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公共腳踏車調配系統之策略性設計

STRATEGIC DESIGN OF PUBLIC BICYCLE DISTRIBUTION SYSTEMS[1]

林振榮 Jenn-Rong Lin [2]
楊大輝 Ta-Hui Yang[3]

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摘 要

本研究建構公共腳踏車調配系統的策略性設計模型，並對其進行分析測試，所提出的模型同時考量長期的策略層級及營運的操作層級因素。模型中主要的長期策略決策為：腳踏車維修中心之數目及地點、用來運送腳踏車之車輛的車隊規模；營運操作的決策有：如何由維修中心派遣運送腳踏車之車輛、運送腳踏車之車輛的途程規劃、如何收回待維修之公共腳踏車、及如何調配可用公共腳踏車以滿足租賃站收送之需求。本研究以整合性的角度，調整平衡長期策略的決策及營運操作的決策，以求得最佳的系統設計結果，此公共腳踏車調配系統設計問題可被定式為混合整數規劃問題。最後，應用提出的模型在信義計畫區的台北 U-Bike 公共腳踏車系統，進行案例測試分析。

關鍵詞： 公共腳踏車系統；區位途程問題；車隊調派；腳踏車收送；腳踏車租賃站；腳踏車維修中心

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2. 國立臺灣海洋大學運輸科學系教授。
3. 國立高雄科技大學運籌管理系教授 (聯絡地址：82445 高雄市燕巢區大學路 1 號 國立高雄科技大學運籌管理系；電話：07-6011000 轉 33223；E-mail：yang@nkust.edu.tw)。

ABSTRACT

In this study, we formulate and analyze a strategic design model for public bicycle distribution systems with strategic and operational concerns simultaneously. The key design decisions considered are: the number and locations of maintenance centers, the number of transport vehicles and which vehicle should be dispatched at which open maintenance center, the vehicle routing between open maintenance centers and the rental stations, and the transported qualities of vandalized bikes and usable bikes between stations and maintenance centers. The optimal design of this system requires an integrated view of the strategic decisions regarding the maintenance centers and vehicle investments, and operational decisions on how to dispatch vehicles to transport bicycle stocks between pickup and delivery stations and how to collect the vandalized bicycles from rental stations to maintenance centers. The purpose of this study is to create a formal model that provides such an integrated view. The problem is formulated as a mixed integer program. Finally, the model is applied to design a distribution system for U-Bike Taipei.

Key Words: *Public bicycle system; Location-routing problem; Vehicle dispatching; Bicycle pick-up and delivery; Bicycle rental station; Bicycle maintenance center*

I. INTRODUCTION

The purpose of this research is to formulate and analyze a strategic design model for public bicycle distribution systems with strategic and operational concerns. The key design decisions considered are: the number and locations of maintenance centers, the number of transport vehicles and which vehicle should be dispatched at which open maintenance center, the vehicle routing between open maintenance centers and the rental stations, and the transported qualities of vandalized bikes and usable bikes between stations and maintenance centers. Logistics decisions may be classified into three levels: strategic, tactical, and operational decisions, depending on the scope, the investment, the time horizon, and the frequency of making decisions. In general, the strategic and operational decisions made within different time frames are not linked together. However, in this study, we are concerned with long-term strategic decisions on investments in maintenance centers and vehicle investments and operational decisions on how to dispatch vehicles to satisfy rental stations' pick-up and delivery demands. The long-term location decisions and short-term routing decisions are linked together because it is important to consider the routing implications of location decisions at the strategic level, and the routing decisions must be made within the overall structure determined by the strategic decisions. Balakrishnan et al. [1] point out that integrated models that consider the two-level decisions simultaneously offer a promise of a more effective and economic design. Salhi and Rand [2] also use several test problems to show that ignoring operational routing decisions when making strategic location decisions may lead to a suboptimal design of the distribution system. However, such integrated models are more complex.

Since public bicycles were first introduced in Amsterdam in the 1960s (the so-called White Bicycle Plan), public bicycle systems have been promoted in urban cities around the world such as in Paris, Barcelona, Berlin, Montreal, Salt Lake City, and so on. Public bicycle rental systems are not only viewed as an innovative inner-city transportation mode to meet many commuter needs and to integrate other public transit systems, but are also viewed as part of an ambitious program to cut traffic, reduce pollution, and enhance the city's image as a greener and quieter place with a better way of life. However, existing examples show that some logistics issues exist and need to be smoothed out.

It is crucial for the success of a public bicycle rental system to guarantee the availability of bicycles. Existing systems show that users feel frustrated when they can not find a bicycle when they need one. Existing systems also show that pick-up and drop-off by users over a day often leads to an unequal distribution of bicycles throughout the city. This means that at certain times in certain places riders can not find an available bike or find a rack space to return a bike. For example, stations at greater elevation suffer from greater demand. Many users in high-lying districts take a bike downhill to work, but take the metro or a bus home rather than struggling back up the hill by bike. In addition, there is a net inflow of bikes from suburban districts to city business centers earlier in the day and a net outflow outwards in the evening. In this case, a distribution of bicycle stocks is needed to guarantee the availability of bicycles and avoid the frustrations of users who are unable to find an available bicycle or else can not drop it off because the racks are full.

Existing systems also show that the degree of vandalism and theft is underestimated. To guarantee the availability of bicycles, the system must provide maintenance and replace the stolen bicycles. The broken bicycles need to be transported to maintenance centers for repair, and maintenance centers need to dispatch replenishment vehicles to replace the stolen bicycles at rental stations without sufficient stocks of bicycles. In addition, the dispatching vehicle plan needs to consider how to pick up broken bikes at rental stations and how to transport available usable bikes between pick-up and delivery rental stations simultaneously to enhance efficiency.

The general structure of the existing system under study is represented in Figure 1. The structure represents the transportation of available usable bicycle stocks from open maintenance centers and rental stations, with extra bicycle stocks being delivered to rental stations without enough bicycle stocks and vandalized bicycles being collected from rental stations and delivered to maintenance centers. A rental station with vandalized bicycles may demand that those vandalized bicycles be picked up and delivered to open maintenance centers. A rental station with extra usable bicycle stocks may demand that extra usable bicycles be picked up and delivered to some rental stations without enough bicycle stocks, in order to provide service. By contrast, a rental station without enough bicycle stocks may demand that some usable bicycles being picked up from other rental stations with extra bicycle stocks or open maintenance centers be delivered to the rental station to provide service. According to the combination of demand, rental stations can be classified into five types, namely, the stations demanding that only broken bikes be picked up, the stations demanding that only usable bikes be picked up, the stations demanding that only usable bikes be delivered, the stations demanding that both broken and usable bikes be picked up, and the stations demanding the simultaneous pick-up of broken bikes and delivery of usable bikes (see (1), (2), (3), (4), (5) in Figure 1, respectively). If a transport vehicle leaves the maintenance center without enough bicycle stocks, it will then need to pick up some usable bicycles at some rental stations with extra bicycle stocks before delivering some bicycle stocks to those rental stations without sufficient bicycle stocks. On the way, there is a mixed load of usable and broken bikes on the transport vehicle. It is assumed that the transportation of available usable bike stocks and the collection of broken bikes takes place overnight and once a day. All collected broken bicycles have to be transported to an open maintenance center. Each transportation vehicle has to finish the duty of distributing bicycles and return to the maintenance centers before the next morning. The rental stations will then have sufficient and adequate bicycle stocks to provide the next day's service. Therefore, there is a maximum time allowed for bike distribution. We use a maximum distance allowed for any route as a surrogate for the maximum time allowed for bike distribution. In addition, it is not necessary to consider the details of operations such as time window constraints at rental stations from the perspective of long-term planning.

