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Optimizing the level of service quality of a bike-sharing system ☆

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ABSTRACT

Public bike-sharing programs have been deployed in hundreds of cities worldwide, improving mobility in a socially equitable and environmentally sustainable way. However, the quality of the service is drastically affected by imbalances in the distribution of bicycles among stations. We address this problem in two stages. First, we estimate the unsatisfied demand (lack of free lockers or lack of bicycles) at each station for a given time period in the future and for each possible number of bicycles at the beginning of the period. In a second stage, we use these estimates to guide our redistribution algorithms. Computational results using real data from the bike-sharing system in Palma de Mallorca (Spain) are reported.

1. Introduction

A public bike-sharing system consists of a set of stations scattered over the city and a set of bicycles available to the system users. A user can take a bicycle at a station, use it for a short journey, and leave it at the same or any other station. Since the first system was established in Amsterdam in 1965, there has been a rapidly increasing number of cities providing their citizens with this type of service, which has many advantages of various kinds: it is an environmentally sustainable and socially equitable mode of transportation, it can be used as part of an intermodal public transport system, it reduces motorized traffic and therefore emissions of contaminants, and it promotes a healthier way of life. According to the consultancy company MetroBike LCC [1], in July 2014, 721 cities had a public bike-sharing system, with a total of approximately 814,000 bicycles, and 228 were planned or under construction. These systems range from less than one hundred bicycles in small towns to many thousands in cities like Paris (20,600), Hangzhou (78,000), or Wuhan (90,000).

The most important factor for the success of a public bike-sharing system is its ability to satisfy the varying demands of the users. Underlying the random variations of everyday demands, there are patterns of demand that have to be identified and estimated and the system has to be planned and managed to maximize the level of customer satisfaction. Situations in which the user arrives at a station to take a bicycle and finds the station empty, and those in which he/she arrives at the station to leave the bicycle and the station is completely full, have to be avoided as far as possible. For the bike-sharing system to become a sensible alternative to other modes of transportation, it has to be reliable. The everyday users have to be confident that they will find bicycles to start their trips and available lockers to leave them when the trips are finished wherever and whenever they need them. This can be achieved in the three phases of design and operation. First, at a strategic level, the number of stations and their location and size have to be decided. Second, at a tactical level, the number of bicycles in the system has to be determined. Third, at an operational level, a bike-repositioning system has to be adopted for moving bicycles from stations with an excess to stations with a shortage in order to satisfy the demands forecast for the next periods.

Repositioning is done by means of light trucks based at one or several depots, that pick up bicycles from stations at which there are too many and move them to stations where there are too few. Sometimes there are bicycles at the depots, for instance those that were damaged and have been repaired, and these can also be used when constructing the repositioning routes.

There are two types of repositioning systems. In the static case, the system is considered closed, so the users do not interact with it, its initial state is considered known and fixed, and the aim of the repositioning is to get the system to a desired, predefined state. In the dynamic case, the repositioning system operates while the bike-sharing system is being used. Therefore, users are continuously taking and leaving bicycles at the stations, modifying their states. The dynamic repositioning system has to take these changes into account and adapt its decisions to the actual state of the stations.

In this study we focus on the static repositioning system at the operational level. In the city of Palma de Mallorca (Spain), whose bike-sharing system gave rise to this study, the system operates

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every day from 07:00 until 24:00. Every night, when the system closes, the states of the stations do not correspond to the desired states for the next morning. Therefore the trucks of the repositioning system move some bicycles between stations in order to leave the system as close as possible to the ideal state when it opens in the morning.

There are several features of the Palma system and of our approach that make this study different from previously published studies. First, the desired state of each station is not given but calculated from the system information. Most of the previous papers on the static repositioning problem consider the desired or target state of each station as a given constant, assuming implicitly that these targets are attainable. In our approach, the ideal state of each station is calculated from the database in which the system has recorded every single bicycle move. Using these data, we can estimate the demands (in both directions, taking and returning bicycles) for every time interval and compute the unsatisfied demand for each possible station state. Using these estimated unsatisfied demands and the number of available bicycles in the system we calculate the state of each station that minimizes the overall cost of unsatisfied demands. If there are enough bicycles to attain for each station the state that minimizes its estimated unmet demand, that will be the solution. However, if the number of available bicycles is lower than the sum of these individual optimal states, the available bicycles have to be placed at the stations where they minimize the overall unsatisfied demands.

A second special characteristic concerns the design of the truck routes. The city is not split beforehand into as many zones as there are trucks available. In our proposal, all the trucks work jointly and the routes are constructed simultaneously, taking into account balance criteria such as the total distance or total time of each route. There is also flexibility about the initial and final points of the truck routes and about the number of bicycles a truck can carry when it starts its route.

