area without pre-existing services, the resulting pattern is called a p-centre (Jong, Maritz et al.).

Maximize individual market share: to maximize the overall increase in service coverage by adding the service that will have the most impact on the increase in the amount of covered customers (J.Breukelman, G.Brink et al. 2009).

- **Relocation model:**

Relocation model can be regarded as a further optimization model for improving the existing locations of facilities with same alternatives including “minimum average distance”, “minimum worst case distance” and “minimize spatial competition”.

- **Reduction model:**

Reduction model is designed as an opposite solution to against expansion model. Four alternative choices are contained accordingly as “least effect on customer coverage”, “least effect on average distance”, “least effect on worst case distance” and “remove worst marked position”.

In conclusion, bus stop optimization can be realized by using expansion model firstly to distribute minimal number of bus stops that can satisfy the basic transport demand within defined service range. Secondly, relocation model can be applied to improve system efficiency by minimizing average bus stop distance along road networks or enhance system equity by minimizing longest stop distance.

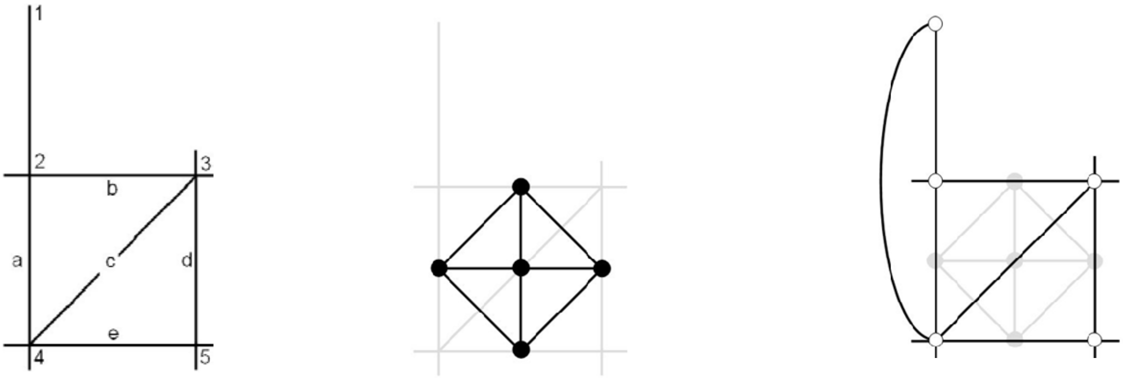
2.2.4. Researches of spatial structure of road network for bus stop selection

The spatial structure of road networks is another important factor in bus stop selection. Given that the road capacity will be fully utilized when the distribution of traffic flows fits well with the road network configuration (Zhu Canghui, Chai Gan et al. 2008), the efficiency of urban traffic system will be highly improved if the bus stops, which largely determine the routes of bus driving, are composed of locations with high connectivity and road capacity.

Two kind of spatial structure analysis, i.e. Space syntax analysis and Random walking calculation are introduced here.

- **Space syntax analysis**

Space syntax has been addressed by Bill Hillier to investigate the spatial relationship between the structure and functions of cities based on grapy theory. The global integration, an important measure in Space Syntax, is correlated with rush hour movements of adults. It is generally accepted that the spatial configuration of the urban grid is a consistent factor to determine the movement flows(Hillier 1999). Batty claims that Space syntax focuses on lines not points, streets not the conjunctions (Figure 2-2). The importance of a street will increase as the number of nodes associated with goes greater(Batty 2004).



a. The Street Network as an Axial Map

b. The Primal Syntax between Streets/Lines

c. The Dual Syntax between Junctions/Points

Figure 2-2 Space Syntax Representation
(Cited from (Batty 2004))

Li Jiang introduced the mathematic definition of basic variables of Space Syntax which includes Connectivity, Depth value and Integration(Li jiang and Guo Qingsheng 2003). Connectivity refers to the amount of spatial unites which are connected with the given spatial unit. Depth value indicates the minimum number of spatial units connected to the given spatial unit in a certain steps. Croxford found that counts of vehicles are closely correlated with the ‘Integration radius 3’ and street width. Both vehicular and pedestrian movements are related to the street grid configuration. Zhou applied Space Syntax in analyzing the spatial structure of Wuhan city to evaluate bus stops (Figure 2-3). The global integration values and local integration values of streets have been calculated and assigned to their nearest bus stop locations(Jingnan 2009).

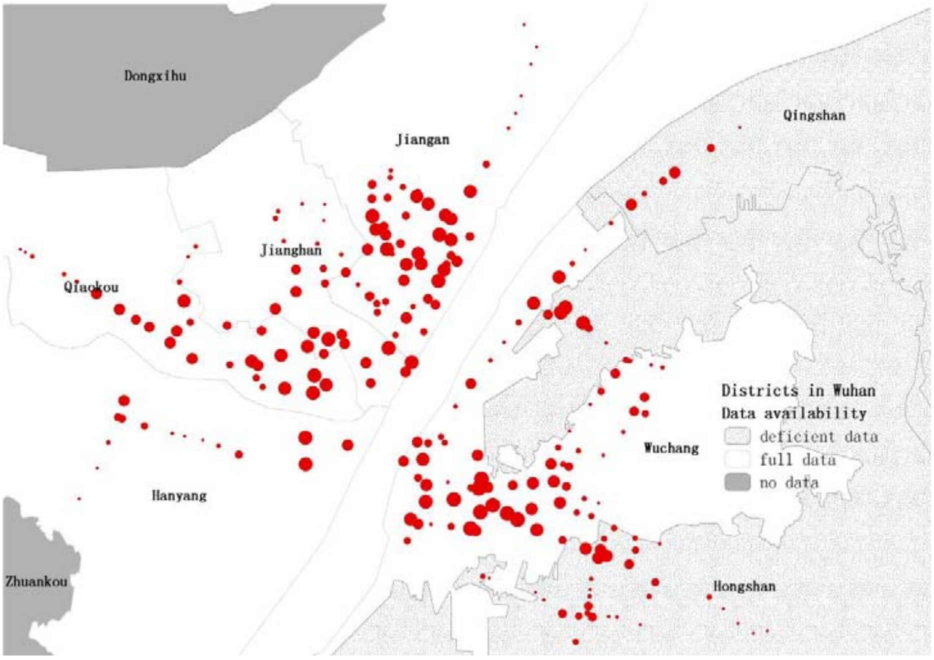
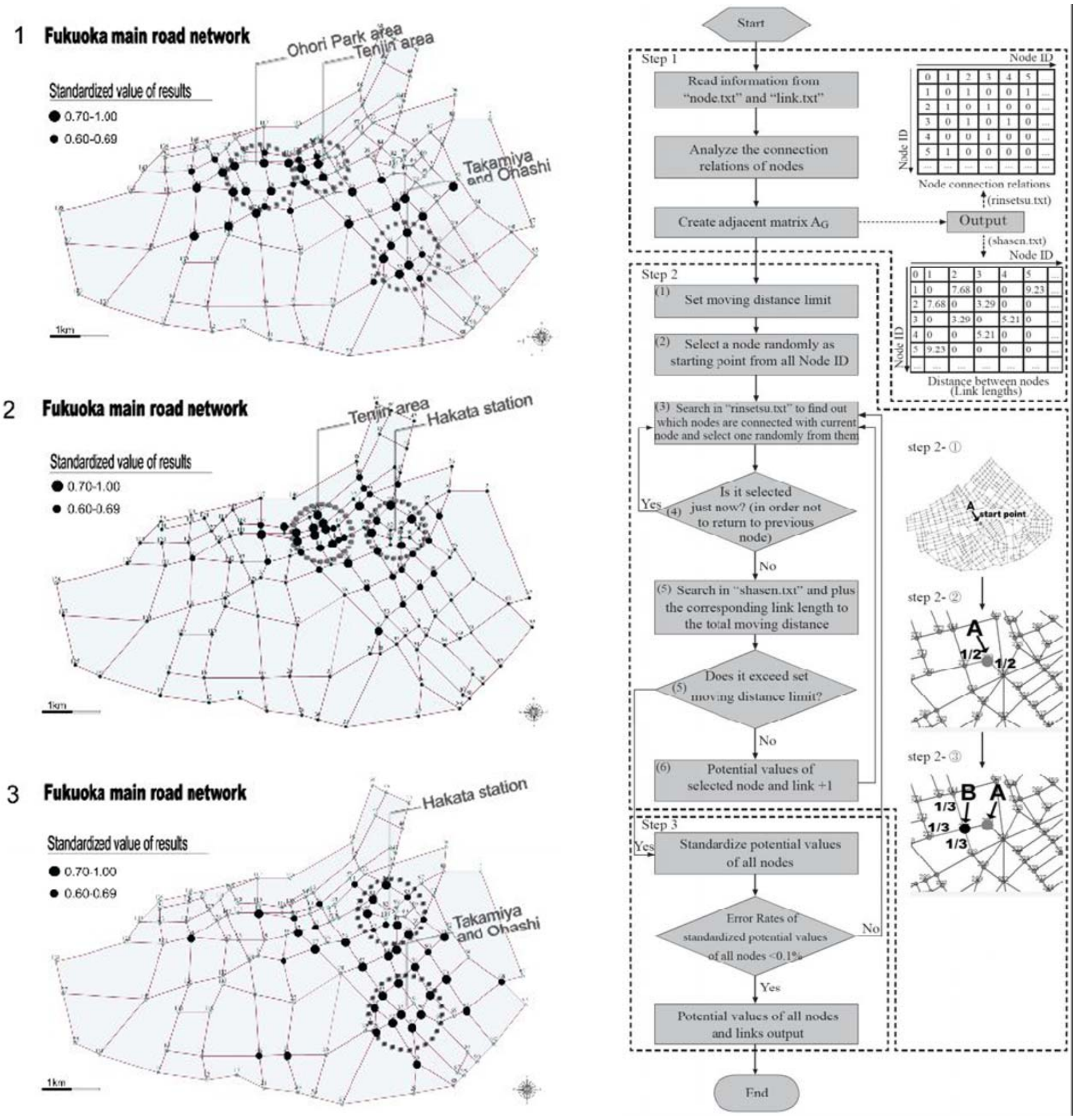


Figure 2-3 Assign the local integration value to the bus stops, Wuhan
(Cited from (Jingnan 2009))

- **Random walking calculation**

For analyzing the spatial importance of nodes in road networks, random walking calculation has been introduced by Li to calculate the position potential by simulating people's random walking in urban road networks with given trip length (Li Zhuoran, Zhao Shichen et al. 2009). Based on graph modeling principles, random walking algorithm can be applied to characterize the structural properties of an urban street network, and to select important places or streets.
Random walking calculation is to simulate a person who is walking randomly on urban road networks. After several random walking trips which are limited by a given trip length, the road nods or segments through which the citizens are walking with a large number of times are considered as places with high spatial importance. The locations with high spatial importance in analysis of Fukuoka are illustrated in Figure 2-4.

In sum, Space syntax and Random walking can both indicate the important locations in a given spatial road networks. The efficiency of bus system will be improved if bus stops include key stops with high spatial importance, i.e. connectivity.



1. Analysis result 2. Analysis flowchart

Figure 2-4 Locations of nodes with high values in Fukuoka
(Cited from (Li Zhuoran, Zhao Shichen et al. 2009))

2.3. Conclusion

Public bus system plays an important role in urban traffic system. Moreover, optimized bus stop locations can improve the efficiency of public bus system thus offer more economical and social advantages. Therefore, it is an essential problem to optimize spatial locations of bus stop. Bus stop optimization mainly aims at distributing a set of stops locations that can mostly satisfy public demand, maintain adequate walking accessibility and cover sufficient service coverage with minimal number of stops.

Fortunately, FLOWMAP offers a set of location models to resolve such problems avoiding such mathematical complexity. For instance, bus stop optimization can be realized by using expansion model firstly to determine minimal number of bus stops that can satisfy the basic transport demand within defined service range. Secondly, relocation model can be applied to enhance system efficiency by minimizing average bus stop distance along road networks or to assure system equity by minimizing longest stop distance along road networks.

On the other hand, places with high spatial importance should be paid more attention, because efficiency of bus system will be improved if bus stops include key stops with high spatial importance, i.e. connectivity. Space syntax and Random Walking Algorithm can be easily applied to find such places.

3. Background of study area

3.1. General description of Wuhan city

The study area in this research is Wuhan, a metropolitan city of China with 4.65 million populations and approximate 4.50 km^2 urban areas (WHSB 2008). As a historical city locating on the intersection of Chinese railway network, Wuhan has been the most important transport hub in central China (Figure 3-1). Limited by its natural terrain, Wuhan is geographically partitioned into three sub-towns by Yangzi River and Han River. Those three sub-towns, i.e. Hankou, Wuchang and Hanyang, are economically and politically interacted. Current insufficient distribution of bridges causes that they have become serious bottlenecks of traffic flows, largely constraining motor vehicle utilization. In 2006, the average amount of vehicles passing over the Yangzi River each day using these bridges ranged from 220,000 to 230,000, and nearly 250,000 vehicles were crossing the neighboring Han River daily (WTPI 2007). Moreover, the major roads in the city center function both as commercial and traffic channels. Severe congestion is aroused due to such irrational functioning of the cities and bridges (Figure 3-2).

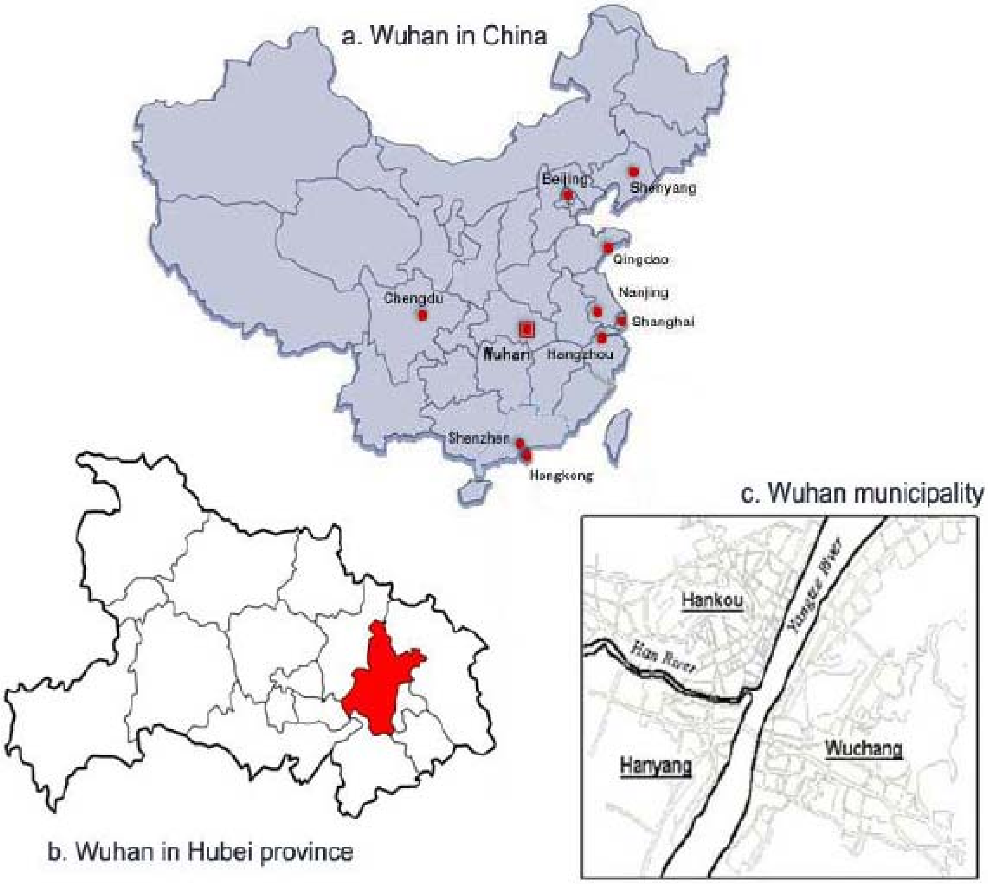


Figure 3-1 Location of Wuhan in China
(Cited from (Xiaotang 2009))

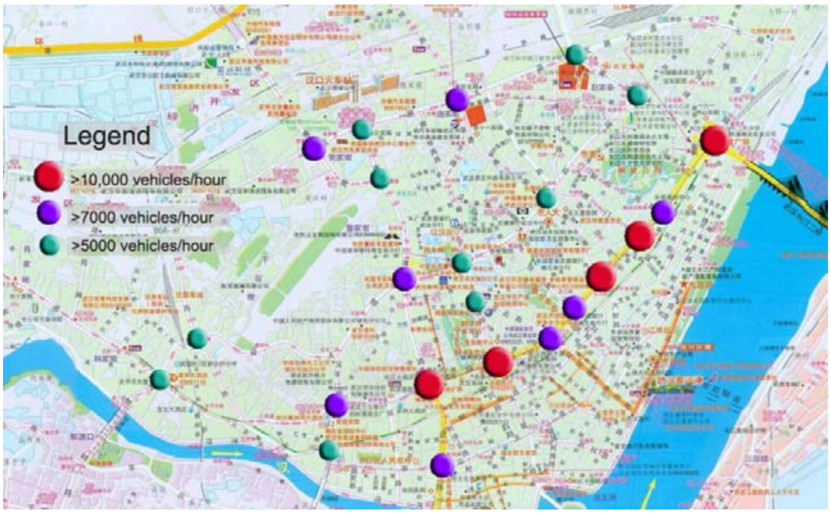


Figure 3-2 Distribution of traffic congestions in city center in Wuhan
(Cited from (WTPI 2007))

3.2. Characteristics of traffic operation in Wuhan

1. Current transport facilities can hardly satisfy such high traffic demand

High population density, stable economical growth, and rapid increase of number of vehicles contribute to a high traffic demand. Firstly, traffic demand that is generated by daily movement of persons, which is largely dependent on population density. The population density of Wuhan in urban areas is 964 persons/km^2 (WHSB 2008), and causes a significant high traffic demand. Secondly, robust economic development assures a stable employment rate and motivates the business activities. Economic activity is mainly described by the Gross Domestic Product (GDP) of Wuhan (Figure 3-3). Wuhan prospers stably over the past few years. The total GDP of Wuhan is 369.01 billion yuan in 2008, arising with 15.1% as compared with previous years (WTPI 2008). Trips with purposes working and schooling increase accordingly. Furthermore, the ownership of motor vehicles is strongly coupled with the economical development and shows a constant increase (Figure 3-4). The total motor vehicle population of Wuhan is 781,000, increasing with 2.8% against previous year(WTPI 2008). The rapid growth of motor vehicles is a critical factor for the high traffic demand.