The distribution of bicycle stocks over the system from rental stations to rental stations requires a fleet of transport vehicles. The efficiency of the distribution of bicycles depends on the number of transport vehicles invested in the system and the number of maintenance centers and their locations. The larger the number of transport vehicles and the number of maintenance centers, the shorter the transport routes that can be achieved. A distribution system with more maintenance centers and transport vehicles allows shorter transport routes (which implies lower vehicle operating costs). However, additional costs of constructing and operating maintenance centers and vehicle investments may be incurred. There is therefore a tradeoff between the long-term investment and short-term operating costs.

Thus the optimal design of this system requires an integrated view of the strategic decisions regarding the maintenance centers and vehicle investments and operational decisions on how to dispatch vehicles to transport bicycle stocks between pick-up and delivery stations and how to collect the vandalized bicycles from stations and deliver them to maintenance centers. The purpose of this study is to create a formal model that provides such an integrated view. Based on our review of the related literature, we do not find any studies that address the network design of public bicycle distribution systems. This study therefore develops a mathematical model for the strategic network design of a public bicycle distribution system. This has so far not been proposed in the literature.

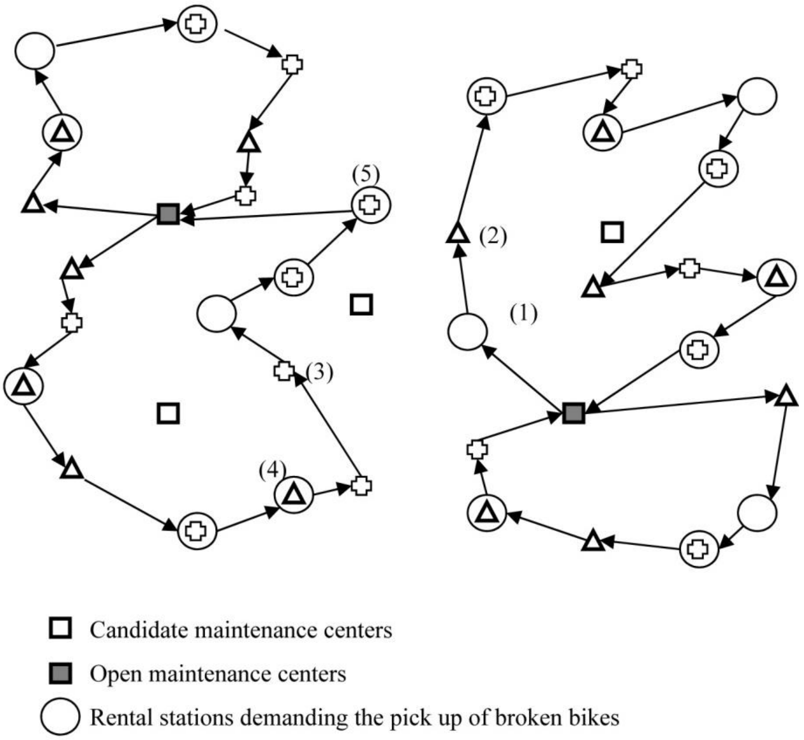

Figure 1　Network structure of public bicycle distribution systems.

By means of the taxonomy used in the location routing literature, the problem can be summarized as follows. Given a set of potential depot sites, a set of vehicles, two commodities (one a broken commodity that needs to be collected and taken back to depots and the other a usable commodity that can be picked up at some customer locations with extra stocks and delivered to some other customer locations without sufficient stocks to provide service) and a set of customers with request demands to pick up the broken commodity and either pick up or deliver the usable commodity, we would like to know where to locate the depot, and which vehicle should be dispatched at which open depot, to determine the vehicle routing between open depots and the customers, and to determine how to transport broken and usable commodities between customers and open depots, in order to minimize the total distribution cost, which is the sum of the fixed costs of the depots, the throughput costs of the usable commodity at the depot, the throughput costs of the broken commodity at the depots, the fixed costs of dispatching vehicles and the variable delivery costs in the routing. The problem is a new variant of the location routing problem with simultaneous pick-up and delivery.

This study makes the following contributions: (1) Although there are some studies related to bicycle systems, most of them focus on promotion policy and safety issues, the history and development of public bicycle systems, bicycle travel patterns, the strategic design of public bicycle systems and bicycle repositioning. In our review of the related literature, we do not find any studies that address the integration of strategic location decisions with the operational bicycle distribution decisions in public bicycle systems. This paper therefore develops a mathematical model for the strategic design of a public bicycle distribution system. This has so far not been proposed in the literature. (2) The proposed model is a new variant of the location routing problem with pick-up and delivery. (3) A case study is used to test the proposed model. Sensitivity analysis is also conducted to gain better insights into, and understandings of, the properties of the proposed model.

The remainder of this article is organized as follows. In Section II, we review the relevant literature. In Section III, the problem definition is presented and a mathematical model introduced to formulate the strategic design of the public bicycle distribution system. In Section IV, we apply the model to design a public bicycle distribution system for U-Bike Taipei. In Section V, we draw some conclusions.

II. LITERATURE REVIEW

The proposed strategic design of public bicycle distribution systems can be viewed as a location routing problem with simultaneous pick-up and delivery service. Therefore, this research draws on the literature in three areas: public bicycle systems, vehicle routing problems with pick-up and delivery and location routing problems.

In the operation of public bicycle sharing systems where imbalances among flows exists, there is an important question of interest that needs to be answered: How are unused bicycles redistributed elsewhere to provide service? However, most of the studies related to bicycle sharing systems in the literature focus on the promotion of policy and safety issues [3, 4], the history and development of public bicycle systems [5, 6], the analysis of bicycle temporal and geographical usage patterns [7] and the strategic design of public bicycle systems [8, 9]. Past studies related to the distribution of shared bicycles include Nair and Miller-Hooks [10], Raviv et al. [11] and Shu et al. [12] and. There are relatively more past studies related to the distribution of shared cars [10, 13-16]. A notable study that has attempted to integrate the location of strategic depots with the distribution of operational vehicles is that by Correia and Antunes [17]. However, to the best of our knowledge, there is no study that addresses the integration of strategic location decisions with operational bicycle distribution decisions.