A third distinctive characteristic of our proposal is the management of damaged bicycles. These damaged, out-of-service bicycles are detected by the system and we were asked to include their collection in the repositioning routes. In our system, when the trucks visit the stations these damaged bicycles are collected, whenever possible, and taken to the depot. In this way, no special collection routes for damaged bicycles are needed.

2. Previous work

There are a number of existing papers in the literature about the static case [2–11], but very few on the dynamic case [12–14]. Although all of them deal with the problem of repositioning, the objectives, constraints, and solution techniques are different.

Among the different objectives considered, we find minimization of total traveling cost or time [2–4], total unmet demand [13], maximum tour length [9], the sum of travel time and holding cost [10], the weighted sum of total time of the routes, deviation from the targeted number of bicycles at each station, and number of moves between stations [8,15,16].

The characteristics of the problem considered in each study are also different. For example, in some of them only one vehicle is available [2,10,11]. In others, a limit to the number of visits to the stations is imposed: only one [4,11], or a maximum fixed number [3]. In some cases, the perfect balance requirement is a hard constraint [2,3] but in most of them the imbalances are penalized. A key question is how the target state for each station is computed. In most of the studies, this quantity is fixed, generally at half the station capacity, as in Rainer-Harbach et al. [6], Raidl et al. [7], and Papazek et al. [8]. Schuijbroek et al. [9] compute a lower and upper bound on the service level requirement of each station by using a queuing system and Raviv and Kolka [17] compute a measure of dissatisfaction for different replenishment periods, given an initial inventory, the station size, and stochastic demand patterns.

Several types of heuristics have been proposed. For instance, a 9.5 approximate algorithm [2], a cluster-first, route-second algorithm [9], tabu search [3,11], variable neighborhood search [6,7], PILOT/GRASP [8], ant colony and constraint programming [15,16], and matheuristics [18]. In three studies [4,5,19], MIP formulations and/or relaxations of the problem are solved. To our knowledge, only four exact methods have been proposed: one branch-and-prize [13] and three branch-and-cut algorithms [3,10,19].

3. Description of the problem and data analysis of the Palma system

A bike-sharing system is composed of a set of stations, from which the bicycles are taken and to which they are returned. The registered users can take a bicycle from any station at any time, use it, and return it to another station. Each city has its own rules of usage. In Palma de Mallorca, the first 30 min are free of charge and a small fee is paid for extra time. Each movement is recorded and stored in the system's database. The quality of the service can be measured as the amount of time a station remains empty or completely full, and either the withdrawal demands cannot be satisfied or the bicycles cannot be returned. Another alternative measure would be to count or estimate the number of unsatisfied demands of both types at each station. The repositioning system includes one or several depots to which damaged bicycles are brought to be repaired and from which repaired or new bicycles are incorporated into the system, and a set of vehicles that take bicycles from the depots or from the stations and carry them to other stations in order to improve the quality of the service.

The system can be represented by a complete graph $G=(V,E)$, where $V=\mathcal{S}\cup\mathcal{D}\cup\mathcal{V}$ contains a vertex for each depot, each station, and each vehicle, representing its initial location.

For each station $i\in\mathcal{S}$ (set of stations) we know:

- C_i, capacity (number of lockers),
- bs_i, current number of bicycles ready to be used,
- bs_i^{dam}, current number of damaged bicycles.

For each vehicle $l\in\mathcal{V}$ (set of repositioning vehicles):

- P_l, capacity (number of places),
- bv_l, number of bicycles in good condition on the vehicle,
- bv_l^{dam}, number of damaged bicycles on the vehicle.

For each depot $k\in\mathcal{D}$ (set of depots):

- bd_k, number of bicycles stored in the depot.

We also know:

- t_{ij}, travel time from location i to location j; $i,j\in\mathcal{S}\cup\mathcal{D}\cup\mathcal{V}$,
- t^{park}, parking time,
- t^{load}, time to load/unload one bicycle.

As of November 2013, in *bicipalma*, the bike-sharing system of Palma de Mallorca (Spain), there were 28 stations and over 200 bicycles. The capacity of each station varies from 10 to 30 bicycles. Fig. 1 shows the distribution of the stations on the Palma map.

The usage of each station is neither uniform nor correlated with its capacity. Fig. 2 shows the capacity and the average number of movements on working days. The horizontal axis shows the stations' capacities (10, 15, 20, 30 lockers) and the vertical axis the average daily movements at each station. A large variability can be observed. Small stations with 10 lockers may have up to 60 movements, while