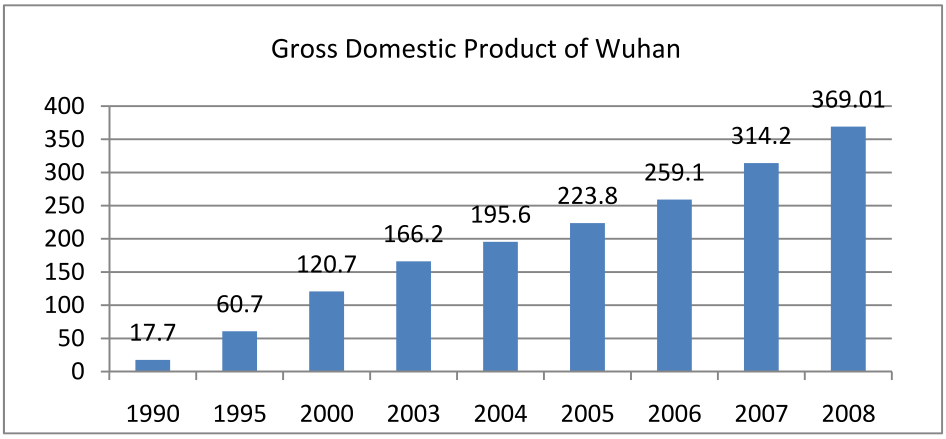


Figure 3-3Gross Domestic Product of Wuhan
(Cited from (WTPI 2008))

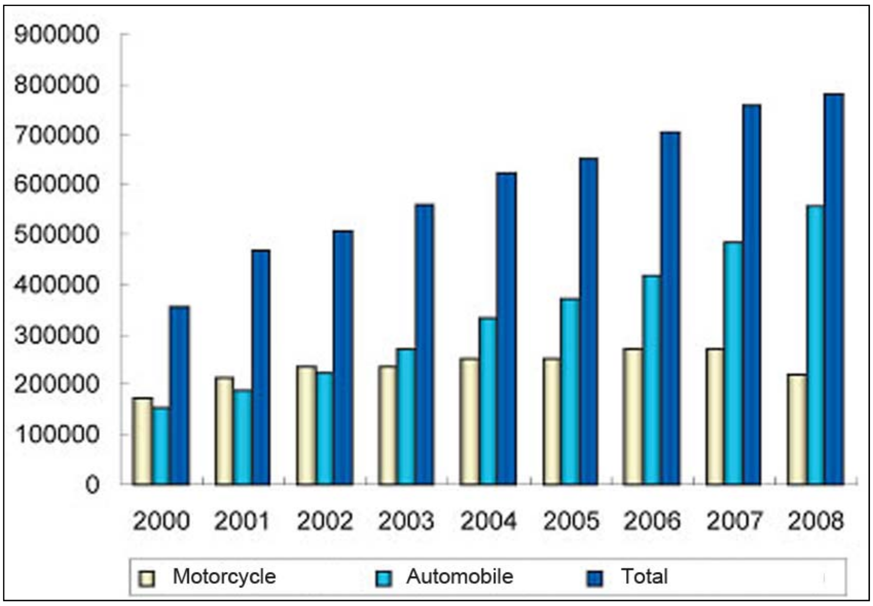


Figure 3-4 Motor vehicles of Wuhan
(Cited from (WTPI 2008))

Unfortunately, existing transport facilities can hardly satisfy such high traffic demand due to the insufficient capacity .The central areas of Wuhan are mostly congested, the average traveling velocity is 23.3 kilometers/hour in 2008, decreasing by 0.6 kilometers/hour as compared with the velocity in 2007(WTPI 2008). The driving speed is relatively slower on the road of commercial centers and the average driving speed on main road is 25.5 kilometers/hour (as shown in Figure 3-5).

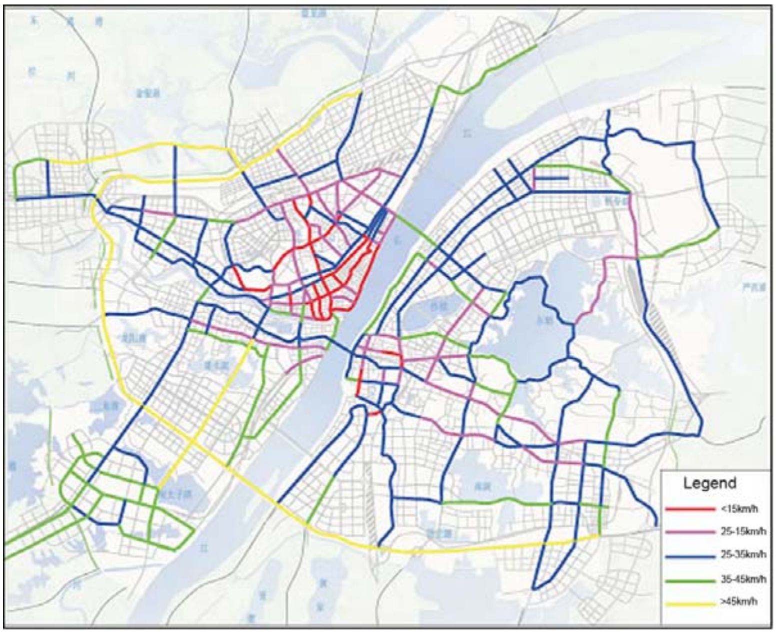


Figure 3-5 Travel velocity of Wuhan
(Cited from (WTPI 2008))

2. The proportion of business and entertainment travel escalates gradually

According to a Travel Behavior research in Wuhan in 2008, the proportion of business and entertainment travel is growing gradually, as a rate of 20%. On the contrary, the proportion of travel demands for work and education is decreased slightly (Figure 3-6). Average number of daily trips for each person is 2.41 trips, raised with 17.2% as compared to the same statistics in 1998(WTPI 2008). It can be concluded that travel demand for various trip purposes is increasing as the city is prospering and improving in terms of living quality.

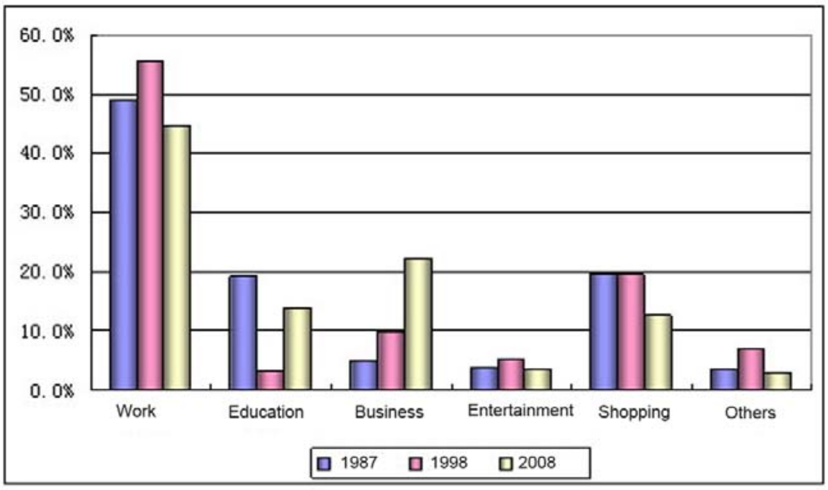


Figure 3-6 Travelling behaviors of Wuhan
(Cited from (WTPI 2008))

3. Large investments in public transport facilities

The central government and local authorities of Wuhan devoted huge monetary investments (Figure 3-7) to construct the urban subway system and High Speed Train System in Wuhan in the belief that such investments could spur economic development and the handling of the global crises while enhancing the capacity of passenger transit. The planned subway system consists of 119 subway stations and 8 routes (Figure 3-8). It is planned to be operational by 2015. Meanwhile, a High Speed Train System connecting Guanzhou is already in operation.

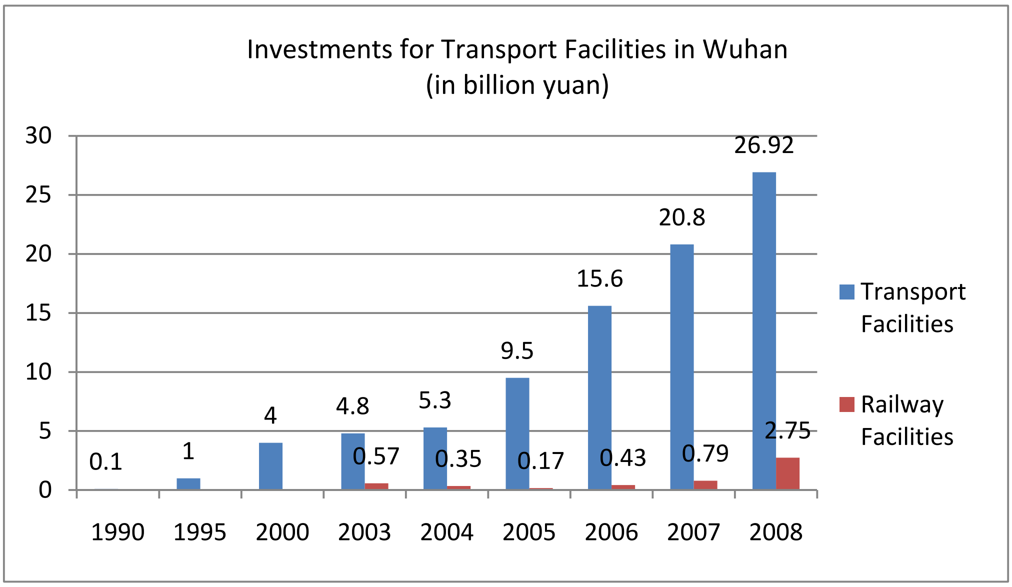


Figure 3-7 Investments for transport facilities in Wuhan
(Cited from (WTPI 2008))

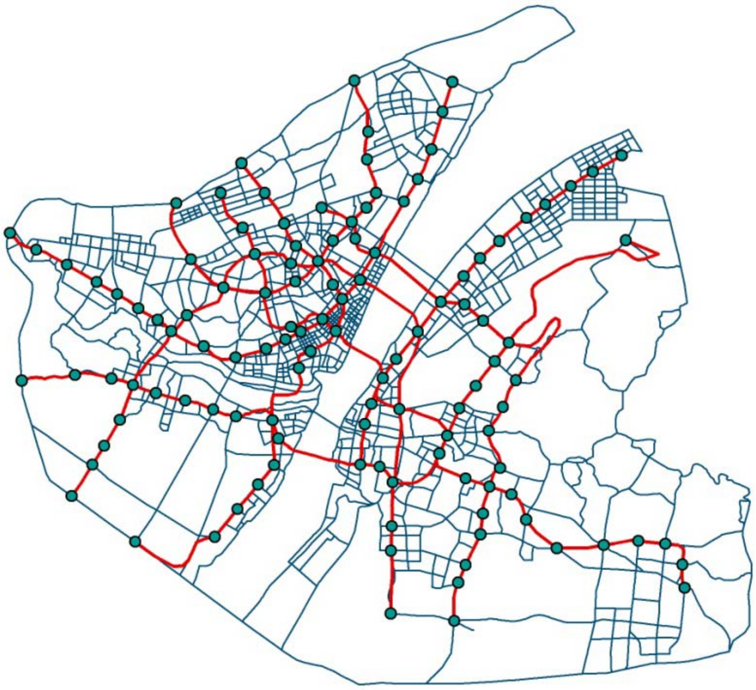


Figure 3-8 The planed subway system in Wuhan

3.3. Public transport utilization in Wuhan

The public transit system in Wuhan is comprised of public buses, taxis, ferry boats and rail transport. Public bus is the major mode of urban passenger in Wuhan. In 2006, there are 1.23 billion people, which comprise 69.11% of the total travelers, who select bus for daily commuting (WTPI 2007). Public buses play an important role in Wuhan public transport system (Figure 1-3).There are 6,976 buses in operation, including 1,191 buses for normal bus lines and 5,267 buses for special lines. The total number of bus routes is 277, containing 70 normal bus lines and 183 special lines. The number of bus stops is 2,446 with 41 terminal stations and 6 transfer stations(WTPI 2008).

However, because of the unique spatial urban morphology of Wuhan, the lengths of bus routes are much longer than the national standard. Such big variation in the lengths of bus routes leads to unpunctual bus dispatching, non-uniform passenger flow along routes and low service quality (Huang Zhengdong, Wei Xuebin et al. 2009).

Furthermore, as discussed in Chapter1.2, irrational distribution of existing bus stops leads to a low public bus service quality. For example, redundant distribution of bus stops within small distances in most central areas elongates unnecessary buses stopping and passengers waiting time, and costs unnecessary public resources. Bus stop inadequacy also exists especially in urban outskirts that results in a low walking accessibility, attracts less public traffic demands and causes social inequity.

4. Methodology and data collection

Data collection for this research went smoothly. Next, the methodology for optimization of bus stops is specified in four steps, i.e. candidate stops generation, candidate stops classification, stops optimization and evaluation.

4.1. Data collection

Based on literature (Chien and Zhaoqiong Qin 2004; Lao Yong and Liu Lin 2009), and considering the availability of data, road network data (Figure 4-1), land use pattern data, data on population distribution (Figure 4-2), existing bus stop locations (Figure 4-3) and key transport facilities (Figure 4-4), i.e. planed subway stations, planed bus terminals, bus transfer stations, train stations and ferry port were collected. Road networks provide the condition for bus stop optimization, as bus stops are located along the roads. Passengers can have access to the public transit system through the road network. In addition, land use patterns and population distribution both contribute to the traffic demand. Land use patterns, especially the distribution of commercial and residential land, steers the direction of traffic flows by determining the locations of traffic attraction and production. Population density is in proportion with the amount of traffic production and indirectly affects the attraction. Meanwhile, there are two purposes of using the existing bus stop locations: for investigating the current problems of existing stop locations as discussed in chapter 1.2 and for making comparison with optimized stop locations to verify the improvements. Finally, key transport facilities, i.e. planned subway stations, planned bus terminals and bus transfer stations, train stations and ferry ports should also be taken into account when considering reducing the transfers of passengers in different transport modes. The obtained data are described as Table 4-1.

Table 4-1 Data description

Data category		Feature type	Purpose	Attribution	Data source
Road networks	Road segments	poly line	Candidate stop generation, Random walking calculation for candidate classification.	Width, length	Wuhan Transportation Planning Institute
	Road nodes	point		Location	
Existing bus stops		point	Comparison with optimized stop locations	Stop name	Field work
Population distribution		raster	Public transport demand calculation		Wuhan Transportation Planning Institute
Land use pattern		polygon			
Metro networks	Metro segments	poly line	Key stop selection.	Length	
	Metro stations	point		Location	

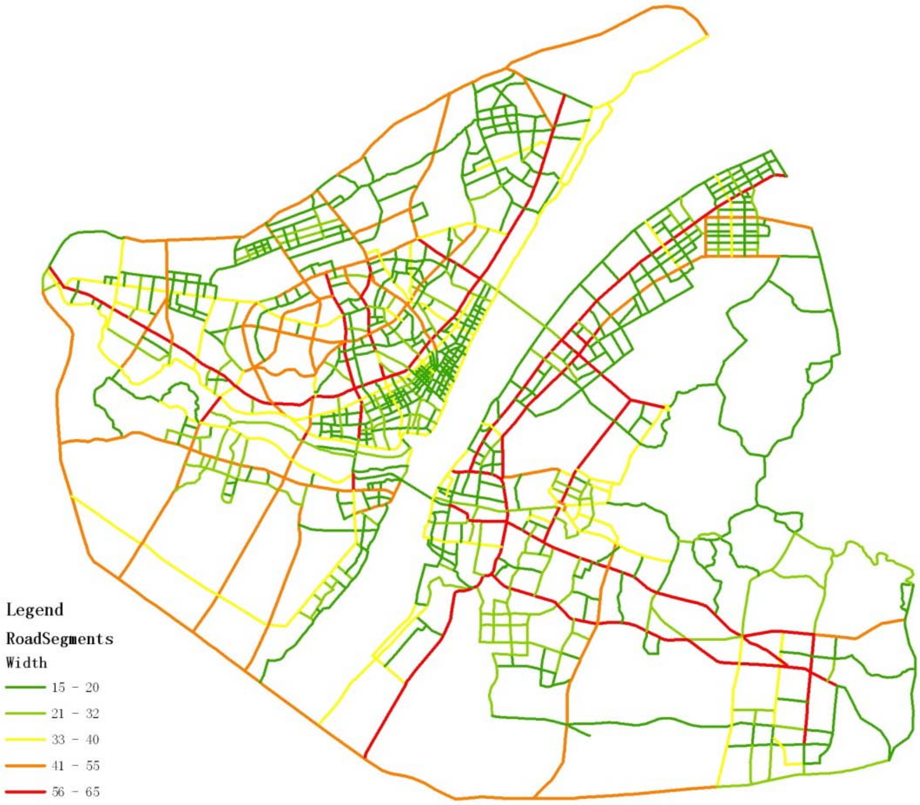


Figure 4-1Road networks with attributions of road width in Wuhan

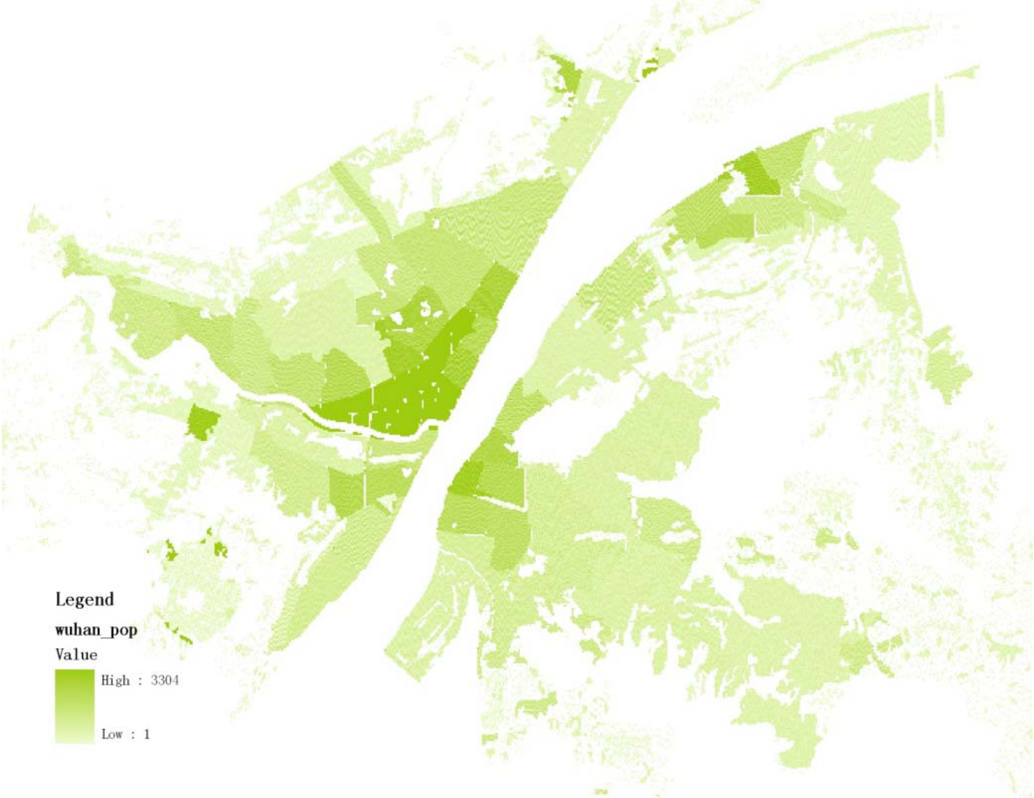


Figure 4-2 Population distribution of Wuhan

Figure 4-3 Existing bus stops in Wuhan

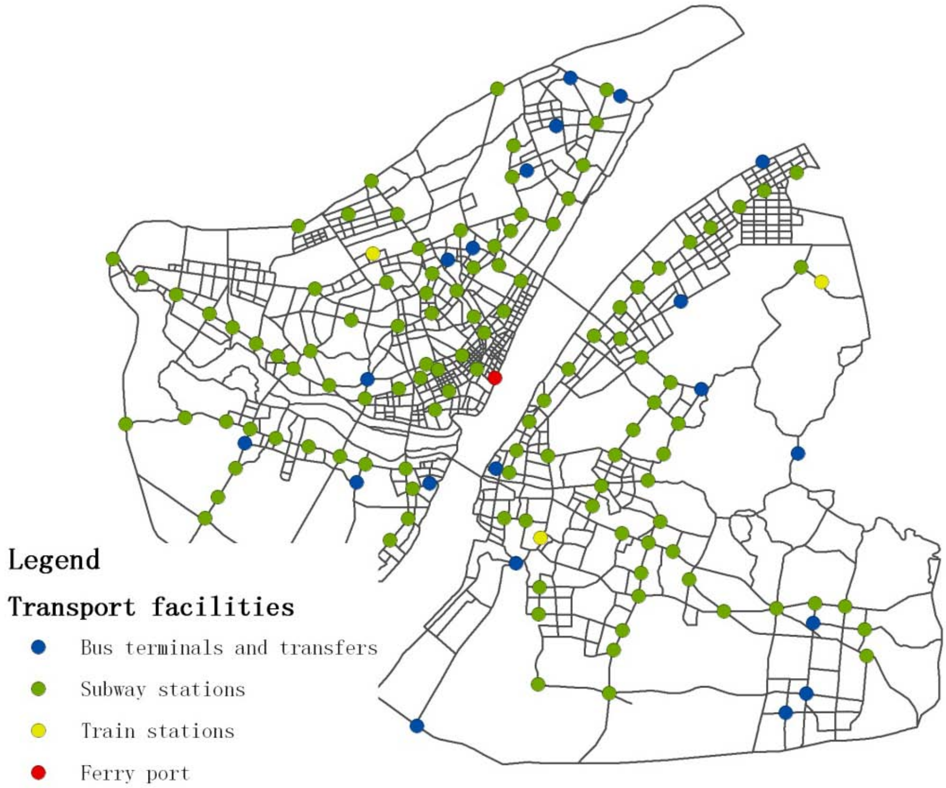


Figure 4-4 Key transport facilities in Wuhan

4.2. Methodology

After data collection and entry, research activities were performed according with the conceptual framework (Figure 1-6). The conceptual framework is mainly concerned with how to achieve the optimized bus stops in the sequence of four procedures, i.e. candidate stops generation, candidate stops classification, stops optimization and evaluation (Figure 4-7).