The vehicle routing problem with pick-up and delivery is a generalization of the vehicle routing problem. Parrragh et al. [18, 19] classify vehicle routing problems with pick-up and delivery service according to two major categories: the vehicle routing problems with backhauls (VRPB) and the pick-up and delivery vehicle routing problems (PDVRP). The first category (VRPB) deals with how to deliver goods from the depot to linehaul customers and pick up goods from the backhaul customers to deliver them to the depot. There are four subtypes of VRPB, namely, the vehicle routing problems with clustered backhaul (all linehauls before backhauls), the vehicle routing problems with mixed linehauls and backhauls (with a mix of linehauls and backhauls in any sequence), the vehicle routing problem with divisible delivery and pick up (customers requesting a delivery and pick-up service can be visited twice), and the vehicle routing problems with simultaneous delivery and pick up (VRPSDP – customers requesting delivery and pick-up service have to visit only once). The second category (PDVRP) deals with how to transport goods between pick-up and delivery customers. There are three subtype problems, namely, the pick-up and delivery vehicle routing problem (PDVRP – unpaired pick-up and delivery customers), the classical pick-up and delivery problem (PDP – paired pick-up and delivery customers), and the Dial-A-Ride problem (DARP – passenger transportation between paired pick-up and delivery customers). For a recent review of VRP, the reader can refer to Laporte [20] and for the reviews of VRP with pick up and delivery, we refer to Berbeglia et al. [21], Cordeau et al. [22], and Parragh et al. [18, 19].

The VRPSDP and PDVRP may be of particular relevance to the current research. Therefore, we will briefly review the studies in the literature related to these two subtypes. The VRPSDP can be defined as follows. Given a depot and a set of customers with pick-up and delivery requests, where customers simultaneously receive the deliveries from the depot and send pick-ups back to the depot, we attempt to determine the routing of each vehicle in order to minimize the transportation cost. The distinct feature of the problem is that the vehicles are loaded with mixed pick-ups and bicycles are delivered. The VRPSDP was first introduced by Min [23]. A branch and price algorithm for the VRPSPD without time windows is proposed by Dell'Amico et al. [24] and the only exact algorithm for the VRPSPD with time windows is proposed by Angelelli and Mansini [25]. A heuristic algorithm for the single vehicle routing problem with pick up and delivery has been studied by Gendreau et al. [26]. Most recent studies focus on how to use heuristic techniques to solve the VRPSDP [27-33]. Dethloff [34] studies the problem from the perspective of reverse logistics. The PDVRP can be defined as follows. Given a depot and a set customers with either pick-up or delivery requests, where the pick-ups at customers' delivery points can be transported to fulfill some other customers' delivery requests, we would like to determine the routing of each vehicle and how to transport goods between un-paired customers in order to minimize the transportation cost. There are relatively few studies published on the PDVRP, with most studies dealing with the one-commodity single vehicle routing problems with pick up and delivery [35-38] and the multi-commodity single vehicle routing problems with pick up and delivery [39]. The only exception is that Dror et al. [40] applied the multiple vehicle PDVRP to redistribute the self-service cars.

The location-routing problem (LRP) is defined in Srivastava and Benton [41] as follows: given a feasible set of depot locations and customer locations, we would like to find the optimal number of depots, their locations, and the routes from the open depots to customers such that the sum of the depots' fixed costs and distribution costs is minimized. The LRP model has been applied to design various distribution systems. For recent review articles on location-routing problems, we refer to Min et al. [42] and Nagy and Salhi [43]. The location routing with the simultaneous pick-up and delivery problem (LRPSPD) and the many-to-many location routing problem (MMLRP) may be of particular relevance to current research. The LRSPD problem is defined in Karaoglan et al. [44, 45] as follows: given a feasible set of depot locations and customer locations with pick-up and delivery demands, we would like to find the optimal number of depots, their locations, and the routes from the open depots to customers such that the sum of the depots' fixed costs and distribution costs is minimized, where customers simultaneously receive the deliveries from the depot and send pick-ups back to the depot. The MMLRP is defined in Nagy and Salhi [46] as follows: given a set of customer locations and a set of paired customer demands which the customers at the origin wish to send to customers at the destination, we would like to find the optimal number of terminals, their locations, the main routes between open terminals and the pick-up and delivery routes between customers and open terminals, such that the sum of the depots' fixed costs and distribution costs is minimized. However, our problem is different from these two LRP problems. In comparison with the LRPSPD problem, our problem still involves the need to pick up the usable bicycles that some customers have dropped off to fulfill the needs of other customers requesting usable bicycles while simultaneously picking up broken bicycles and delivering usable bicycles to different customer locations. In comparison with the MMLRP, our problem requires simultaneously picking up broken bicycles and delivering usable bicycles, and the customers' demands are unpaired.

In the VRP formulation, there are many ways to avoid sub-tours. Introducing flow variables and flow conservation constraints is one of many ways of avoiding sub-tours. Such a formulation is first introduced in the formulation of traveling salesman problems [47], and applied to the LRP [48-50]. In our model formulation, we also introduce flow variables and flow conservation constraints to avoid sub-tours.

III. PROBLEM DEFINITION

The problem can be summarized as follows. Given a set of potential maintenance center sites, a set of vehicles, and a set of bicycle rental stations with request demand to pick up vandalized bicycle stocks and either pick up or deliver usable bicycle stocks, we would like to know where to locate maintenance centers, and which vehicle should be dispatched at which open maintenance center, to determine the vehicle routing between open maintenance centers and the rental stations, and to determine how to transport vandalized bikes and usable bikes between stations and maintenance centers, in order to minimize the total cost, which is the sum of the fixed costs of the maintenance centers, the throughput costs of usable bicycles at the maintenance centers, the throughput costs of vandalized bicycles at the maintenance centers, the fixed costs of dispatching vehicles and the variable delivery costs in the routing.

3.1 Model formulation

We define the following subscripts, sets, decision variables and input parameters.

Subscripts and sets:

$i, j \in I$ denotes the bicycle rental stations.

$m \in M$ denotes the potential maintenance centers..

$k \in K$ denotes the set of vehicles available for use in the routing.

$I_0 = I \cup M$ denotes the set of nodes involved in the routing decisions.