4.2.1. Candidate stops generation

The objective of candidate stops generation is to produce the locations in Wuhan that can potentially be selected as bus stops. Considering the accessibility and connectivity with planned subway stations, which are normally located beneath the intersections of urban roads, all the intersections of urban roads are firstly selected as candidate stops through a Network Analysis in ArcGIS. In addition, given that the road segments in the central areas are generally shorter than in the urban outskirts that may influence the precision of optimized result, road segments of which (excluding bridges) the lengths are more than 1,000 meters are broken down manually (Figure 4-6), and more candidate stops have been added accordingly to maintain the point density geographically equal. Although, more candidate stops can assure a more rational optimized output, too much candidate stops require high computational ability that may be beyond the scope of this research. Therefore, only 1,500 nodes are selected as candidate stops and accordingly 2,355 road segments are maintained in the road network (Figure 4-5).

Figure 4-5 Candidate bus stops

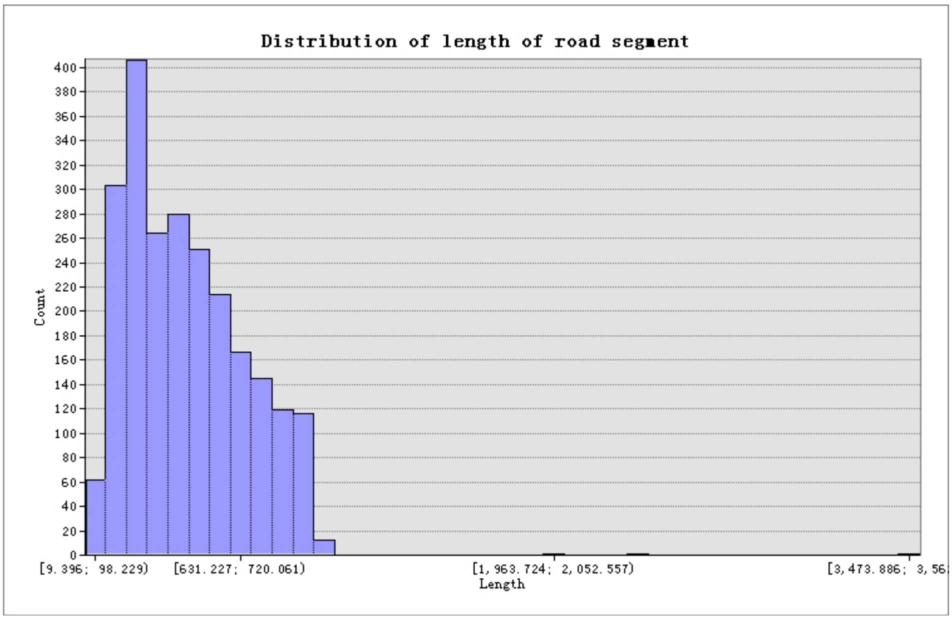


Figure 4-6 Length of road segments connected with candidate bus stops

4.2.2. Candidate bus stop classification

Given that a bus system that is comprised of highly connective and accessible stops will perform more efficiently, the candidate stops are classified depending on the spatial importance. The objective of such classification is to make sure that those locations with high spatial importance will be firstly selected in the optimization to improve efficiency of bus system. As discussed in chapter 2.2.4, the random walking calculation can indicate the spatial importance (Li Zhuoran, Zhao Shichen et al. 2009) of an individual bus stop position, the potential value of each candidate stop that is calculated by random walking algorithm is set as weight for selecting key bus stops with high connectivity. The random walking calculation is realized in C# programming. The details of an improved algorithm and procedure will be described in Chapter 5.

4.2.3. Stops optimization

As discussed in Chapter 2.4, the objective of optimization of bus stops is to obtain a trade-off between reducing stop redundancy, while maintaining walk accessibility and enlarging service coverage to keep the number of bus stops minimal. Furthermore, as discussed in 2.2.3, bus stop optimization can be realized by using expansion model in FLOWMAP firstly to distribute minimal number of bus stops that can satisfy the basic transport demand within defined service range. Secondly, relocation model can be applied to improve system efficiency by minimizing average bus stop distance along road networks or enhance system equity by minimizing longest stop distance.

Therefore, as FLOWMAP supplies a set of service location models that can optimize location of bus stops and avoid mathematical complexity, Expansion Models and Relocation Models are selected in this research for stop optimization (J.Breukelman, G.Brink et al. 2009).

Firstly, the Thiessen polygon for each candidate bus stop will be generated to represent the potential locations to be selected.

Secondly, two comparable solutions, i.e. a three-level optimization and a two-level optimization, are adopted. In the three-level optimization, initially, the key transport facilities of Wuhan city are prefixed as the first level of stops to reduce the transfers of passengers in different transport modes. Subsequently, the remaining candidate stops are selected in the Expansion Model to determine the minimal number of stops and then further optimized in the Relocation Model to minimize the total stop distance or minimize the longest stop distance. The optimization of this level is weighted by random walking values to determine the second level stops which are accepted as bus stops with high connectivity. Finally, the third level of bus stops is obtained by employing Expansion Model and Relocation Model again while considering the public transport demand.

The two-level optimization is operated in a similar process but only without pre-locating the key transport facilities of Wuhan city. The purpose of two levels optimization is to test whether the better optimized results can be achieved with more flexibility, namely without considering the connection with existing or known planned transport facilities. The specific processes of operation in FLOWMAP will be described in Chapter 6.

4.2.4. Evaluation

The evaluation phase intends to test whether the expected improvements are virtually achieved. This is performed by doing a comparison between the optimized bus stops with the existing bus stops. ArcGIS can support sufficient spatial analysis tool to calculate served demand and service coverage which are main indicators for bus stop evaluation (Tang Guoan and Yang Xi 2006). Point pattern calculation in R will also be used to calculate walking accessibility (Baddeley 2008). The advantages and limitations will be thoroughly discussed in Chapter 7.

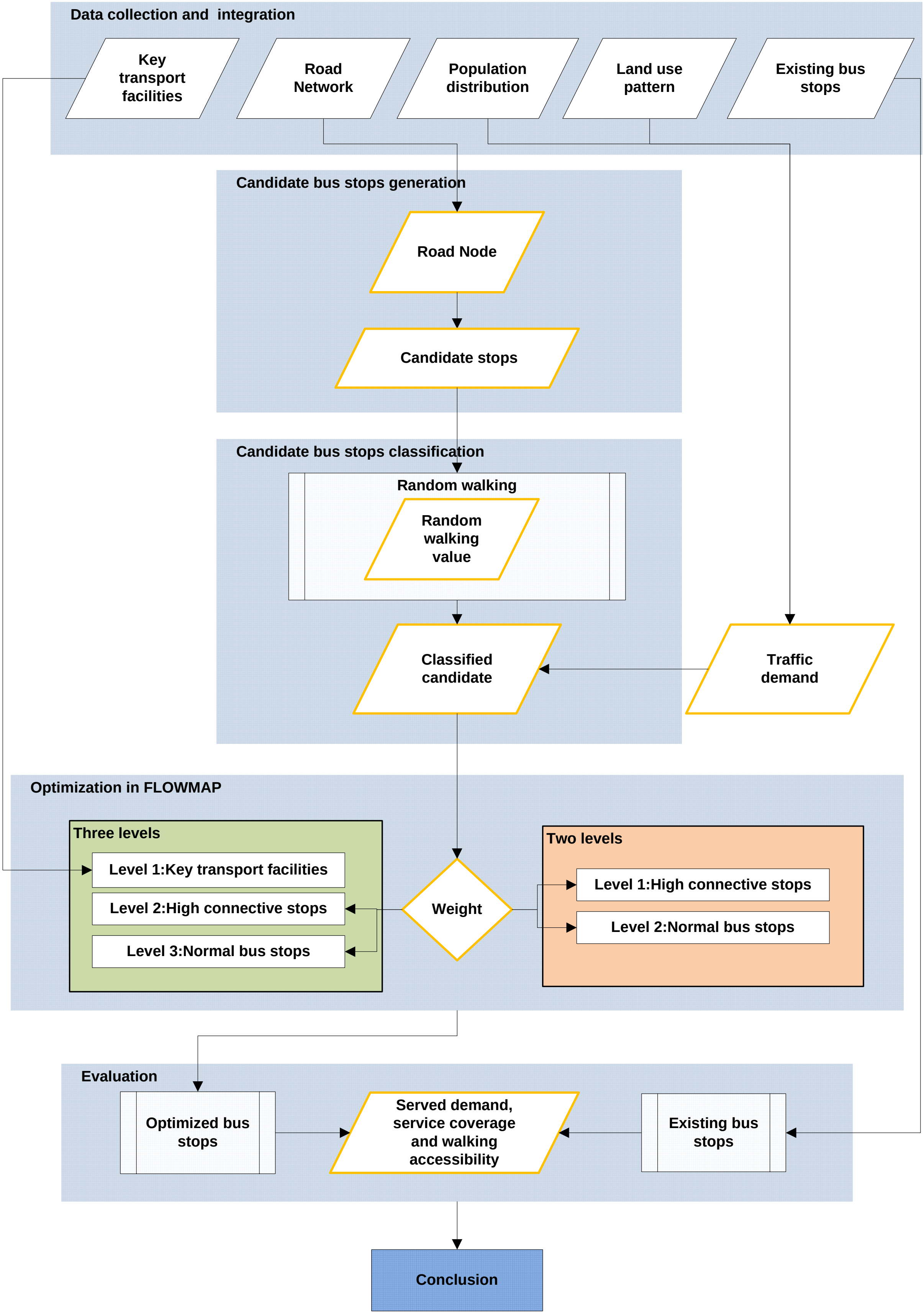


Figure 4-7Research methodology

5. Random walking calculation

As discussed in Chapter 4.2.2, the objective of the Random Walking calculation is to classify the locations with high spatial importance. Since the random walking can indicate the spatial importance (Li Zhuoran, Zhao Shichen et al. 2009),position potential value of each candidate stops which calculated by random walking algorithm is set as weight in further optimization to select key bus stops with high connectivity for enhancing the bus system efficiency.

Random walking calculation is applied to classify the positional value of each road node by simulating citizens' daily travelling in a random walking context. The road nods or segments through which the citizens are walking with a large number of times are considered as places with high spatial importance. The algorithm is realized based on work by Li and Zhao (Li Zhuoran, Zhao Shichen et al. 2009). Some improvements are proposed and implemented in this research by considering the influence of road width on path selection and the limitation of normal trip length in practical traveling. The calculation is realized in C# programming.

5.1. Random walking algorithm

5.1.1. Data organization

The random walking algorithm is programmed in C#, an Objective Orientated Language. Three types of classes are defined as Graph, Grape Vertex and Grape Edge. The Graph which represents the road networks is comprised with Graph Vertex (candidate bus stops) and Graph Edge (road segments). All the classes contain unique ID. To be able to trace every Graph Vertex maintained in the Graph, a list of all the Graph Vertex ID is recorded as an attribution in Graph class. Similarly, the ID of connected Graph Edges is also recorded in a list of each Graph Vertex class. In addition, the attribution of Graph Edge includes length, width and connected Graph Vertex ID. An integer filed is also included to record the random walking value. The relationship of each class is illustrated as following figure (Figure 5-1):

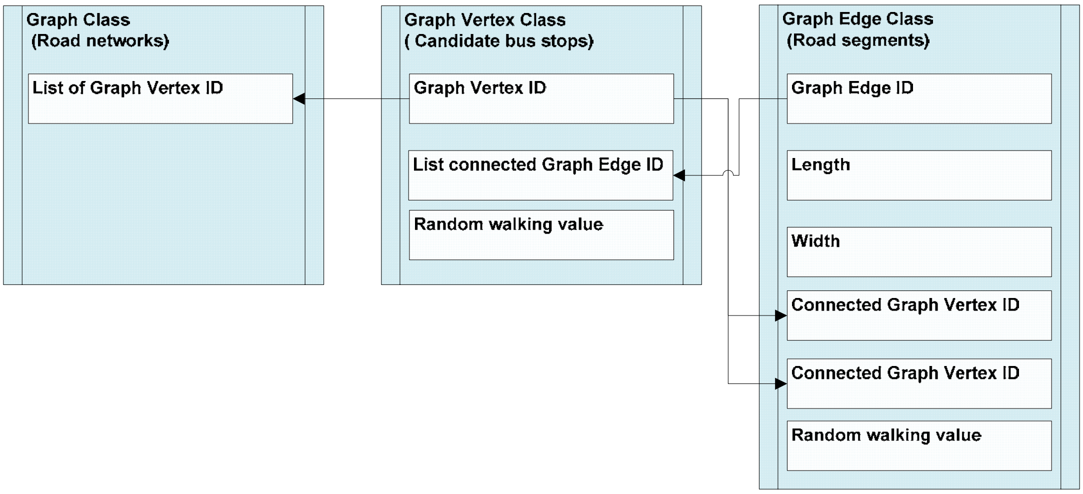


Figure 5-1 Relationship of classes in Random Walking Calculation

5.1.2. Calculation process

To begin with, one vertex will be selected randomly as the walking start point. A length threshold is calculated accordingly to limit the length of this walking journey. Given the fact that an average (normal) trip of Wuhan citizens is around 5km (WTPI 2008), all the length thresholds are randomly generated and normally distributed with a expectation of 5 km and standard deviation of 1km (Figure 5-2). The maximal length is nearly 10 km and the minimal length is about 600 meters. The length threshold is calculated by the following formula:

$$\text{Length threshold} = \text{Expectation} + \text{Standard deviation} \times \sqrt{2 \times \log\left(\frac{1}{1 - \mathrm{R}_1}\right)} \times \cos(2 \times \mathrm{Pi} \times \mathrm{R}_2)$$

Where
Expectation =5,000;
Standard deviation = 1,000;
R_1 and R_2 are randomly generated numbers ranging from 0 to 1.

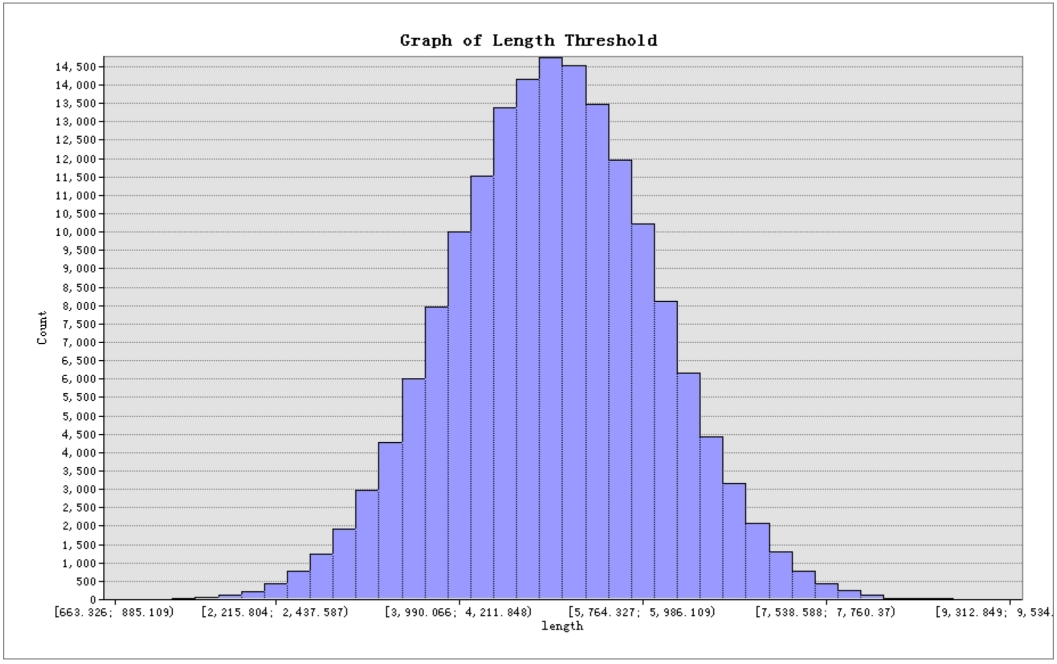


Figure 5-2 Distribution of waling length threshold

Secondly, widths of the connected road segments are compared and one road segment will be selected randomly. Because the citizens are prone to travel on the wider roads that can offer a high traveling velocity, the road segments with higher width value get assigned a higher probability to be selected in the walking path. After that, as the second point is selected accordingly, another random segment selection is performed with the same principles. However, a second judgment needs to be made at the same time, to check contained points of the formed walking journey to avoid a repeated selection of road segments. The purpose of this judgment is to exclude the repeated or circle path in the walking journey as the citizens want to reach their destinations as directly as possible.

When a valid road segment, namely no repeated or circular path, is added in the walking path, the total length of current walking journey will be calculated. On the condition that total length once excesses the threshold length, the random walking trip will stop. The random walking iteration value of each vertex and road segment will be increased by 1. Then, another walking journey will be started.

After each random walking journey, the random walking value of each vertex will be aggregated and then to be compared with the aggregated values of all vertex after the previous walking journey. If the difference of the total random walking value is so small that the influence of additional walking journey can be ignored, the Graph can be considered as a stable situation and the whole random walking calculation will be finished. The stop condition is specified as following:

$$\frac{\sum \text{Rondam walking value}_{\text{current}} - \sum \text{Random walking value}_{\text{previous}}}{\sum \text{Random walking value}_{\text{current}}} \leq 0.00001$$

The flowchart of random walking calculation is illustrated as following figure (Figure 5-3).

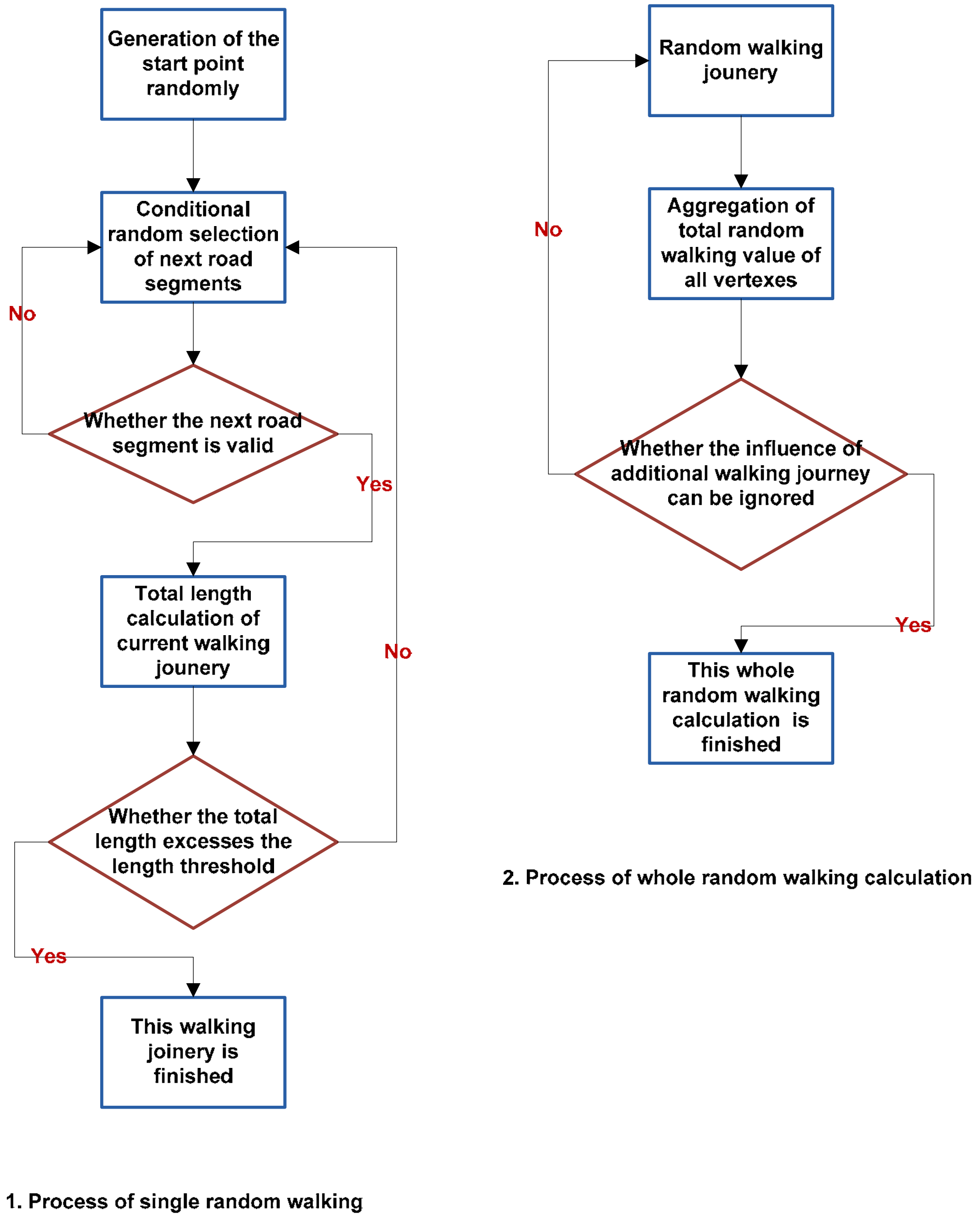


Figure 5-3 The flowchart of Random Waling calculation

5.2. Output of random walking calculation and further discussion

The objective of candidate stop classification is to identify the important locations in the urban spatial structure. Although spatial importance refers some obscure concepts like connectivity and accessibility, random walking calculation offers a practical method to quantify the spatial important places. The output of random walking (Figure 5-4 and Figure 5-5) is sensible. Random walking values of main roads (with more road capacity) are relatively higher than of sideways (less road capacity), which fits the practical traffic situation in Wuhan well. Meanwhile, the nodes located in the city center are given a higher random walking value than those in urban skirts. It is understandable as the higher road density in central areas can offer higher connectivity and more opportunity for traveling.

Figure 5-4 Random walking value of candidate bus stops

Figure 5-5 Random walking value of road segments

5.2.1. Improvement of the algorithm

Based on Li and Zhao work (Li Zhuoran, Zhao Shichen et al. 2009), some improvements have been proposed and implemented by providing walking length threshold in normal distribution and selecting a walking path considering the width of road segments. Rather than keeping a constant length threshold as in Li and Zhao work, applying dynamic thresholds in this research may improve resemblance with normal traffic activities. Furthermore, the decision of path selection is not absolutely stochastic as adopted in Li and Zhao work but rather conditionally random. The broader roads which stand for more traffic capacity are more probably walked through. Such conditional random selection principle not only fits with the realistic traffic behaviors but also be good at fully utilizing the capacity of transport facilities.

5.2.2. Discussion of random walking calculation result

Based on the output of random walking calculation, an assumption can be made that random walking value can indicate the spatial importance of road networks in terms of road capacity and connectivity. First of all, the random walking values (RWV) of road segments are correlated with the width of road segments which can be considered as an indicator of road capacity. It can be detected from Table 5-1 that the random walking values of road segments generally increase as their widths are broader. Nonetheless, the correlation is not strong enough as an exception can be observed in the width range of 50-60 meters (red records in Table 5-1). The correlation value tested with Pearson method between RWV and width is p=0.5332195. This might be because that the capacity is not the only variable determining the random walking value of road segments. The spatial importance is also associated with the location and formation of connections of the road network.

Table 5-1 Comparison width with random walking value of road segments

Width of road segments	Number of road segments	Min RWV	Max RWV	Ave RWV	SD RWV
<=20 meters	607	178	1294	623.1549	180.3548
20-30 meters	584	382	1437	751.1353	223.0471
30-40 meters	311	331	1540	788.5820	257.2481
40-50 meters	299	510	1898	951.2709	286.9885
50-60 meters	295	579	1530	910.6814	191.9982
>=60 meters	246	594	2098	1110.6260	275.9381

Secondly, the random walking value of candidate bus stops are correlated with their number of connected road segments, which can be described by the connectivity of road nodes. In fact, road nodes of networks with a higher number of connected edges have more probability to be connected with other nodes. The candidate bus stops connected with more road segments usually obtain higher random walking value (Table 5-2). The correlation value tested with Pearson method between them is p=0.6885622.

Finally, the random walking value of road segments and candidate bus stops are exchangeable. The random walking value of each candidate bus stop equals to the aggregation of random walking value of its connected road segments. Given that this research is mainly concerned with the location of stops, the random walking value of candidate bus stops will be applied in the further optimization.

Table 5-2 Comparison number of connected segments with random walking value

Number of connected road segments	Count of road segments	Min RWV	Max RWV	Ave RWV	SD RWV
1	1	237	237	237.0000	0.0000
2	336	312	1584	797.2470	179.3873
3	767	553	2893	1310.9087	358.7300
4	421	910	3491	1791.7791	490.2303
5	4	1620	2876	2293.5000	530.7539
6	1	2237	2237	2237.0000	0.0000

1. Similarity between random walking value and virtual traffic flows

Interestingly, similarity can be observed between random walking value and travel velocity of road networks. For example, by comparing the random walking value of road segments (Figure 5-5) with the travel velocity (Figure 3-5), it can be observed that road segments which are calculated with high random walking value get a relative low travel speed (especially in city center). On the contrary, the road segments which are calculated with low random walking value are assigned a high travel speed (especially in urban skirts). Thus, another assumption is obtained that the random walking value may be in positive proportion to traffic flows in road networks. This assumption, however, cannot be tasted in this research because of lacking data of quantitative traffic flows or quantitative traveling velocity.

2. Comparison random walking calculation with analysis of Space Syntax

As mentioned in Chapter 2.3.4, Space Syntax analysis can also describe the spatial importance of a road network. The Local Integration value is proved to correlate with traffic flows (Hillier 1999). Thus, a comparison can be made between random walking calculation (Figure 5-5) and space syntax analysis (Figure 5-6). Although, the spatial important areas indicated by both analyses are slightly similar, the high random walking value is specified and concentrated on the main roads.

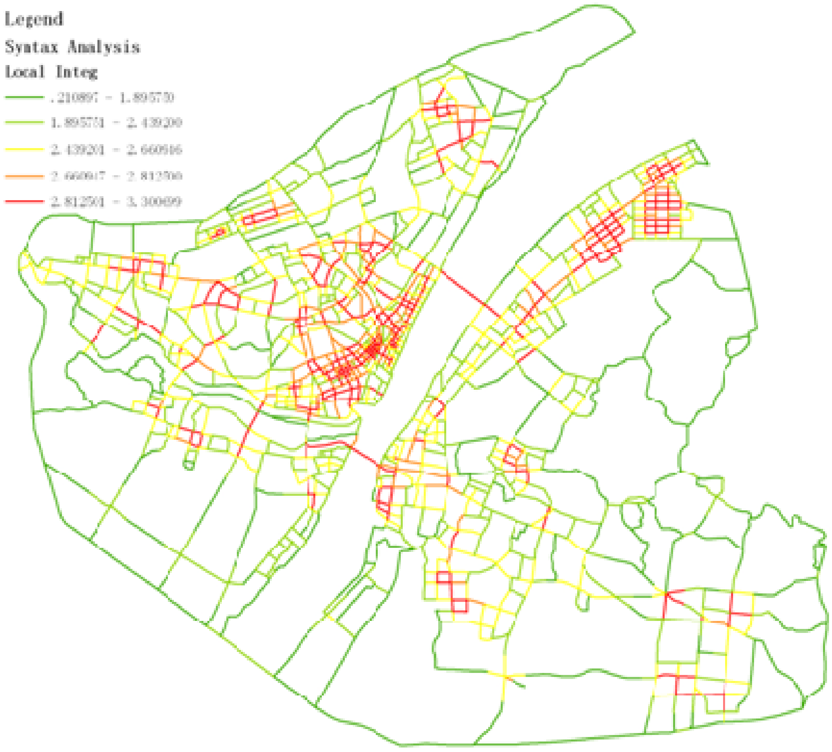


Figure 5-6 Local integration value calculated by Space Syntax of road segments

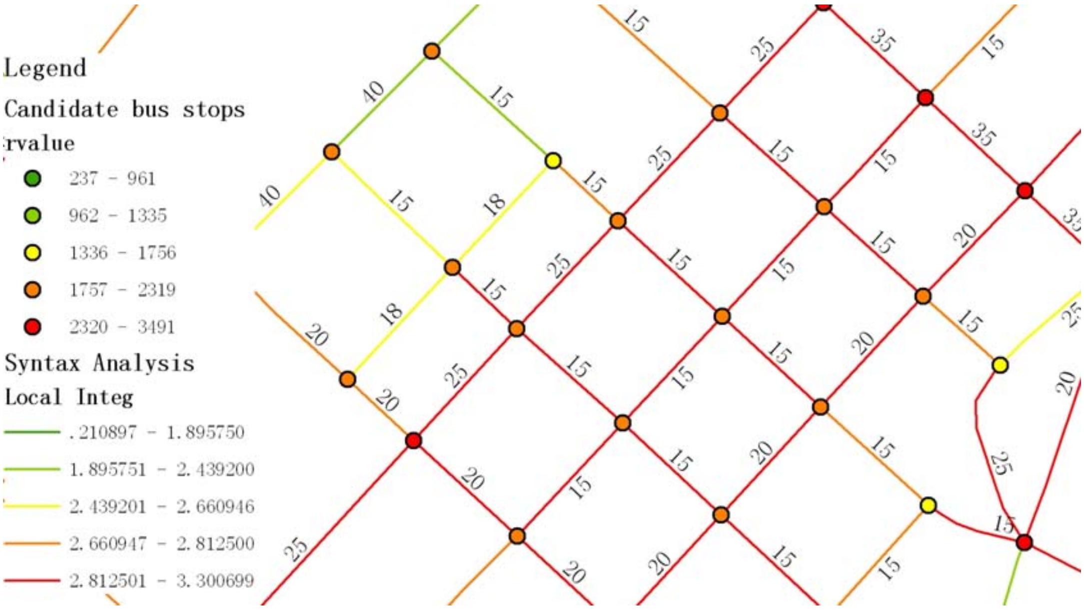
Since the Space Syntax is mainly focused on links rather than nodes (Batty 2004), the Local Integration value of each road segments is aggregated to their nearest connected candidate bus stop to make them comparable. Meanwhile, the widths of road segments are also aggregated in the same way to represent the capacity of each candidate bus stop. The number of connected road segments of each candidate bus stop is utilized to indicate the connectivity. Thus, the matrix of correlation value of involved variables tested with the Pearson method can be achieved as Table 5-3.

The correlation values are understandable. First of all, as the capacity of each candidate bus stop is determined both by the number of connected segments, namely connectivity, and the width of connected segments, the correlation between capacity and connectivity is only p=0.4588749. Secondly, because the local integration refers to the centralization of a given link in the spatial networks (Li jiang and Guo Qingsheng 2003), the aggregation of local integration value of a given point must be higher if it is connected with more links, thus is in proportion to the connectivity. As a result, the aggregated local integration value of candidate bus stops is closely correlated with connectivity but less correlated with the capacity. Finally, as the calculation of random walking of candidate bus stops is performed both considering the number and width of their connected road segments, the value is equally correlated with the capacity and connectivity, at least roughly.

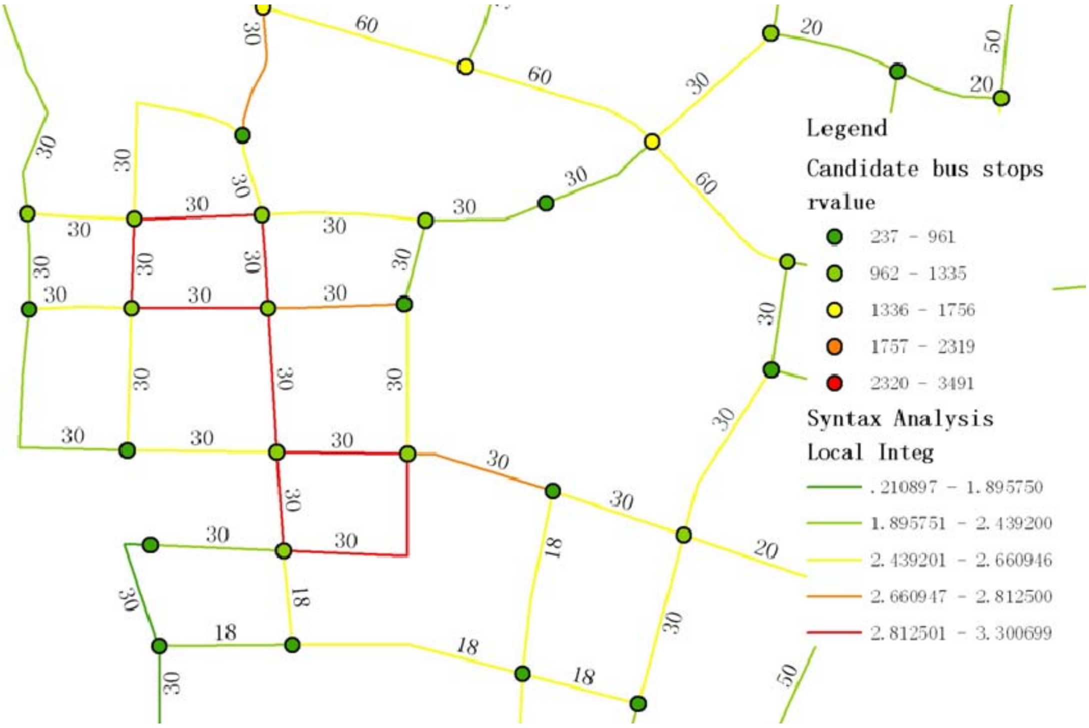
Table 5-3 Matrix of correlation value

	Random walking value	**Aggregated Local Integration Value**	**Aggregated width (Capacity)**	**Number of connected segments (Connectivity)**
Random walking value		0.682519	0.5815025	0.6885622
Aggregated Local Integration Value	0.682519		0.3804857	0.9241091
Aggregated width	0.5815025	0.3804857		0.4588749
Number of connected segments	0.6885622	0.9241091	0.4588749	

In sum, the random walking value is equally correlated with capacity and connectivity. The aggregated local integration is more correlated with connectivity but less correlated with capacity. It can be further observed that, random walking value and location integration are similar if the variation of road with is low (Figure 5-7(1)), otherwise they are different if the variation is high (Figure 5-7(2)).



1. Low variation of road width



2. High variation of road width

Figure 5-7 Comparison Random walking value with Local Integration

5.3. Conclusion of random walking calculation

First of all, the random walking calculation is developed based on Li and Zhao's work (Li Zhuoran, Zhao Shichen et al. 2009), some improvements of algorithm are devised in this research by providing walking length threshold in normal distribution and selecting walking path considering the width of the road segments.

Moreover, based on the output of random walking calculation, an assumption can be achieved that random walking value can indicate the spatial importance of road networks in terms of road capacity and connectivity.

Another assumption is obtained that the random walking value may be in positive proportion to with traffic flows in road networks. This assumption, however, cannot be tested in this research because of lacking data of quantitative traffic flows or quantitative traveling velocity.

Furthermore, by comparing random walking calculation with space syntax analysis of road segments in Wuhan, it can be found that the random walking value is equally correlated with capacity and connectivity. The aggregated local integration is more correlated with connectivity but less correlated with capacity. It can be further observed that, random walking value and location integration are similar if the variation of road with is low; otherwise they are different if the variation is high.

Finally, Random walking value of each candidate stop, mentioned as position potential value in above discussion, is set as weight for further optimization in the belief that those locations with high random walking values should be firstly selected as key bus stops to improve the bus system efficiency.

6. Optimization of stop locations in FLOWMAP

The objective of optimization is to obtain a trade-off of bus stop locations that has reduced stop redundancy, enlarged service areas, and maintained appropriate walking accessibility with minimal number of bus stops. Meanwhile, based on the two assumptions in chapter 5.3, random walking value of each candidate stop is set as weight in optimization to improve the bus system efficiency.

6.1. Procedure of optimization in FLOWMAP

The location models of FLOWMAP are used to calculate a minimal number of bus stops that can maintain sufficient service coverage and appropriate walking accessibility by the following procedures:

1 Key bus stops selection

Key bus stops are selected based on the random walking value to obtain the bus stops with a high spatial importance, i.e. high connectivity and capacity. The philosophy is based on two assumptions that were discussed in Chapter 5.3. Firstly, since the random walking value may indicate the spatial importance of road networks in terms of road capacity and connectivity, key bus stops generated with high random walking value can assure that bus system can fully utilize the road networks thus enhance the efficiency of bus system. Secondly, as the random walking values are in positive proportion to the traffic flows in road networks, bus stops located in high random walking value areas will effectively attract citizens to take buses thus to release traffic congestion and alleviate urban traffic problems.