Input parameters:

p_j is the pick-up demand for vandalized bicycle stocks at rental stations j , $\forall j \in I$

d_j is the pick-up or delivery demand for usable bicycle stocks at rental station j , $\forall j \in I$; if $d_j > 0$: pick-up demand; $d_j < 0$: delivery demand.

l_{ij} is the distance between node i and node j, $\forall i, j \in I_0$

vc_k is the unit transportation cost of vehicle k , $\forall k \in K$

q_k is the capacity of vehicle k , $\forall k \in K$

fv_k is the fixed cost of using vehicle k , $\forall k \in K$

f_m is the fixed cost of opening a maintenance center at site m , $\forall m \in M$

$tc1_m$ is the unit throughput cost of usable bicycles at maintenance center *m* , $\forall m \in M$

$tc2_m$ is the unit throughput cost of vandalized bicycles at maintenance center *m* , $\forall m \in M$

MD is the maximum distance allowed for any route.

Decision variables:

X_m equals 1 if the maintenance center *m* is opened and 0 otherwise, $\forall m \in M$.

Y_{ijk} equals 1 if *i* precedes *j* in the route of vehicle *k* and 0 otherwise, $\forall i, j \in I_0$, $\forall k \in K$.

Z_k equals 1 if vehicle *k* is used and 0 otherwise, $\forall k \in K$.

U_{ijk} is the quantity of usable bicycle stocks transported from node *i* to node *j* on the route of vehicle *k*, $\forall i, j \in I_0$, $\forall k \in K$.

V_{ijk} is the quantity of vandalized bicycle stocks transported from node *i* to node *j* in the route of vehicle *k*, $\forall i, j \in I_0$, $\forall k \in K$.

Based on this notation, we can develop the following mathematical formulation.

$$\min \sum_{m\in M} f_m X_m + \sum_{m\in M} tc1_m \sum_{j\in I}\sum_{k\in K}(U_{mjk}+U_{jmk}) + \sum_{m\in M} tc2_m \sum_{j\in I}\sum_{k\in K} V_{jmk} + \sum_{k\in K} fv_k Z_k + \sum_{i\in I_0}\sum_{j\in I_0}\sum_{k\in K} l_{ij} vc_k Y_{ijk} \tag{1}$$

such that

$$\sum_{k\in K}\sum_{i\in I_0} Y_{ijk} = 1 \quad ,\forall j \in I \tag{2}$$

$$\sum_{i\in I} Y_{imk} \le X_m \quad ,\forall m \in M, \forall k \in K \tag{3}$$

$$\sum_{m\in M}\sum_{j\in I} Y_{mjk} = V_k \quad ,\forall k \in K \tag{4}$$

$$\sum_{i\in I_0} Y_{ijk} - \sum_{i\in I_0} Y_{jik} = 0 \quad ,\forall j \in I_0, \forall k \in K \tag{5}$$

$$U_{ijk} + V_{ijk} \le Y_{ijk} q_k \, ,\forall i, j \in I_0, \forall k \in K \tag{6}$$

$$\sum_{i\in I_0}\sum_{k\in K} U_{jik} - \sum_{i\in I_0}\sum_{k\in K} U_{ijk} = d_j \, ,\forall j \in I \tag{7}$$

$$\sum_{i\in I_0}\sum_{k\in K} V_{jik} - \sum_{i\in I_0}\sum_{k\in K} V_{ijk} = p_j \;\; \forall j \in I \tag{8}$$

$$\sum_{i\in I_0}\sum_{j\in I_0} l_{ij} Y_{ijk} \le MD \, ,\forall k \in K \tag{9}$$

$$X_m = \{0,1\}, \forall m \in M \tag{10}$$

$$Z_k = \{0,1\}, \forall k \in K \tag{11}$$

$$Y_{ijk} = \{0,1\}, \forall i, j \in I_0, \forall k \in K \tag{12}$$

$$U_{ijk} \geq 0, \forall i, j \in I_0, \forall k \in K \tag{13}$$

$$V_{ijk} \geq 0, \forall i, j \in I_0, \forall k \in K \tag{14}$$

The objective function (1) minimizes the sum of the fixed costs of the maintenance centers, throughput costs of usable bicycles at the maintenance centers, throughput costs of vandalized bicycles at the maintenance centers, fixed costs of dispatching vehicles, and variable delivery costs in the routing. The throughput costs of usable bicycles at the maintenance centers are equal to the unit throughput cost times the sum of usable bicycles transported into and out of the maintenance centers. The throughput costs of vandalized bicycles at the maintenance centers are equal to the unit throughput cost times the quantity of vandalized bicycles transported into the maintenance centers. Constraints (2) ensure that each bicycle rental station is visited by exactly one vehicle. Constraints (3) ensure that only the opened maintenance centers can dispatch vehicles. Constraints (4) ensure that a vehicle available for use in the routing can transport goods from a maintenance center only if it is used. Constraints (5) ensure that a vehicle enters and leaves a node once if the vehicle transports bicycle stocks to the node. Constraints (6) ensure that the bicycle stocks transported between two nodes cannot exceed the capacity of the vehicle. Constraints (7-8) are flow conservation constraints of usable and vandalized bicycles at the rental stations, respectively. Constraints (9) are the maximum distance constraints. Constraints (10) are the integrality requirements for the location variables. Constraints (11) are the integrality requirements for the vehicle usage variables. Constraints (12) are the integrality requirements for the link predecessor variables. Constraints (13) and (14) ensure that the flow variables are non-negative. In this formulation, we introduce flow variables and flow conservation constraints to avoid sub-tours.

Based on the mathematical formulation, the model is a mixed integer program. Suppose that we consider a network with *m* candidate maintenance centers, *n* bike stations and the vehicle fleet size of *k*. The number of decision variables is estimated in Table 1 and the number of constraints is listed in Table 2. Note that the total number of constraints did not take account of constraints (10), (11), (12), (13) and (14) since they are binary constraints or non-negative constraints.

Table 1　The Number of Decision Variables for the Proposed Model.

Decision variables	Number of variables
X_m (integer)	m
Z_k (integer)	k
Y_{ijk} (integer)	$(m+n)^2 k$
U_{ijk} (real)	$(m+n)^2 k$
V_{ijk} (real)	$(m+n)^2 k$
Total integer variables	$(n+m)^2 k+m+k$
Total variables	$3(n+m)^2 k+m+k$

Table 2　The Number of Constraints.