2 Normal bus stops selection

Normal bus stops are generated based on public transport demand figures. Because of lacking practical demand data, the theoretical values based population distribution and land use pattern are calculated for each candidate bus stops. Candidates with high traffic demand will get a high priority in bus stop selection.

3 Different kinds of model combination

Bus stops are first selected by the Expansion model to get an initial stop distribution with a minimal number of bus stops that can stratify the defined service range weighted by random walking value or public transport demand figures. After that, the initial stop distribution will be calculated for the second time using the Relocation model to minimize average stop distance for improving system efficiency or to minimize the longest stop distance for enhancing system equity.

Furthermore, two comparable solutions, i.e. three-level optimization and two-level optimization, as discussed in chapter 4.2.3 are adopted. The procedures are described in Figure 6-1:

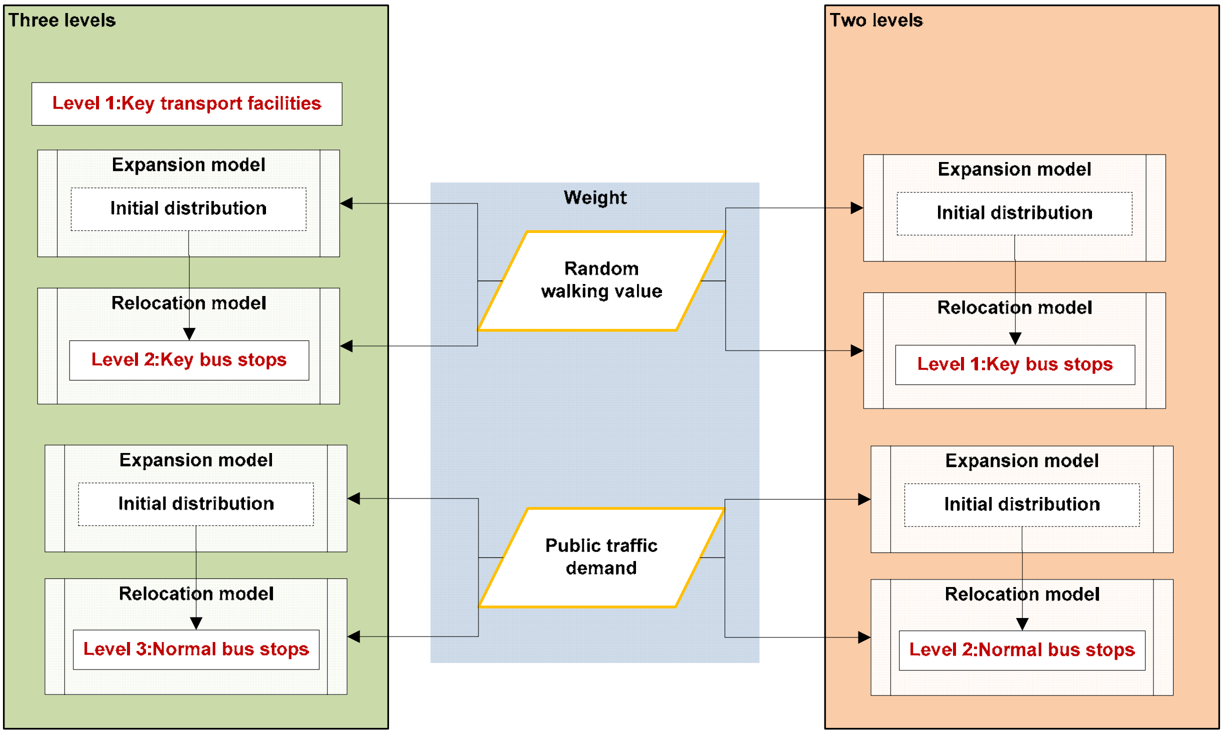


Figure 6-1 Procedure of optimization in FLOWMAP

6.2. Data conversion

Before starting the model operations, the required data has to be converted into feasible format. The Thiessen polygons have to be generated to present the candidate stops as a candidate locations. Meanwhile, the random walking value and public transport demand figures have to be aggregated to each polygon. Finally, the distance table is also required for recording the distances from any possible origins to destinations.

6.2.1. Thiessen polygons generation

Thiessen polygons of each road node are generated to present the bus stop candidates in model calculation. Candidate bus stops locate on centers of gravity of corresponding polygons. The candidate bus stops will be considered as valid bus stops if their polygons are selected in model calculation. Meanwhile, as the bus stops are located nearby the roads, the buffers of each road segments are generated. Those polygons (Figure 6-2) have been clipped with the road buffer to simplify the data.

Figure 6-2 Thiessen polygons presenting candidate bus stops

6.2.2. Weight aggregation

First of all, the random walking values of each candidate bus stop are aggregated to their thiessen polygons (Figure 6-3).

Secondly, the theoretical public production and attraction of each candidate bus stop are calculated by Huang (Zhengdong 2009). The production values are calculated using the accessibility model in which inhabitants living nearer to bus stops have more probability to travel by bus. Meanwhile, the attraction values are calculated using Monte Carlo Method that calculates the probability of people getting off buses which are different based on locations of urban areas and land use patterns. All the calculations are done on the basis of known population distribution, land use pattern and road networks. For each candidate bus stop, the public transport demand is defined as:

$$\mathrm{Demand_i} = \mathrm{Production_i} + \mathrm{Attraction_i}$$

Admittedly, the theoretic public transport demand figures can only indicate the relative importance of each candidate bus stops, and they might be overlapped in production calculation. The figures are aggregated to each thiessen polygon as Figure 6-4.

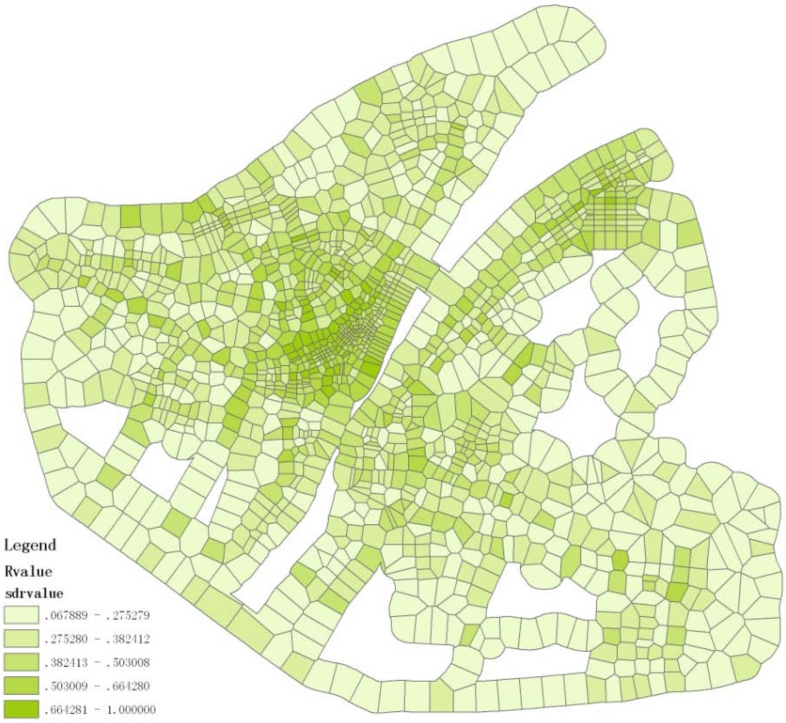


Figure 6-3 Random walking values aggregated to thiessen polygons

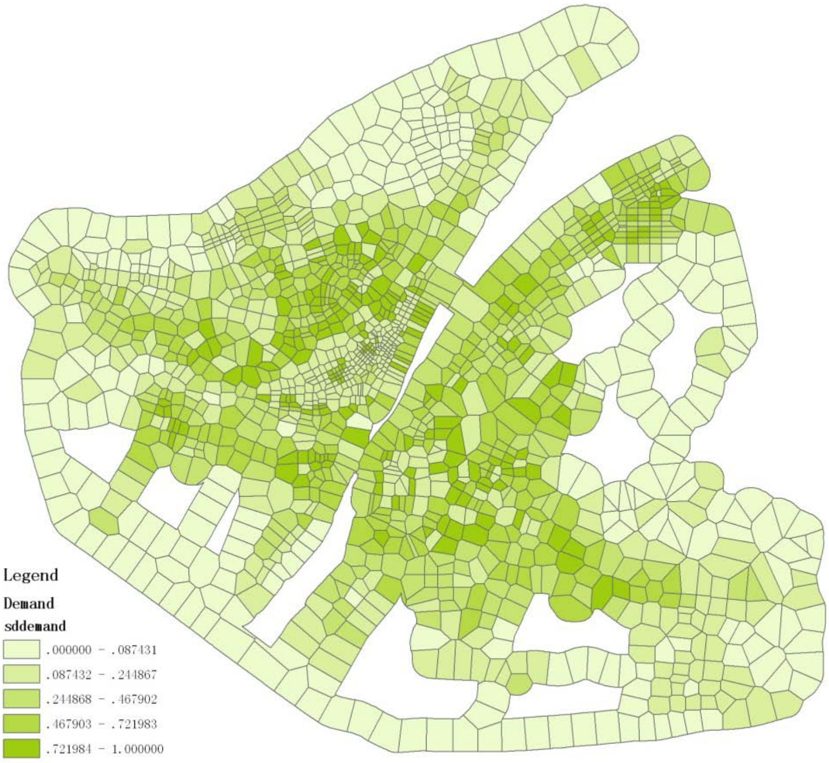


Figure 6-4 Public traffic demands aggregated to thiessen polygon

6.2.3. Distance table creation

The distance table is created to record the distances from any possible origins to destinations for model calculation. The connection method is selected as “node to node” to make sure that the service coverage calculation is started from candidate bus stops. Meanwhile, as any locations are possible for citizens walking as origins or destinations to or from candidate bus stops, the distance from any origin/destination to the nearest network node is 0 meter. The largest distance from any origin/destination to nearest network node is 54,913 meters and the largest distance between any origin/destination combinations is 39,578.48 meters.

6.3. Model operation

6.3.1. Three-level optimization

Level one: the planed and existing key transport facilities (Figure 4-4), i.e. planned subway stations, planned bus terminals and bus transfer stations, train stations and ferry port, are pre-selected as level one bus stops to reduce transfers of passengers in different traffic modes. The number of level one bus stop is 141.

Level two: key bus stops are selected based on random walking value to get the bus stops with a high spatial importance. Firstly, all candidate bus stops have been calculated in the expansion model to maximize the customer coverage with the range of 3,000 meters weighted by Random Value (Figure 6-5). Secondly, the outputs have been optimized in Relocation model to minimize the average distance weighted by Random Value. There are 59 key bus stops obtained finally.

Level three: normal bus stops have been selected in Expansion model by maximizing the customer coverage with the range of 800 meters and 1,000 meters weighted by public traffic demand separately (Figure 6-6). There are 423 or 258 normal bus stops obtained respectively.

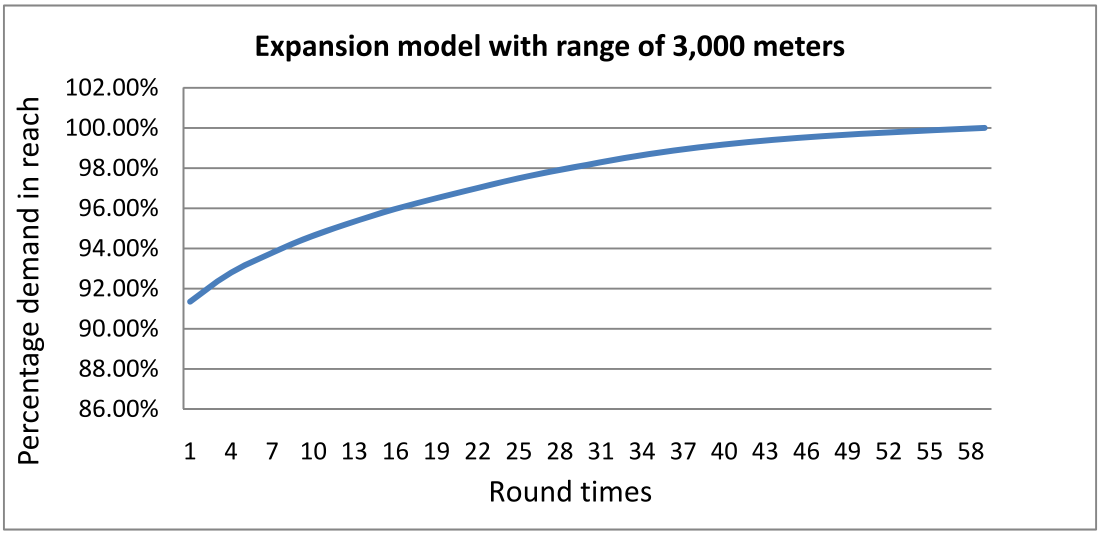
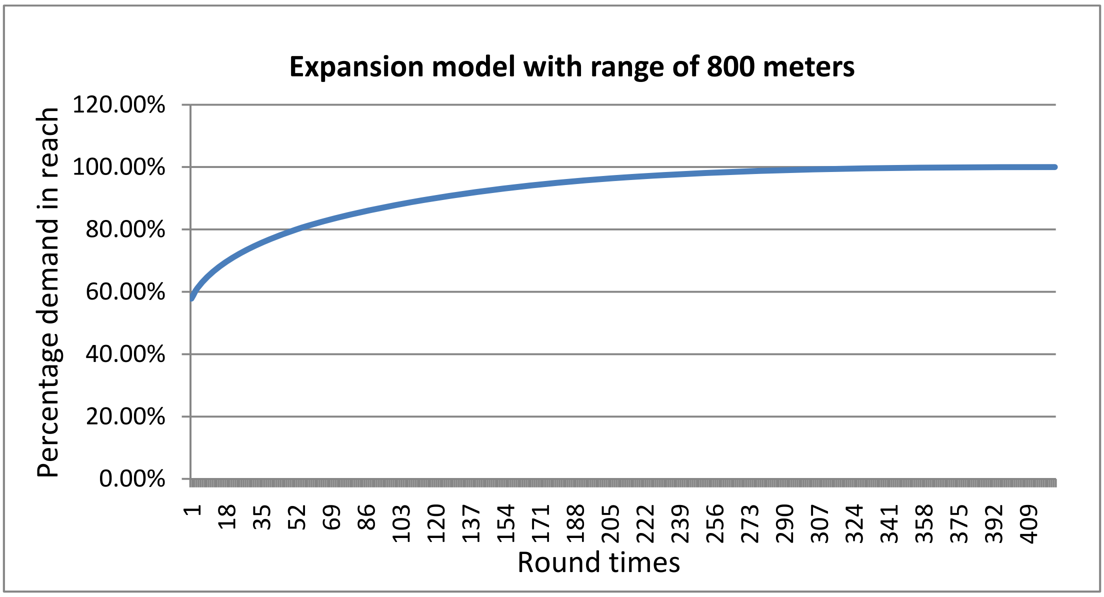


Figure 6-5 Key bus stops calculation in three levels optimization



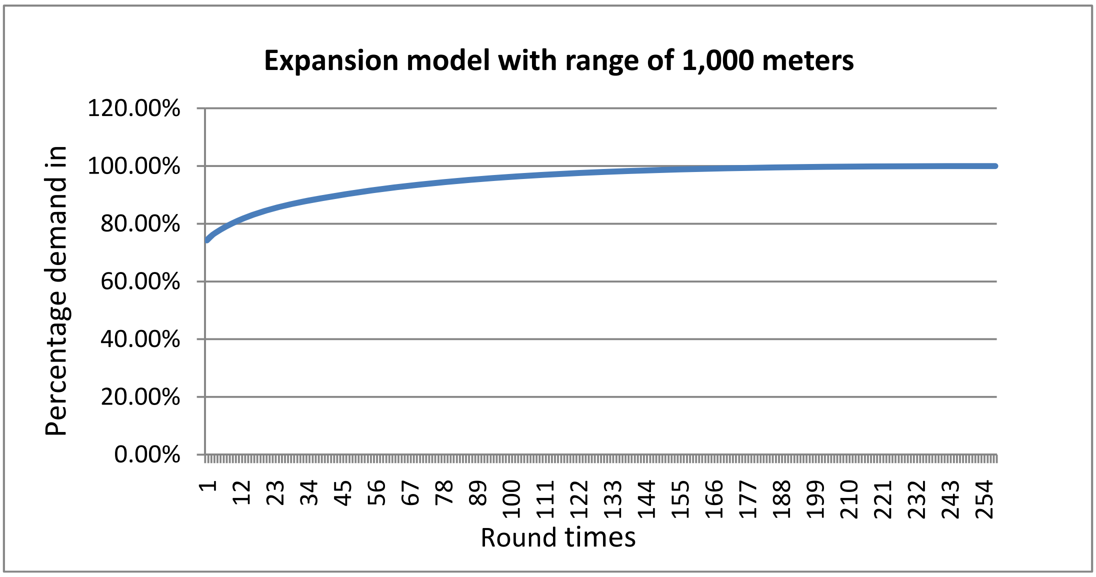


Figure 6-6 Normal bus stops calculation in three levels optimization

After that, the normal bus stops have been further optimized in the Relocation model to minimize the average distance and minimize the overall worst case distance weighted by public transport demand separately. The other option in the relocation model, namely to maximize individual market share, is not performed because it costs too much time.

The nearest distances of the optimized result for all cases are compared and illustrated in Table 6-1 and Figure 6-7. It can be concluded that, more bus stops are required if the service range is greater. In the optimization of using the expansion model with an 800 meters range, there are no significant differences among three kinds of optimization of model combinations. Among those outputs, the combination with using relocation model of minimal average distances can reduce the average stop distance mostly to improve system efficiency.

Nonetheless, in using the expansion model with a 1,000 meter threshold, the combination with using minimal average distances model can increase the minimal stop distance and reduce the average stop distance thus improved the system efficiency. While the minimal overall worst case distances combination decrease the maximal stop distance thus improve system equity.

In conclusion, in three-level optimization, the expansion model has determined minimal number of bus stops based on defined service range. More bus stops are needed if the range goes smaller. Meanwhile, the relocation model of minimizing average distance can reduce the average stop distance relatively to improve system efficiency. Meanwhile, the relocation model of minimizing overall worst distance can reduce longest stop distance to improve system equity. Finally, due to the limited research time, only the output (Figure 6-8) optimized with an expansion model with 800 meters range combining with minimal average distances model has been selected stand for three level optimization result in further evaluation.

Table 6-1 Nearest distances comparison in three levels optimization

Bus stop number	Selected model	Range (meter)	Min ND (meter)	Max ND (meter)	Ave ND (meter)	SD ND (meter)
623	Expansion only	800	196.79	1834.90	680.67	221.53
623	Expansion, Relocation using minimize average distance	800	196.79	1834.90	674.41	215.12
623	Expansion, Relocation using minimize overall worst case distance	800	196.79	1834.90	694.69	211.36
458	Expansion only	1,000	63.64	2134.91	803.85	302.01
458	Expansion, Relocation using minimize average distance	1,000	106.06	2300.20	821.35	292.88
458	Expansion, Relocation using minimize overall worst case distance	1,000	63.64	2296.96	831.45	286.48

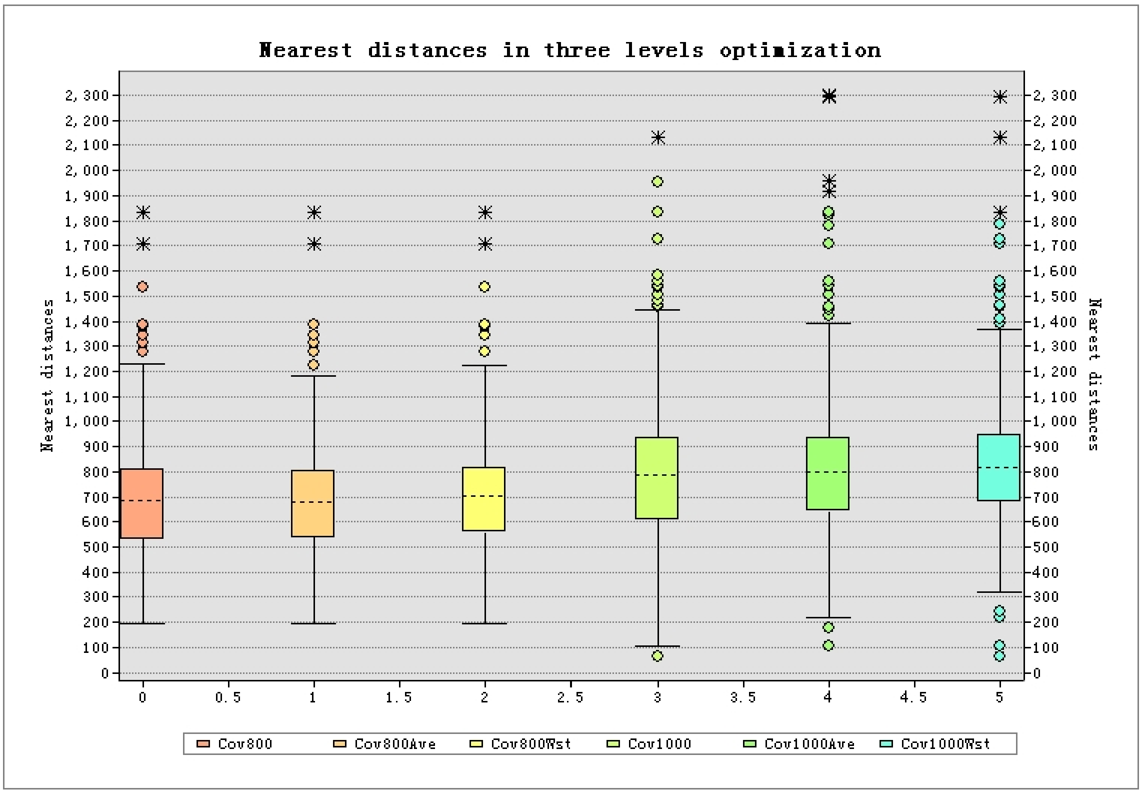


Figure 6-7 Nearest distances comparison in three levels optimization

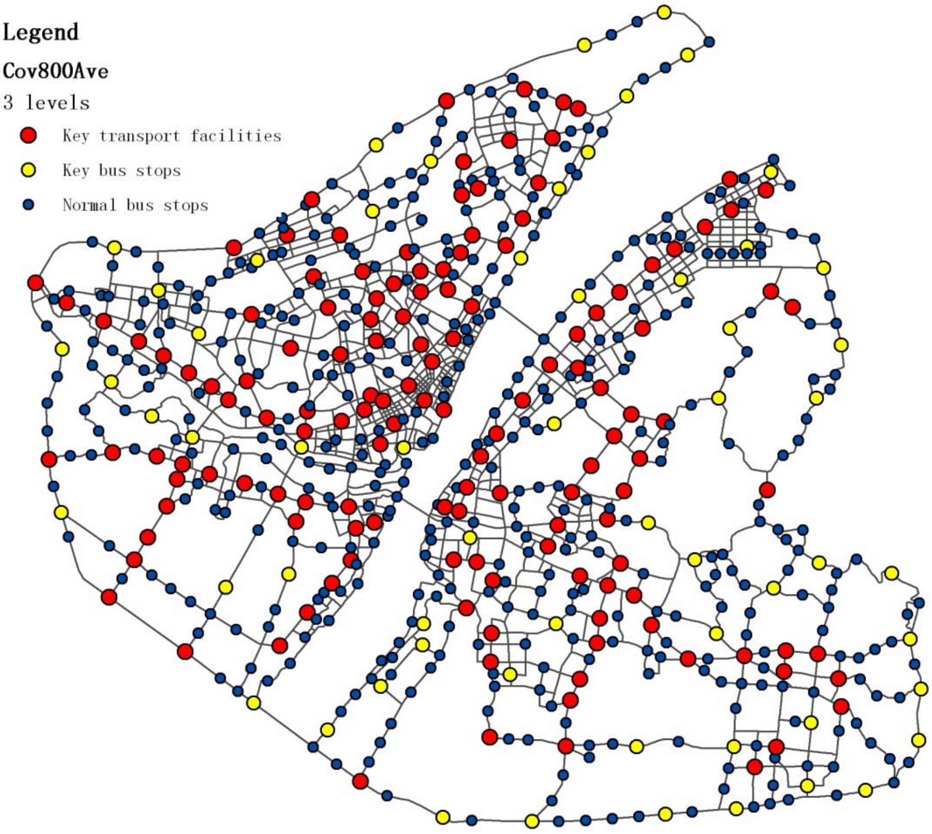


Figure 6-8 The output of optimization in three-level

6.3.2. Two-level optimization

Level one: key bus stops are selected with the same principles as three-level optimization. Firstly, all candidate bus stops have been calculated in the expansion model to maximize the customer coverage with the range of 5,000 meters weighted by Random Value (Figure 6-9). Secondly, the outputs have been optimized in Relocation model to minimize the average distance weighted by Random Value. There are 27 key bus stops obtained finally.

Level two: normal bus stops have been selected using the same principle utilized in the three-level optimization (Figure 6-10Figure 6-6). There are 563 or 366 normal bus stops obtained respectively.

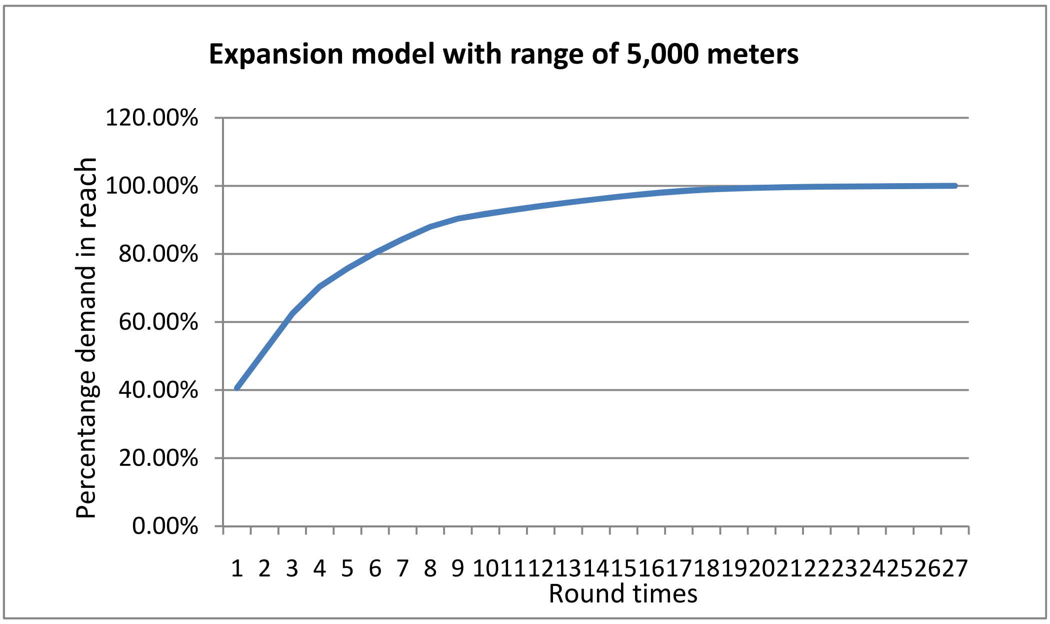
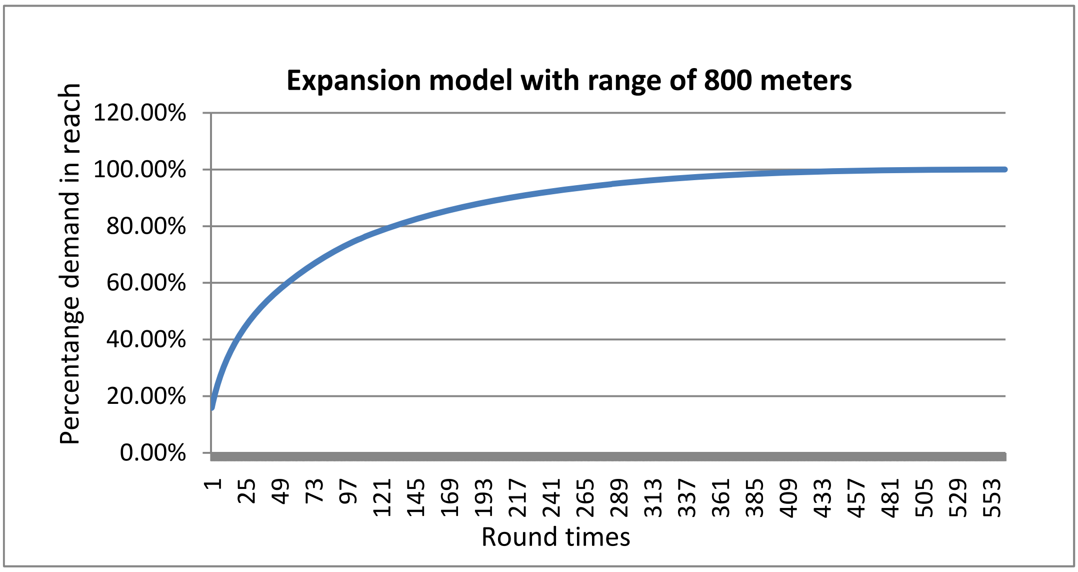


Figure 6-9 Key bus stops calculation in two levels optimization



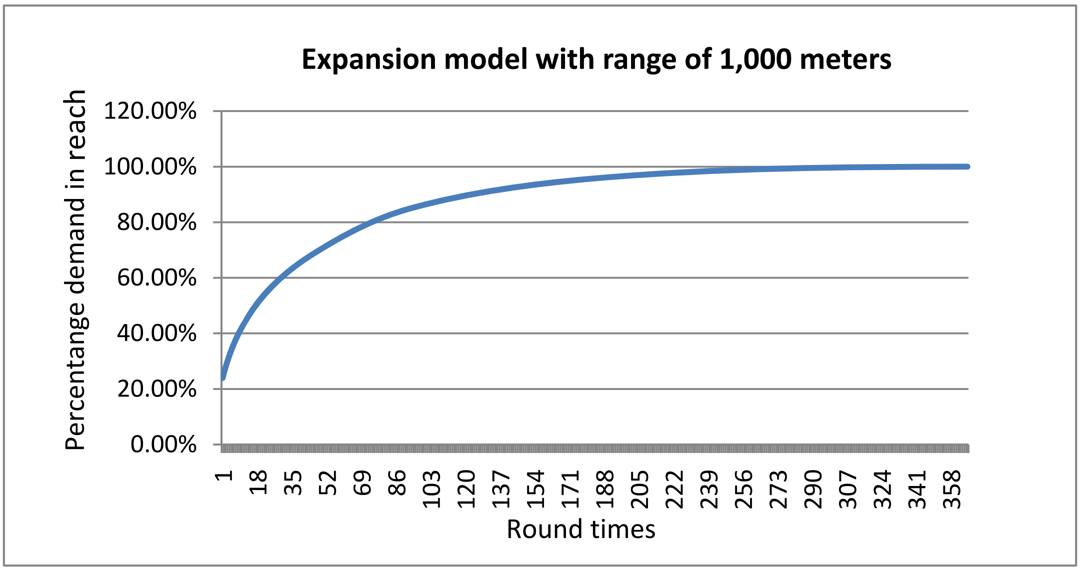


Figure 6-10 Normal bus stops calculation in two levels optimization

After that, the normal bus stops have been further optimized in the relocation model to minimize the average distance and minimize the overall worst case distances weighted by public transport demand separately. The nearest distances of optimized result for all cases are compared and illustrated in Table 6-2 and Figure 6-11. The output is understandable. First of all, as no limitation of pre-fixing key transport facilities, fewer bus stops are required to reach the same service range. Secondly, the relocation model of minimizing average distances can offer a more concentrated nearest stop distances namely small average stop distance that improve system efficiency, but causes some extreme maximal stop distances that impair system equity. The combination with minimizing overall case worst distance option, however, can avoid such extreme cases that improve system equity. However, it generated an output which is slightly higher in terms of mean stop distance and larger standard deviation that impair system efficiency. Finally, the output (Figure 6-12) that have be optimized by using the expansion model with an 800 meters range combining with minimal average distances model has been selected to stand for the optimized result of two level optimization in evaluation.

Table 6-2 Nearest distances comparison in two levels optimization

Bus stop number	Selected model	Range (meter)	Min ND (meter)	Max ND (meter)	Ave ND (meter)	SD ND (meter)
590	Expansion only	800	196.79	1710.01	708.65	241.64
590	Expansion, Relocation using minimize average distance	800	196.79	1796.84	692.19	229.03
590	Expansion, Relocation using minimize overall worst case distance	800	196.79	1710.01	715.52	226.96
393	Expansion only	1,000	221.23	1920.52	901.48	327.13
393	Expansion, Relocation using minimize average distance	1,000	286.06	2597.57	887.99	296.74
393	Expansion, Relocation using minimize overall worst case distance	1,000	232.87	2073.10	931.51	304.12

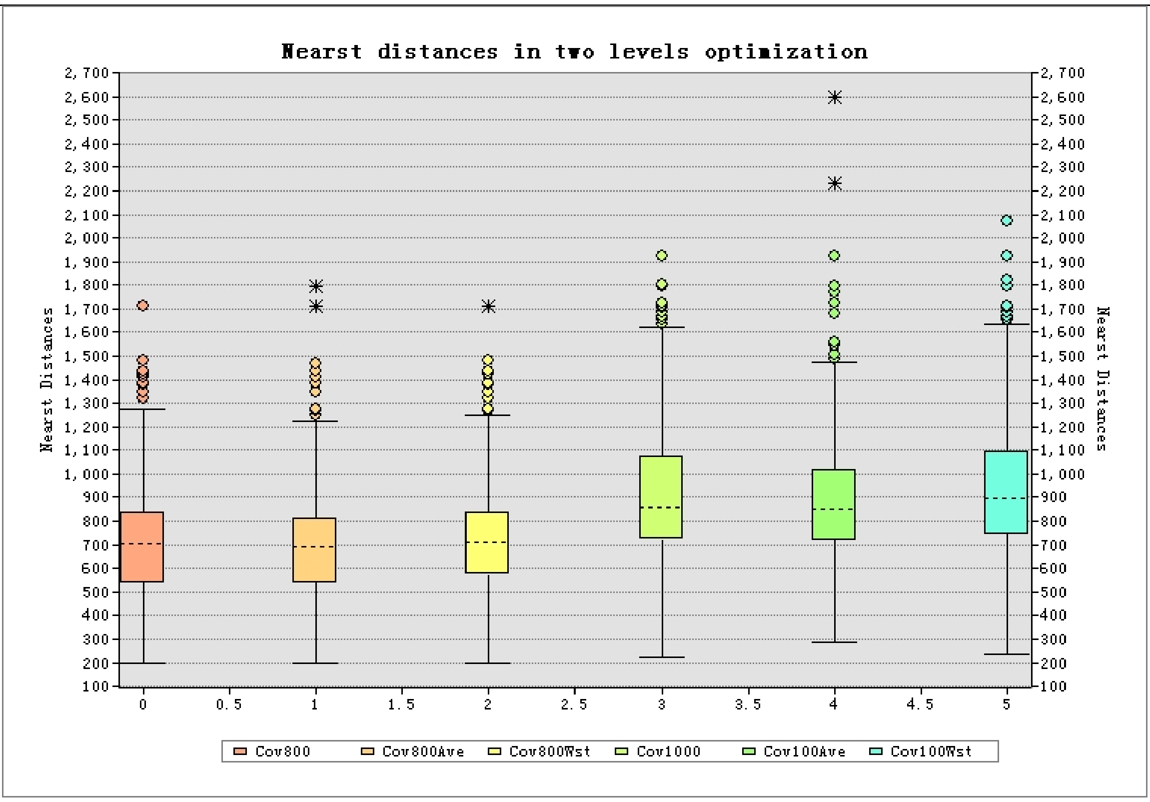


Figure 6-11 Nearest distances comparison in two levels optimization

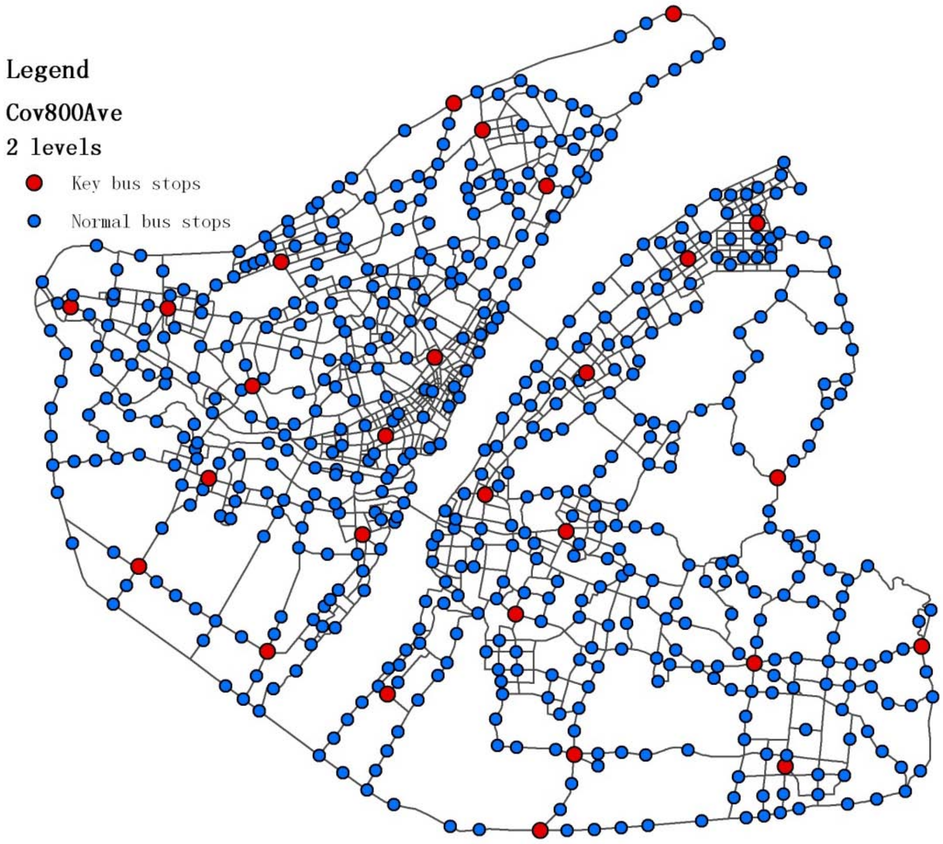


Figure 6-12 The output of optimization in two-level

6.4. Conclusion of bus stop optimization

Three kinds of model combinations with two kinds of services ranges are executed in the optimization. Generally, smaller service range requires more bus stops in expansion model calculation. Relocation model performs more effetely in two-level optimization. This may because of no pre-fixed bus stops in two-level optimization that models can calculate with more flexibility.