Constraints	Number of constraints
(2)	n
(3)	mk
(4)	k
(5)	$(n+m)k$
(6)	$(n+m)^2 k$
(7)	n
(8)	n
(9)	k
Total	$3n+2k+k(n+m)(n+m+1)$

IV. CASE STUDY

4.1 Data Setting

This study focuses on U-Bike Taipei (a public bicycle sharing system implemented in the central business district of Taipei). There are five potential maintenance center locations, located in five public parking lots in the district. We consider a set of 11 bicycle rental stations near the bus/MRT stations of office buildings in the districts. The locations of five potential maintenance centers (node A, B, C, D, and E) and 11 bicycles rental stations (node 1 to node 11) are shown in Figure 2. While the scale of U-Bike Taipei is smaller than that of VELIB implemented in Paris, France, U-bike Taipei is, however, comparable in size to many worldwide bike sharing programs implemented in Brazil, Chile, the Czech Republic, India, Ireland, New Zealand, Poland, Romania, South Korea and Switzerland, etc. The two figures in the parentheses near a rental station refer to the pick-up or delivery demand for usable bikes and the pick-up demand for broken bikes, respectively. For example, the two figures in parentheses near rental station 1 (-3, 1) refer to the pick-up or delivery demand for usable bikes and the pick-up demand for broken bikes, respectively. U-Bike Taipei posts the information regarding the number of

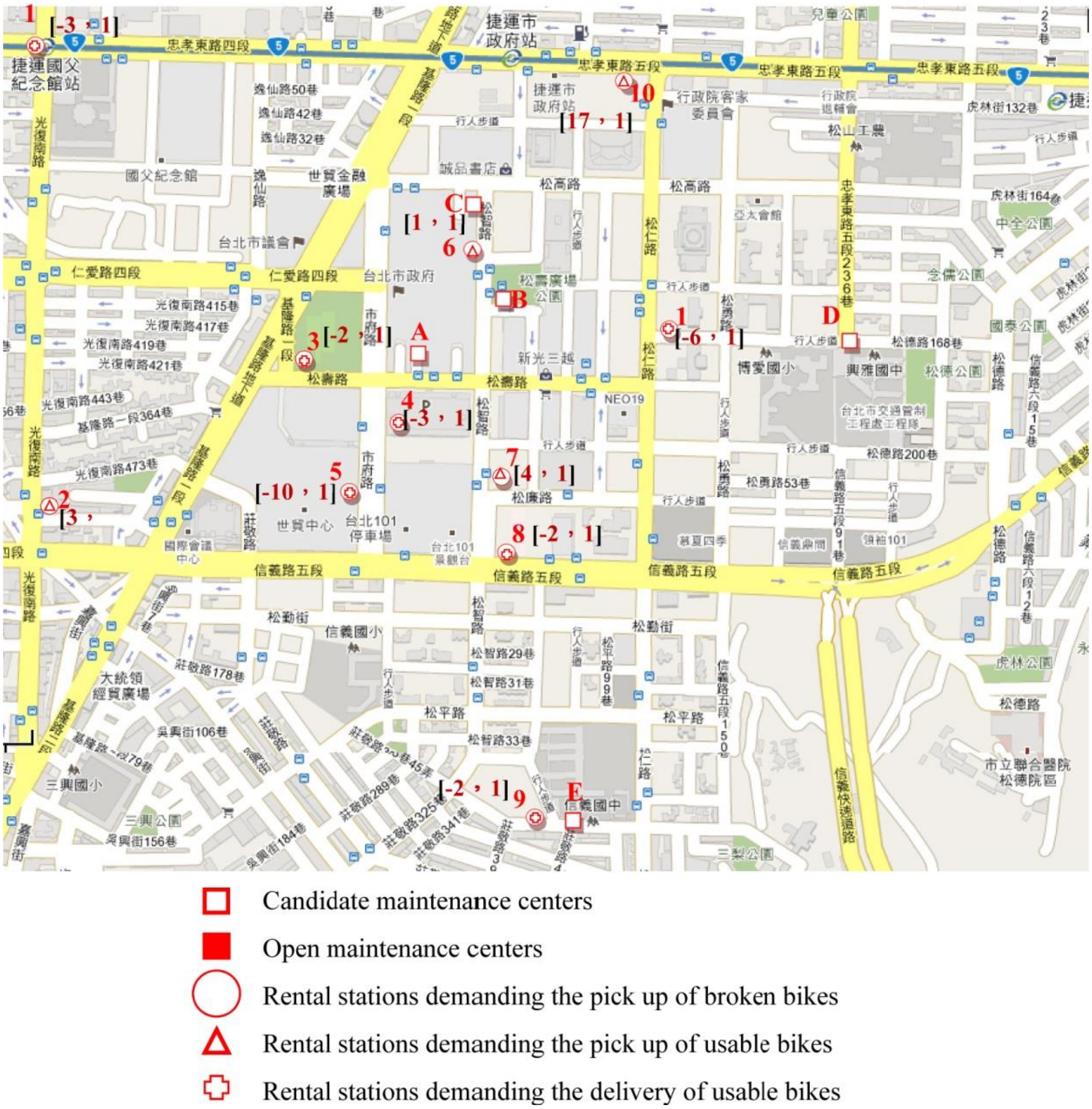

Figure 2 Location sites for the case study.

available usable bicycles and the number of available rack spaces at each rental station on its website. The distribution of bicycles takes place during the middle of the night. We recorded the data regarding the number of available usable bicycles at each rental station before midnight and just before riders started checking out bicycles for two months. The differences between the data collected at these two time points represent the demand for usable bicycles at each station. We also checked the rental station everyday during the two-month period and recorded the number of broken bicycles at each rental station for two months. Both the demand for usable bicycles and the number of broken bicycles varied daily. The average demand (rounded up to the closest integer) was used in this analysis. The distance matrices between potential maintenance centers and bicycle rental stations are shown in Table 3 and the distance matrices between bicycle rental stations and other bicycle rental stations are shown in Table 4, respectively. All the distances between any two locations are calculated based on the street network data provided by a government agency.

Table 3　The Distance Matrix from Maintenance Centers to Rental Stations (unit: meter)

	1	2	3	4	5	6	7	8	9	10	11
A	1592	944	242	79	209	434	284	516	1054	997	548
B	1546	1230	554	396	540	93	287	479	1042	1023	536
C	1173	1562	571	444	648	0	338	557	1112	962	668
D	1901	2480	1333	1552	1681	1006	1394	1571	1949	849	363
E	2276	1799	1235	1075	1301	1098	796	489	23	1671	1144

Table 4　The Distance Matrix from Rental Stations to Rental Stations (unit: meter)

	1	2	3	4	5	6	7	8	9	10	11
1	0	857	1302	1234	1333	1173	1495	1709	2276	1102	1598
2	857	0	1807	1244	1426	1562	1533	1283	1824	1928	1830
3	1302	1807	0	159	362	571	445	664	1226	1517	727
4	1234	1244	159	0	186	444	327	543	1088	1014	602
5	1333	1426	362	186	0	648	523	744	1301	1209	806
6	1173	1562	571	444	648	0	338	557	1112	962	688
7	1495	1533	445	327	523	338	0	223	776	1292	490
8	1709	1283	664	543	744	557	223	0	552	1521	731
9	2276	1824	1226	1088	1301	1112	776	552	0	1671	1144
10	1102	1928	1517	1014	1209	962	1292	1521	1671	0	507
11	1598	1830	727	602	806	668	490	731	1144	507	0

All cost parameters are estimated on an annual basis. We assume that the annual fixed cost of opening a maintenance center is NTD 1 million. As the district situated with finical holding head-quarters and high-end residential areas, the average labor cost of the area is much higher than the average labor cost in Taiwan. Because there is no statistics wage data of the district, we are forced to use the average cost of finical and insurance industries in 2018 (about NTD 460 per hour) as a surrogate of the average labor cost of the district. In addition, Isacsson et al. [51] estimate the value of commuting time is about 1.8 times the average hourly wage. The commuting time value of users in the district is about NTD 800 per hour, which is roughly 1.8 times the average labor cost of the district. We assume that the throughput cost associated with usable bicycles transported into and out of maintenance centers is NTD 10 per unit. The throughput cost associated with usable bicycles transported into and out of maintenance centers represents the cost of unloading a bicycle from a transport vehicle and loading a bicycle on to a transport vehicle. Since both unloading a bicycle from a transport vehicle and loading a bicycle on to a transport vehicle take less than a minute, the throughput cost associated with usable bicycles transported into and out of maintenance centers is around NTD 10 per unit. The throughput cost associated with broken bicycles transported into maintenance centers is assumed to be NTD 100 per unit. The throughput cost associated with broken bicycles transported into maintenance centers represents the average cost of repairing a broken bicycle. The throughput cost associated with broken bicycles transported into maintenance centers is relatively high compared to the throughput cost associated with usable bicycles transported into and out of maintenance centers. There is only one type of vehicle used to transport bicycles. The capacity of such a vehicle is 25 bicycles. The fixed cost of a vehicle is NTD 350 thousand and the variable cost is NTD 8 per kilometer/per vehicle. The maximum distance allowed for a route is 4 kilometers. We assume that pick-ups and deliveries of bicycles are made every day. Since the system operates every day, all the variable costs associated with routing need to be multiplied by the number of days in a year (365 days).

4.2 Results of the Analysis

The problem was solved by a Branch and Bound solver of a commercial optimization software, LINGO 11.0, on a desktop computer (Intel 3.2 GHz Core i5 and 1.89 GB of memory) with a Microsoft Windows XP operating system. Figure 3 illustrates the solution. The system design yielded an optimal recommendation of 1 maintenance center located at node A and two routes. The first route (shown in solid arrow lines) starts from the maintenance center located at node A and goes to rental stations 2, 1, 10 and 11, and then back to the maintenance center. The two figures in parentheses near an arrow line refer to the quantity of usable bikes and broken bikes transported between the two nodes, respectively. For example, the first transport vehicle leaves the maintenance center empty and then picks up 3 usable bikes and 1 broken bike at rental station 2. On the way to rental station 1, there are thus 3 usable bikes and 1 broken bike on the first transport vehicle. After the delivery of 3 usable bikes and the picking up of another broken bike, there are two broken bikes left on the first transport vehicle. After serving rental stations 10 and 11 sequentially, the first transport vehicle comes back to the maintenance center with 11 usable bikes and 4 broken bikes. The second route (shown in broken arrow lines) starts from the maintenance center and goes to rental stations 5, 4, 3, 6, 7, 8 and 9, and then back to the

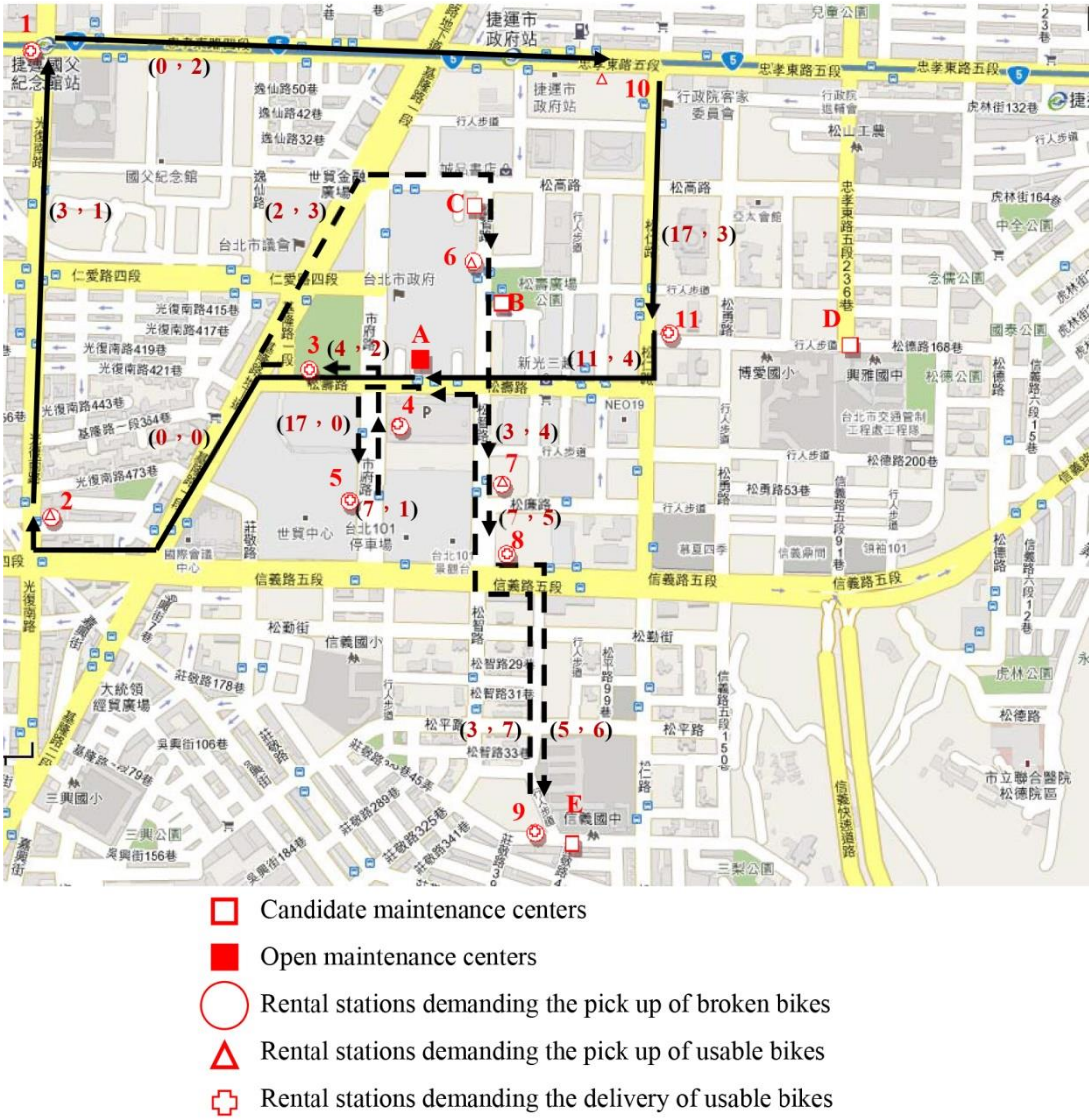

Figure 3　Network design and routing choices for the illustrative example where the maximum distance allowed for a route is 4 kilometers.