Although it is incomplete to evaluate the locations just by the nearest stop distances, only the comparison of nearest distances are performed because of the time limitation. It can be concluded that expansion model can offer an initial location of bus stops that satisfy the defined service coverage. Relocation model can further optimize the initial location by minimizing average stop distance to improve system efficiency or by minimizing longest stop distance to improve system equity.

Finally, the outputs optimized by the expansion model with 800 meters range combined with relocation model with a minimal average distances have been selected for further evaluation with respects to valid service coverage, served public transport demand and walking accessibility.

7. Evaluation and discussion

The objective of evaluation the result is to test whether the expected improvements are achieved by above optimization. As the objective of optimization is to reduce the redundancy in city center and enlarge service coverage in the urban outskirts, the valid service coverage is assessed firstly. Meanwhile, concerning that relocation of bus stops may affect walking accessibility and service coverage that further influences served demands, walking accessibility and served public transport demands are also estimated. Finally, the deficiency of this research is also discussed.

7.1. Evaluation of optimized bus stops

To reduce the stop redundancy in the city center, the number of bus stops locating on places with superabundant bus stops will be reduced that might cause lower walking accessibly and fewer served demand. On the other hand, to enlarge service areas in the urban outskirts, the total bus stop number will increase that may cause a higher operational costs for the system. Therefore, an evaluation is performed to proof whether the trade-off can be reached that not only reducing the redundant stops and enlarging service coverage, but also maintaining an adequate bus stop number, served demand and walking accessibility.

First of all, the service coverage and served demand are evaluated by comparing the valid service areas and covered population between existing bus stops and optimized bus stops using Spatial Analysis in ArcGIS. Secondly, the walking accessibility is assessed by calculating Point Pattern in R.

7.1.1. Valid service coverage and served demand

Considering the fact that citizens usually walk to the nearest stops taking buses, the valid service coverage is generated as the Thiessen polygons of each bus stops. Meanwhile, assuming that citizens are only willing to walk to the bus stops within 500 meters from their origins or destinations, those Thiessen polygons are limited by being clipped with the buffer of each bus stop within 500 meters.

Consequently, diameters of each valid crevice areas are computed as well to estimate the stop distances. By simplifying the coverage as a circle, the diameter is defined as follows:

$$\text{Diameter of stop coverage} = \frac{\text{Area of stop coverage}}{\text{Perimeter of stop coverage}} \times 4$$

Since the coverage of each stop is limited by the buffer of each stop within 500 meters, the maximal diameter of a bus stop catchment should not be more than 1,000 meters.

The covered population of each stop is calculated to evaluate the served demands for three reasons: firstly, the virtual public demands are not available in this research; secondly, the public demand which is utilized as weight in optimization is theoretical value that can only indicate the relative importance of each candidate bus stops, and they might be overlapped in production calculation; thirdly, population distribution is available in this research, and it is in proportion to the public traffic production.

The areas of valid service coverage, stop number and served demands of existing bus stops and bus stops optimized in three-level or two level are summarized in Table 7-1:

Table 7-1 Valid service coverage and demand

	Number	Total areas (square meters)	Average areas (square meters)	Total demands	Average demands
Existing bus stops	733	283,688,618.05	387,024.04	2,983,904	4,071
Optimized bus stops in three levels	623	351,430,792.50	564,094.37	2,992,516	4,803
Optimized bus stops in two levels	590	339,539,531.86	575,490.73	2,896,379	4,909

It can be concluded that the areas of service coverage is enlarged in both optimizations by maintaining a fewer stop number. In the three-level optimization, the total demands and average demands are both increased. Although, the total demands in the two level optimization are decreased slightly, the average served demands are increased which indicates a higher efficient service quality.

The valid service area of bus stops is depicted in Figure 7-1, Figure 7-2 and Figure 7-3:

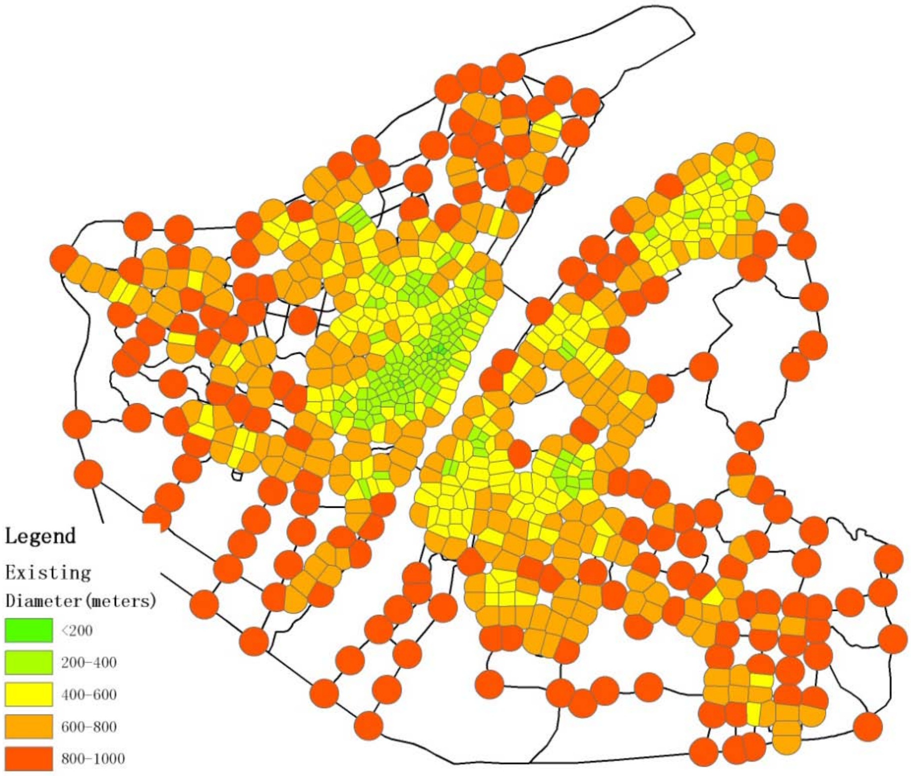


Figure 7-1 Valid service areas of existing bus stops

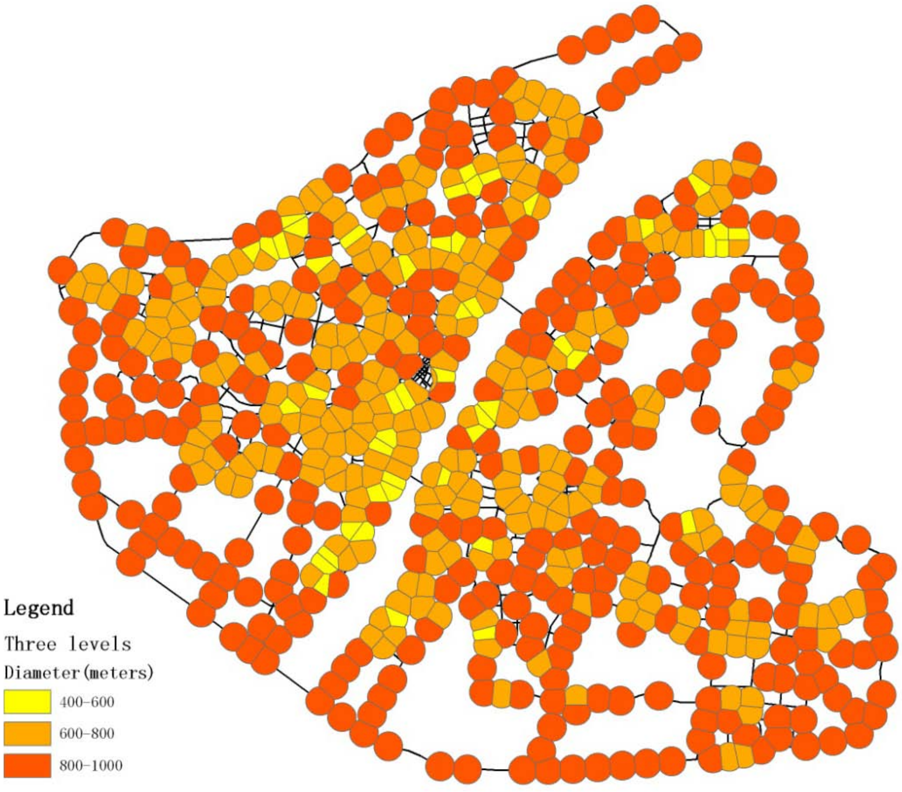


Figure 7-2 Valid service areas of three-level optimized bus stops

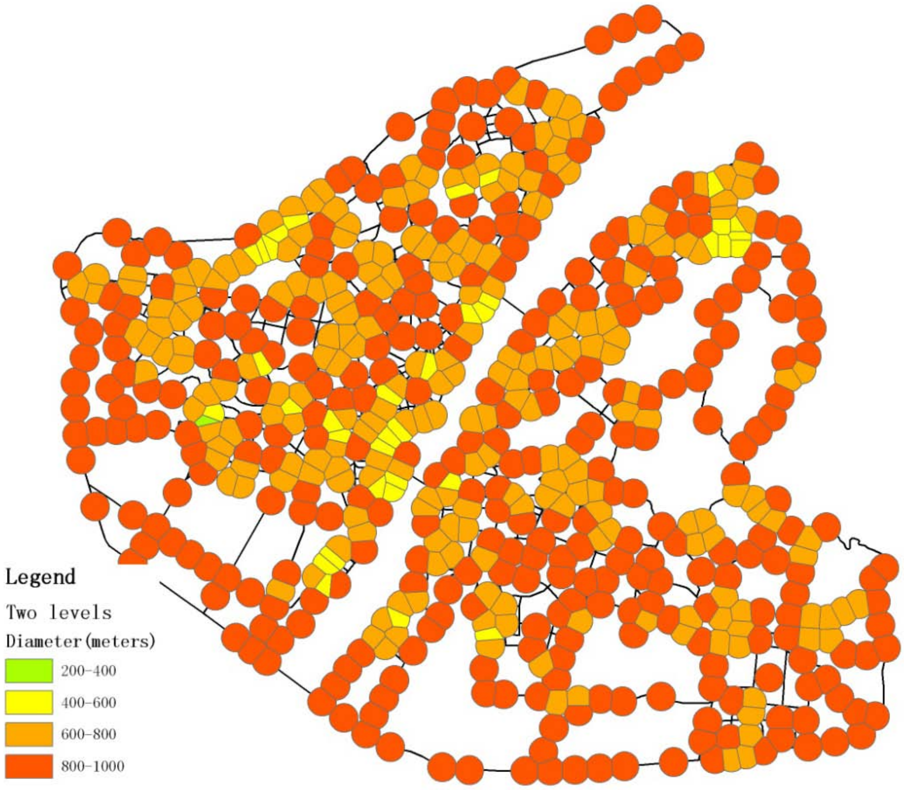


Figure 7-3 Valid service areas of two-level optimized bus stops

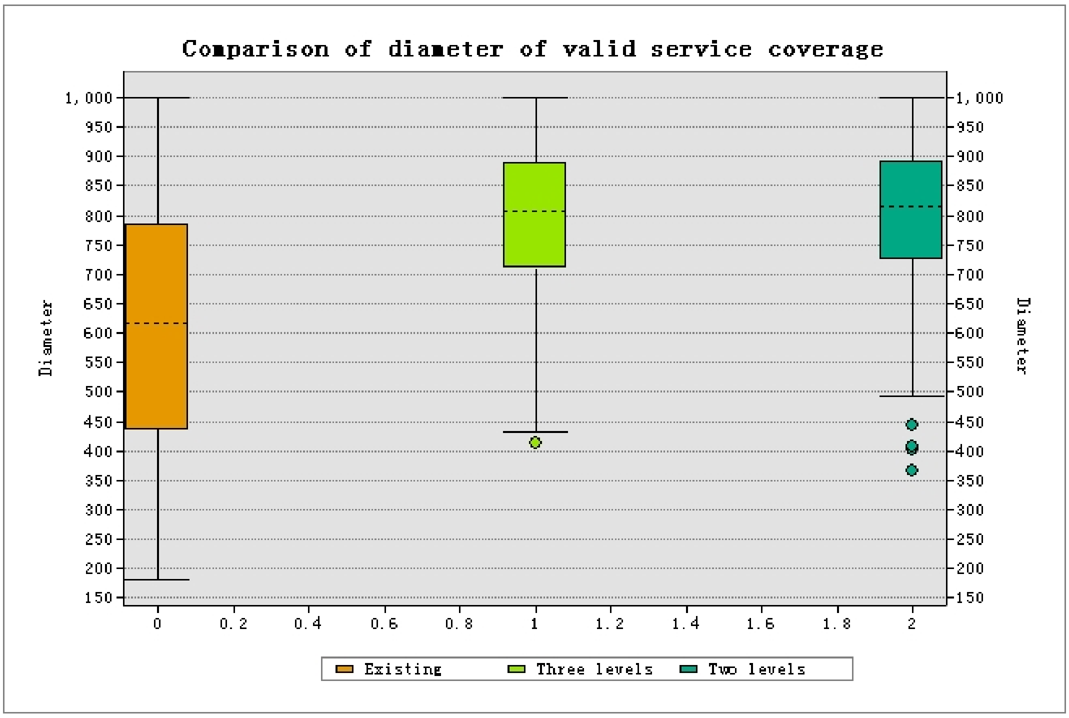
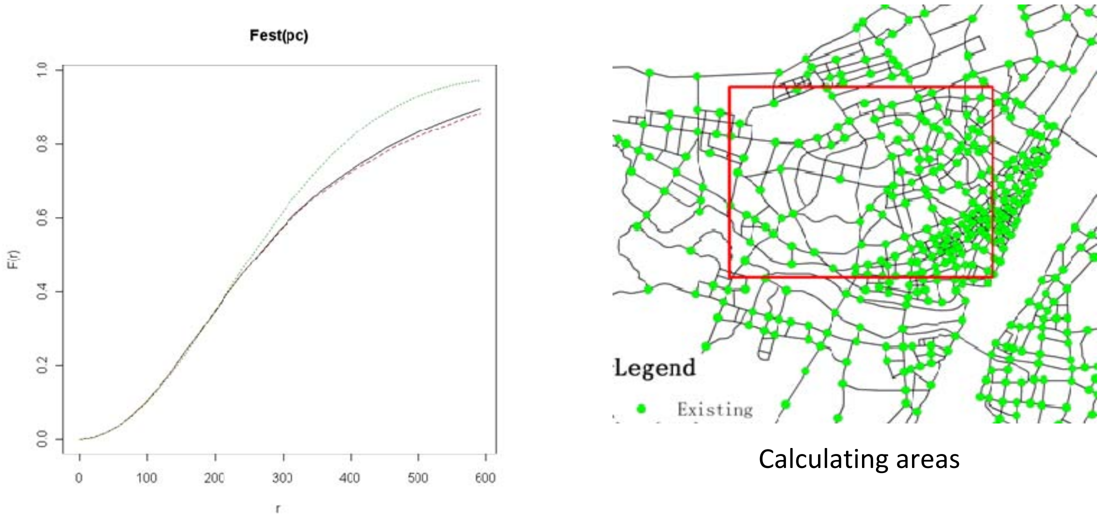


Figure 7-4 Comparison of diameters of valid service areas

By comparing the service areas, the redundant bus stops in central areas are reduced and the service coverage of urban outskirts is enlarged. Statistically, minimal diameters of valid service areas of optimized bus stops are more than 350 meters, and the main diameters are concentrated from 700 meters to 900 meters. While the diameters of existing bus stops are majorly distributed from 400 meters to 800 meters, with a minimal diameter less than 200 meters (Figure 7-4).

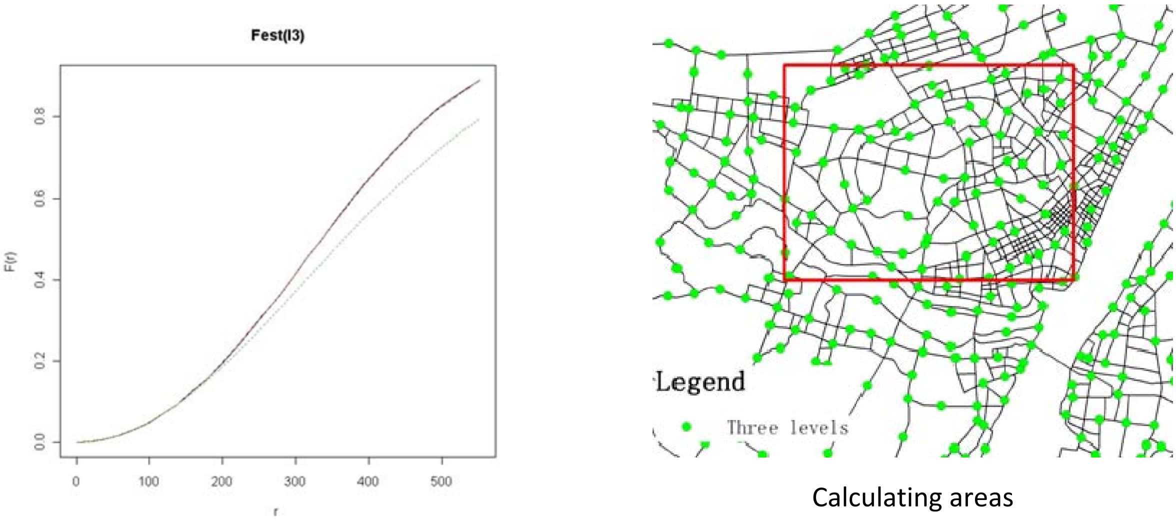
7.1.2. Walking accessibility

As the redundant bus stops are mainly reduced in the city centers, the evaluation of walking accessibility is evaluated in central areas by calculating point patterns in R. F function of point pattern calculation is computed.



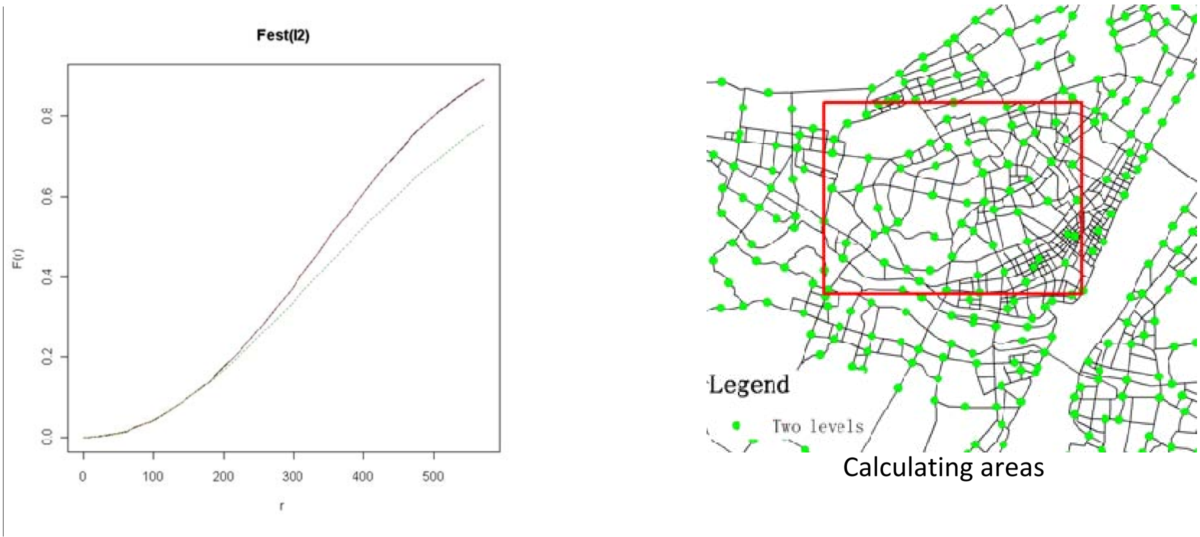
Calculating areas

Figure 7-5 Point pattern calculation of existing stops



Calculating areas

Figure 7-6 Point pattern calculation of three-level optimized stops



Calculating areas

Figure 7-7 Point pattern calculation of two-level optimized stops

In the central areas, the probability of reaching one existing bus stop for citizens walking within 200 meters is nearly 40%, and will increase to nearly 80% if they walk more than 500 meters (Figure 7-5). While, for the optimized bus stops, the probability is less than 20% for citizens walking within a range of 200 meters, and it will goes up more than 80% for citizens walking more than 500 meters (Figure 7-6 and Figure 7-7). The walking accessibility of optimized bus stops is maintained as citizens in central areas can reach equivalent number of bus stops within appropriate walking distance, namely 400 to 500 meters.