maintenance center. The second transport vehicle leaves the maintenance center with 17 usable bikes and then delivers 10 usable bikes and picks up 1 broken bike at rental station 5. On the way to rental station 4, there are thus 7 usable bikes left and 1 broken bike on the second transport vehicle. After serving rental stations 4, 3, 6, 7, 8, and 9 sequentially, the second transport vehicle comes back to the maintenance center with 3 usable bikes and 7 broken bikes.

The proposed design model described in Section 3 provides several parameters that are significant levers affecting the solution, especially the maximum distance allowed for any route. The maximum distance allowed for any route is used as a surrogate for the maximum time allowed for bike distribution. In practice, pick-ups and deliveries of bicycles are made during the middle of the night or just before commuters start checking out bicycles the next morning. If the bike distribution takes place during the middle of the night, the maximum time allowed for bike distribution is long (this implies a higher maximum route distance allowed). If the bike distribution takes place early in the morning, the maximum time allowed for bike distribution is relatively short (this implies a lower maximum route distance allowed). To illustrate how the maximum distance allowed for any route affects the solution, we first change the maximum distance allowed for any route to higher values to identify a network design with fewer distribution routes, and to lower values to identify a network design with more distribution routes.

Figure 4 illustrates the network design and routing choices when the model setup involves a higher maximum route distance allowed (with a value of 10 kilometers per route). In comparison with the network design of the above example, the solution yields a recommendation of 1 maintenance center located at node A and one route. The transport vehicle leaves the maintenance center with 6 usable bikes. After serving rental stations 11, 10, 1, 2, 5, 4, 3, 6, 7, 8 and 9 sequentially, the transport vehicle comes back to the maintenance center with 3 usable bikes and 11 broken bikes.

Figure 5 illustrates the network design and routing choices when the model setup involves a lower maximum route distance allowed (with a value of 3 kilometers per route). In comparison with the network design of the above example, the solution yields a recommendation that 1 maintenance center be located at node A and that there be four routes. The first transport vehicle leaves the maintenance center with 5 usable bikes. After serving rental stations 6, 1 and 4 sequentially, the first transport vehicle comes back to the maintenance center with 3 broken bikes. The second route departs from the maintenance center to rental stations 2 and 8, and then comes back to the maintenance center. The third route leaves from the maintenance center to rental stations 7 and 9, and then comes back to the maintenance center. The fourth route leaves from the maintenance center to rental stations 10, 11, 3 and 5, and then comes back to the maintenance center.

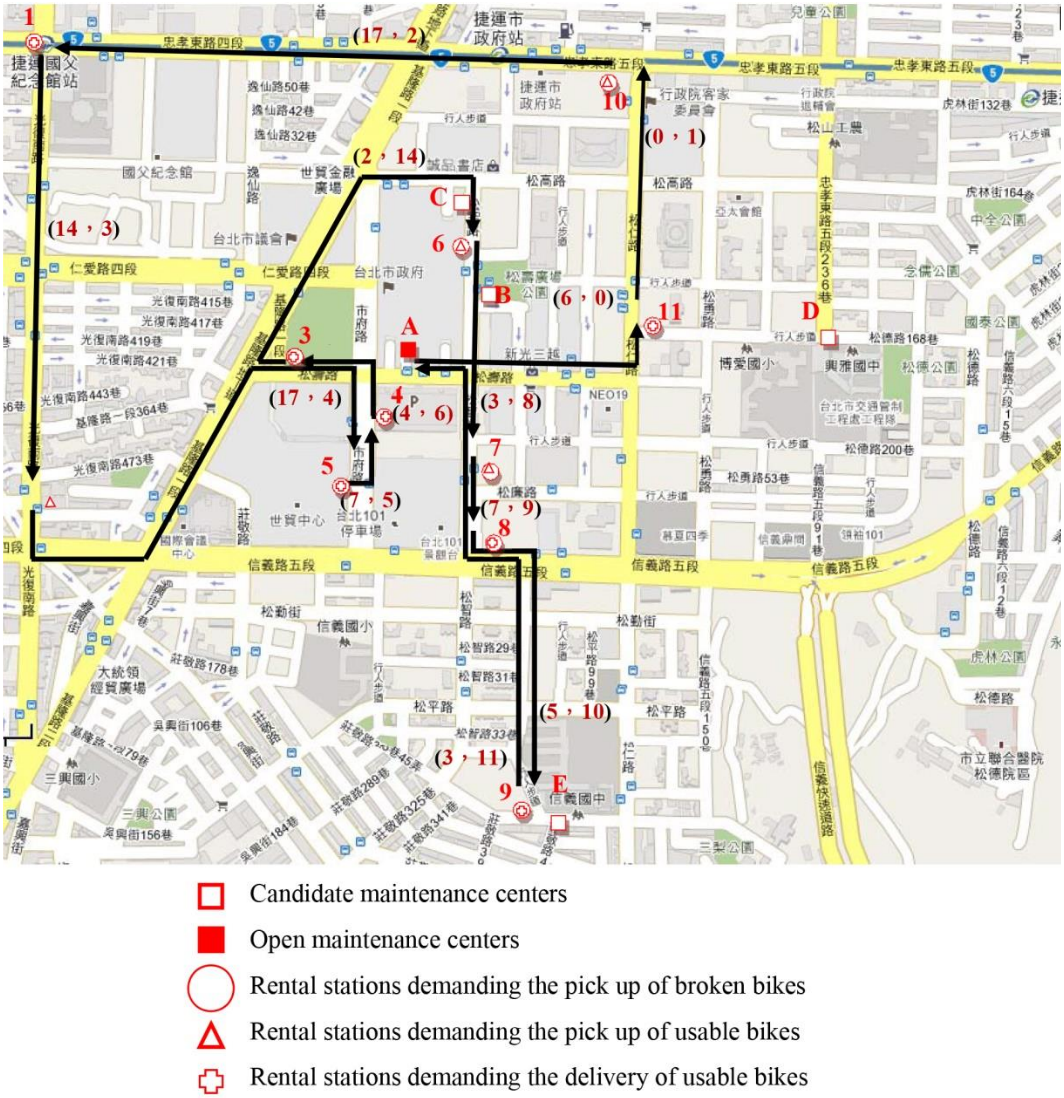

Figure 4　Network design and routing choices while setting higher maximum route distance allowed.

Several additional randomly generated test problems with different numbers of candidate maintenance centers, bicycle stations and vehicles are used to test the model. Table 5 describes each of the test problems and presents the computation times required. For test problem 1-4, five additional test problems with different cost parameters are created to test the model. For the test problem 1-4, each problem is solved to within 0.8% optimal. The average computation times required are summarized in Table 5. For test problem 5, LINGO can not find a feasible solution within 0.8% optimal within 2 days. Developing an efficient solution procedure for the problem could be a topic of future research.

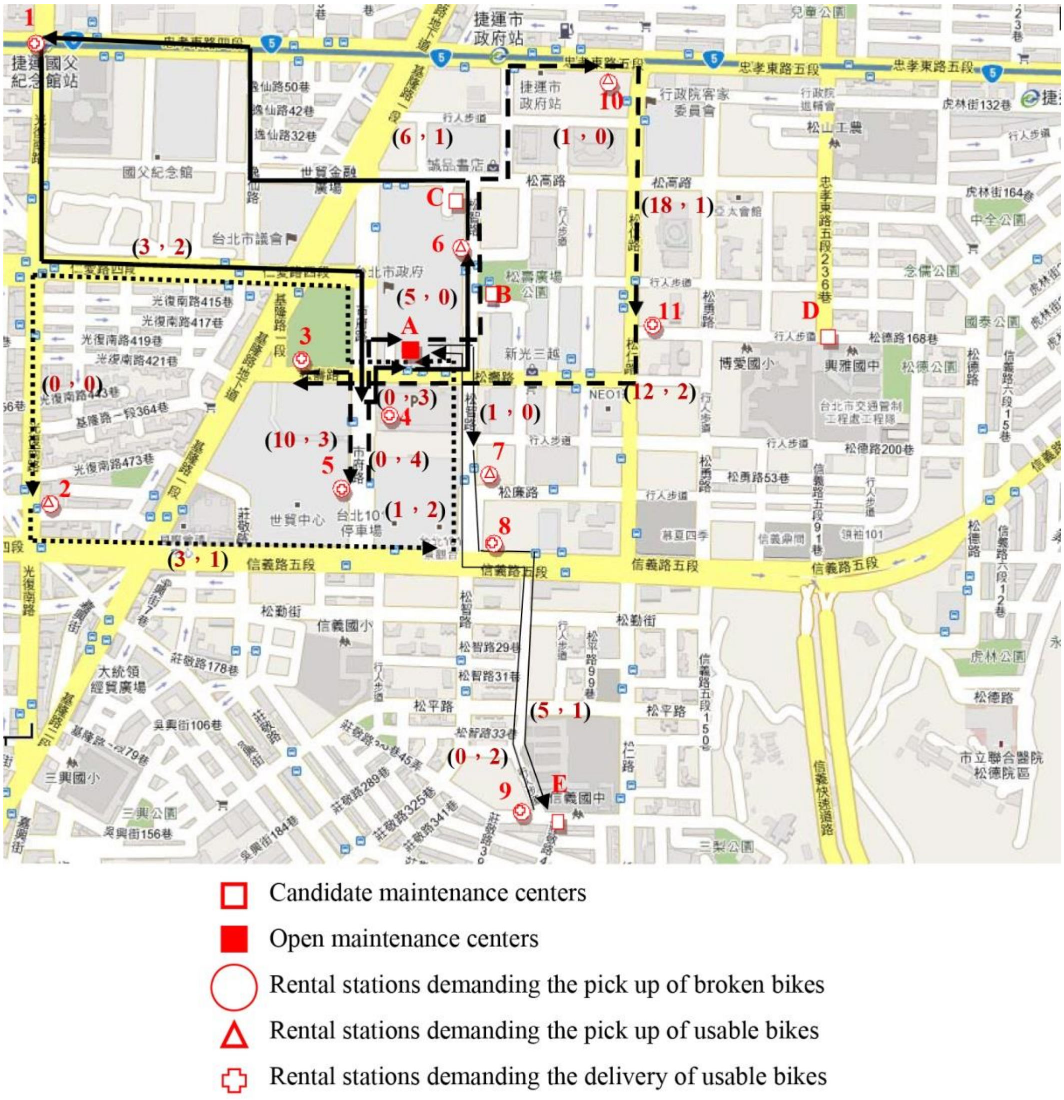

Figure 5 **Network design and routing choices while setting lower maximum route distance allowed.**

V. CONCLUSIONS

Public bicycle systems have attracted a great deal of attention in recent years, having been used as a new inner-city transportation mode that can be integrated with existing public transit systems in many cities. With most of the studies related to bicycle systems in the literature having focused on promotion policy and safety issues, the history and development of public

Table 5　Test Problems and Computation Times Required

Problem	m	n	k	Average Times (minute)
Case Study	5	11	5	16.2
1	2	12	2	1.6
2	5	10	5	15.2
3	5	20	5	124.3
4	10	20	10	1334.6
5	15	55	15	>2880

bicycle systems, bicycle travel patterns, the strategic design of public bicycle systems and bicycle repositioning, we have not found a study that has addressed the integration of strategic location decisions with the operational bicycle distribution decisions in public bicycle systems. This study therefore considers both the long-term strategic decisions regarding maintenance center investments and vehicle investments and the operational decisions as to how to dispatch vehicles to replenish the rental stations' bicycle stocks. The long-term location decisions and short-term routing decisions are linked together because it is important to consider the routing implications of location decisions at the strategic level, and the routing decisions must be made within the overall structure determined by the strategic decisions. The optimal design of this system requires an integrated view of the strategic decisions regarding the maintenance centers and vehicle investments as well as the operational decisions on how to dispatch vehicles to transport bicycle stocks between pick-up and delivery stations and how to collect the vandalized bicycles from stations and deliver them to maintenance centers. This paper has developed a mathematical model that provides such an integrated view. The problem is formulated as a mixed integer program and solved by LINGO 11.0. Finally, the model is applied to design a public bicycle distribution system for U-Bike Taipei.

Future research would be useful in at least the following directions. First, the pick-up demand in relation to broken bikes may be uncertain. It would therefore be helpful to develop a formal model incorporating demand uncertainty. Second, the pick-up and delivery demands of usable bikes may vary day by day (or the demands may vary by time periods). It would therefore be helpful to develop a formal model incorporating demand variation and to evaluate the influence of demand variation on the system design and routing decisions. Third, we assume that each rental station may be visited only once. It would be helpful to develop a formal model to allow each rental station to be visited more than once.

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