In sum, after stop location optimization, redundant stops in city centers are reduced; service coverage in urban outskirts is enlarged. Meanwhile, the serviced demands and walking accessibility are maintained by distributing fewer bus stops. Operational costs will be saved accordingly.

7.2. Limitation of the used optimization

Due to the limited research time and because of unavailable data, some deficiencies of this research are:

1. The evaluation of efficacy of key bus stop is infeasible

The efficacy of key bus stops optimized based on random walking values cannot be assessed. The philosophy for selection of key bus stops is constructed on the basis of two key assumptions as discussed in Chapter 5.3.

However, the operating efficacy and efficiency are impossible to be evaluated by existing data. It might be implemented when the optimized bus stops are practically utilized o quantitive traffic flow data are collected.

2. Extreme concentrated public transport demands exist in central areas

As the number of bus stops has been reduced in central areas (Figure 7-8, Figure 7-9 and Figure 7-10), extreme public transport demands concentrate in such areas that may cause congestion of waiting people and overlapped bus routes distributions.

However, the locations with a high concentrated public transport demand can be further optimized by distributing more bus stops to release the congestion of waiting people and maintain the sufficiency of public facilities (Figure 7-11). The additional stops are selected in the expansion model by defining a smaller service range.

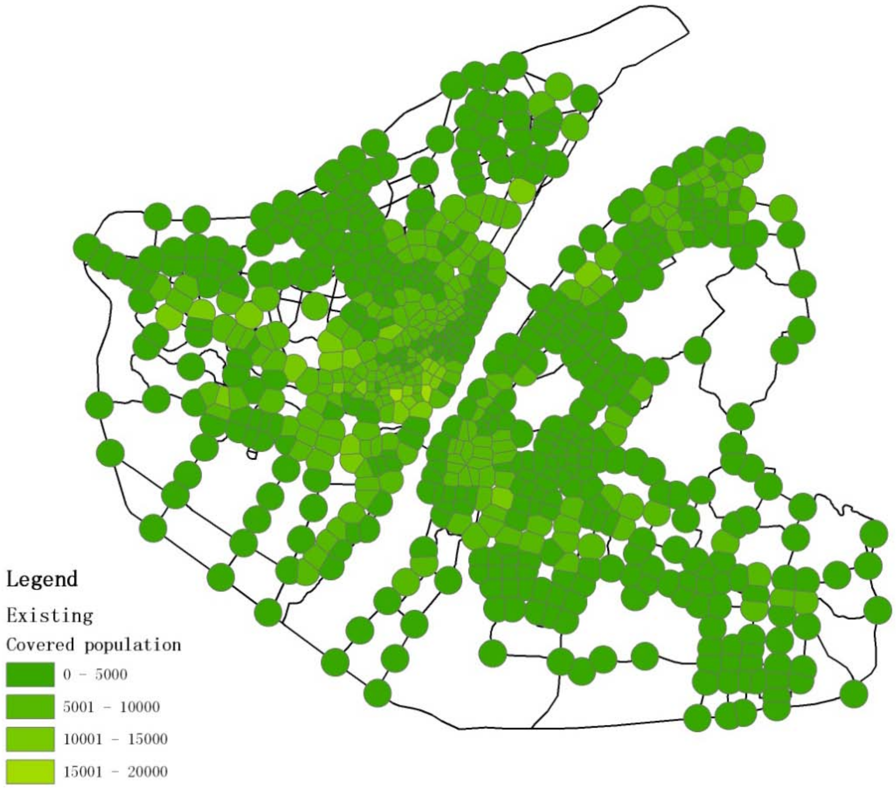


Figure 7-8 Population covered by service coverage of existing bus stops

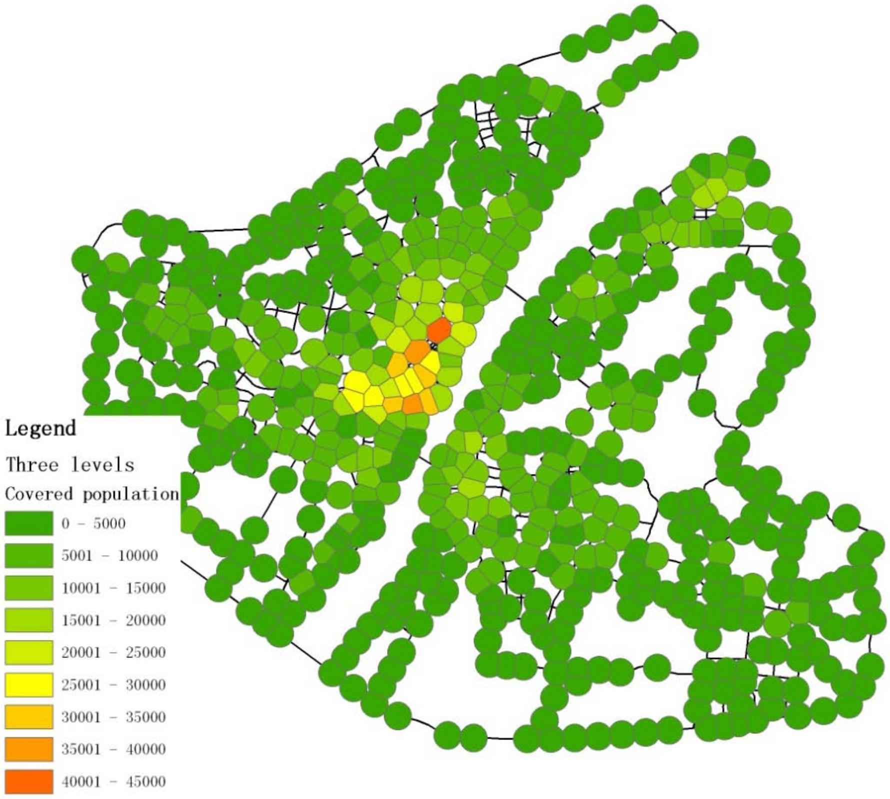


Figure 7-9 Population covered by service coverage of optimized bus stops in three-level

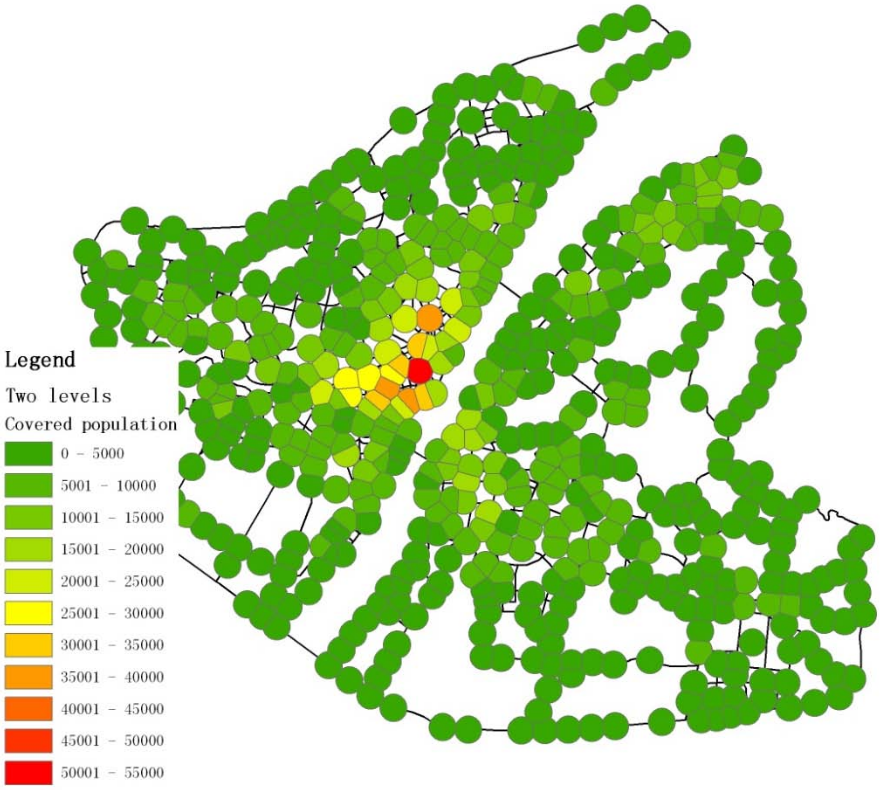


Figure 7-10 Population covered by service coverage of optimized bus stops in two-level

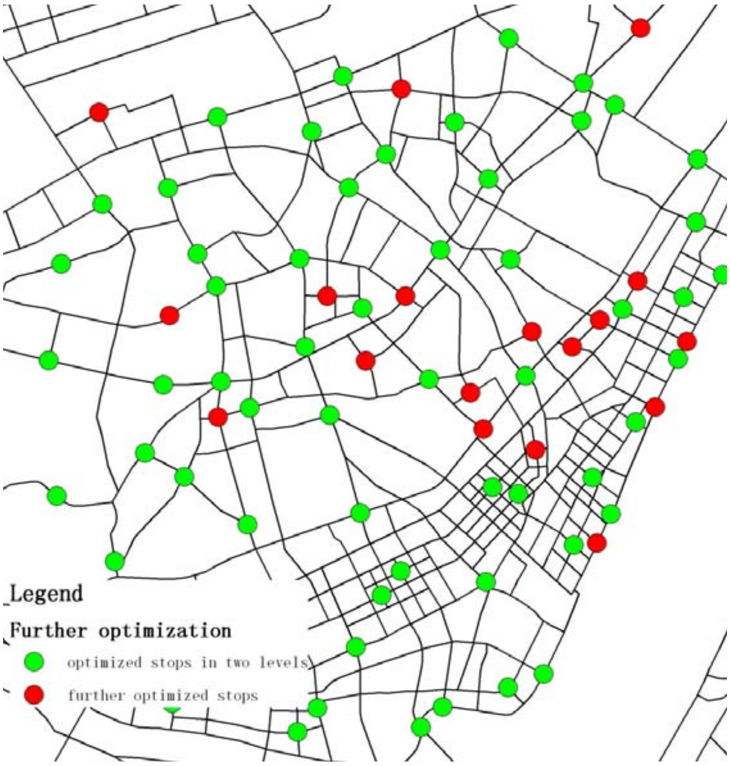


Figure 7-11 Further optimization in central area

3. Insufficient candidate bus stops impair the precision of optimized result

The lengths of road segments connected to each candidate bus stop are less than 1,000 meters (Figure 4-6). Comparing with road segments with length of up to 60 meters which are utilized in Ibeas' stop space optimization model (Ibeas, dell'Olio et al.), the lengths road segments in this research are very high thus leading to an insufficient number of candidate bus stops. The large lengths of road segments will highly constraint the efficacies of model calculation in FLOWMAP thus impair the precision of optimized result.

7.3. Conclusion

The objective of evaluation is to test whether the expected improvements are achieved by stop optimization. The valid service coverage is assessed first. Meanwhile, walking accessibility and served demands are also estimated. Based on the evaluation, it can be concluded that after stop location optimization, redundant stops in city centers are reduced; service coverage in urban skirts is enlarged. Moreover, the serviced demands and walking accessibility are maintained by distributing fewer bus stops. The operational costs will be saved accordingly.

Due to limited research time and unavailability of certain data, some deficiencies of this research exist. For example, the evaluation of efficacy of key bus stop is infeasible. Moreover, extreme public transport demands concentrated in central areas that may cause high numbers of waiting people and overlap of bus routes. Fortunately, such concentrated public transport demand can be released by distributing more bus stops. Finally, insufficient candidate bus stops impair the precision of the optimization result due to the limitation of computation power.

8. Conclusion

8.1. Achievement of this research

The objective of this research is to optimize bus stop locations in Wuhan in order to reach a trade-off that reduces redundant bus stops in central areas and enlarge service coverage in urban skirts by maintaining sufficient served traffic demand, walking accessibility and adequate bus stops. Several research questions have been addressed accordingly.

The optimized bus stop locations are finally obtained following the proposed research mythology, the research questions are answered accordingly.

Question1: What factors should be considered when selecting bus stops?

Bus stop optimization mainly aims at distributing a set of bus stop locations that can mostly satisfy public transport demand, maintain adequate walking accessibility and cover sufficient service areas with minimal number of stops. From the viewpoint of public transport operators, the operational costs, served traffic demand, and existing transport facilities including road networks, key transport facilities will be considered for bus stop selection. However, from the viewpoint of bus users, walking accessibility, connection with other traffic modes and service quality are important factors.

Furthermore, the spatial structure of road networks is another important factor in bus stop selection. The efficiency of urban traffic system will be highly improved if the bus stops, which largely determine the routes of bus driving, are composed of locations with high connectivity and road capacity.

Question2: What data is required for candidate bus stops generation?

Associating with literature (Chien and Zhaoqiong Qin 2004; Lao Yong and Liu Lin 2009),and considering the availability of appropriate data, the required data includes road and route networks, land use pattern, population distribution, existing bus stop locations and key transport facilities, i.e. planned subway stations, planned bus terminals, bus transfer stations, train stations and ferry port.

Road networks provide the condition for bus stop optimization, as bus stops are located along the roads. Passengers can have access to the public transit system through the road network. In addition, land use patterns and population distribution both contribute to the traffic demand. Land use patterns, especially the distribution of commercial and residential land, steer the direction of traffic flows by determining the locations of traffic attraction and production. Population density is in proportion with the amount of traffic production and indirectly affects the attraction. Meanwhile, there are two purposes of using the existing bus stop locations: for investigating the current problems of existing stop locations as discussed in chapter 1.2 and for making comparison with optimized stop locations to verify the improvements. Finally, key transport facilities, i.e. planned subway stations, planned bus terminals and bus transfer stations, train stations and ferry ports should also be taken into account when considering reducing the transfers of passengers in different transport modes.

Question3: How to perform the spatial selection with respect to the determined factors?

The objective of candidate bus stop generation is to produce the locations in Wuhan that can potentially be selected as bus stops. Considering the accessibility and connectivity with planned subway stations, which are normally located beneath the intersections of urban roads, all the intersections of urban roads are firstly selected as candidate stops through a Network Analysis in ArcGIS. In addition, given that the road segments in the central areas are generally shorter than in the urban outskirts that may influence the precision of the optimized result, road segments of which (excluding bridges) the lengths are more than 1,000 meters are broken down manually, and more candidate stops have been added accordingly to maintain the point density equally spread geographically. Although, more candidate stops can assure a more rational optimized output, too much candidate bus stops require high computational ability that may be beyond the scope of this research. Therefore, only 1,500 nodes are selected as candidate stops and accordingly 2,355 road segments are maintained in the road network.

Question4: How to operationalize the random walking model?

The random walking calculation is developed based on Li and Zhao’s work (Li Zhuoran, Zhao Shichen et al. 2009). Some improvements of their algorithm have been implemented in this research by providing walking length threshold in normal distribution and selecting walking path considering the width of the road segments.

Moreover, based on the output of random walking calculation, the assumption has been made that the random walking value indicates the spatial importance of road networks in terms of road capacity and connectivity.

Another assumption is obtained that the random walking value may be in positive proportion to with traffic flows in road networks. This assumption, however, cannot be tested in this research because of lacking data of quantitative traffic flows or quantitative traveling velocity.

Question5: What indicators can be set as goal for optimization?

The objective of optimization is to obtain a trade-off of bus stop locations that has reduced stop redundancy, enlarged service areas, and maintained appropriate walking accessibility and served public transport demand with minimal number of bus stops. Therefore, the indicators for bus stop optimization include number of bus stops, area of service coverage, and number of passengers that covered by valid bus service areas. Meanwhile, the walking distances from origins/ destinations to the nearest bus stop should also be considered.

Question6: How to utilize the location models in FLOWMAP?

Three kinds of model combinations with two kinds of service ranges are executed in the optimization. Bus stops are first selected by the expansion model to get an initial stop distribution with a minimal number of bus stops that can stratify the defined service range weighted by random walking value or public transport demand figures. After that, the initial stop distribution will be calculated for the second time using the relocation model to minimize average stop distance for improving system efficiency or to minimize the longest stop distance for enhancing system equity.

Generally, smaller service range requires more bus stops in the expansion model calculation. Relocation models perform more effectively in the two-level optimization. This may because of the fact that there are no pre-fixed bus stops in two-level optimization that models can calculate with more flexibility.

Question7: How to evaluate the optimized bus stop locations?

The objective of evaluation is to test whether the improvements are achieved by stop optimization. As the objective of optimization is to reduce the redundancy in city center and enlarge service coverage in urban skirts, the valid service coverage is assessed firstly. Meanwhile, concerning that relocation of bus stops may affect walking accessibility and service coverage that further influences served demands, walking accessibility and served demands are also estimated.

In conclusion, after the stop location optimization, redundant stops in the city centers are reduced; service coverage in urban outskirts is enlarged. Meanwhile, the serviced demands and walking accessibility are maintained by distributing fewer bus stops. The operation costs will be saved accordingly. The research objective is achieved finally.

8.2. Recommendation for future research

1. All the optimized bus stops by different model combinations should be evaluated and compared

Due to the limitation of research time, only two kinds of optimized bus stops are evaluated in this research. Other outputs are only compared by the nearest distance. All the optimized bus stops should be evaluated and compared with regards to service coverage, served demand and walking accessibility to obtain a complete understanding.

2. Quantitive traffic flow data collection is needed to assess the efficacy of key bus stops

Because of the unavailability of traffic flow data, the efficacy of key bus stops optimized based on random walking values cannot be assessed. Collection of traffic flow data will be help for evaluating of key bus stops and finally understanding the random walking calculation.

3. Methodology of stop optimization can be improved

To avoid locations with concentrated traffic demands, optimization process can be improved by defining different service rang according the variation of demand distribution. For example, in city centers the range can be set smaller than in the urban outskirts. Meanwhile, more sufficient candidate bus stops can improve the precision of optimization. Furthermore, to reduce the cost of implementing optimized bus stops, the optimization method can be improved by utilizing reduction model of FLOWMAP. To maintain as much existing bus stops as possible, the reduction model can be applied first to reduce the redundancy based on existing bus stops. Following that, key bus stops and normal bus stops can be added in expansion model to enlarge service coverage.

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