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A branch-and-bound algorithm for solving the static rebalancing problem in bicycle-sharing systems

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ABSTRACT

Bicycle sharing systems are transportation systems that allow the users to rent a bicycle at one of many automatic rental stations scattered around the city, use them for a short travel and return them at any station. A crucial factor for the success of such a system is its ability to ensure a good quality of service to users. It means the availability of bicycles for pick-up and free places to return them. This is performed by means of a rebalancing operation, which consists in removing bicycles from some stations and transferring them to other stations, using dedicated vehicles. In this paper, we study the rebalancing vehicles routing problem by considering the static case. Vehicles conduct tours between stations to return them to their desired levels, which are known in advance, and each station must be visited exactly once and only once by a vehicle. This problem is similar to the traveling salesman problem with additional constraints. The aim is to find an optimal scheduling of the vehicle that minimizes the total waiting time of the stations in disequilibrium states. We propose several lower and upper bounds. These bounding procedures are used in a branch-and-bound algorithm. Computational experiments are carried out on a large set of instances and the obtained results show the effectiveness of our method.

1. Introduction and state of the art

With increased concerns on the global oil prices, traffic congestion and reducing noise/air pollution, many cities around the world are encouraging their residents to use public transportation instead of private automobiles to travel. One of the most interesting solution is the bicycle-sharing systems (BSS), which are an increasingly popular system whereby bicycles are made available on a large scale in a city allowing people to have ready access to these public bicycles (DeMaio, 2009), they are especially useful for short travels. A given amount of bicycles are being positioned in stations situated near metro stations, residential communities, business centers, scenic spots, administrations, etc. to facilitate the movements of people within the city. As presented in Fig. 1, a customer uses a bicycle to travel from a station to another one. A bicycle can be taken out from any station and returned to any station at any time, provided that there is an empty locking berth. A BSS requires more than just bicycles and stations, a variety of other equipment and systems (e.g., bike fleets, parking and locking mechanisms, user interface and check-out protocols, and station networks), as well as maintenance and management requirements (e.g., fleet and station maintenance, status information systems and bike redistribution systems) are needed to keep the bicycles and stations functioning at adequate level of service.

The scientific research in the field of bicycle-sharing systems can take various orientations related to many raised issues which may be tactical, strategic and/or operational. These issues are crucial for the performance and economic viability of these systems. However, formulate and solve all these issues require the development of analytical and suitable optimization methods that take into account the complexity of the characteristics and the dynamic of these systems. Their complexity is reflected by many factors including:

- *Dense and large networks*: a network such as Vélib' in Paris has over 1258 stations and a fleet of 13,820 bicycles.
- *Complex and dynamic random*: the dynamics of a bicycle-sharing network is very complex given that it is impossible to predict all movements to be carried out and/or bicycles flow.
- *Operating in self-service mode*: the operating of these systems, in a self-service mode, makes their dynamic behavior even more complex.

To help designers, planners and managers of bicycle-sharing systems, performance and optimization models as well as decision

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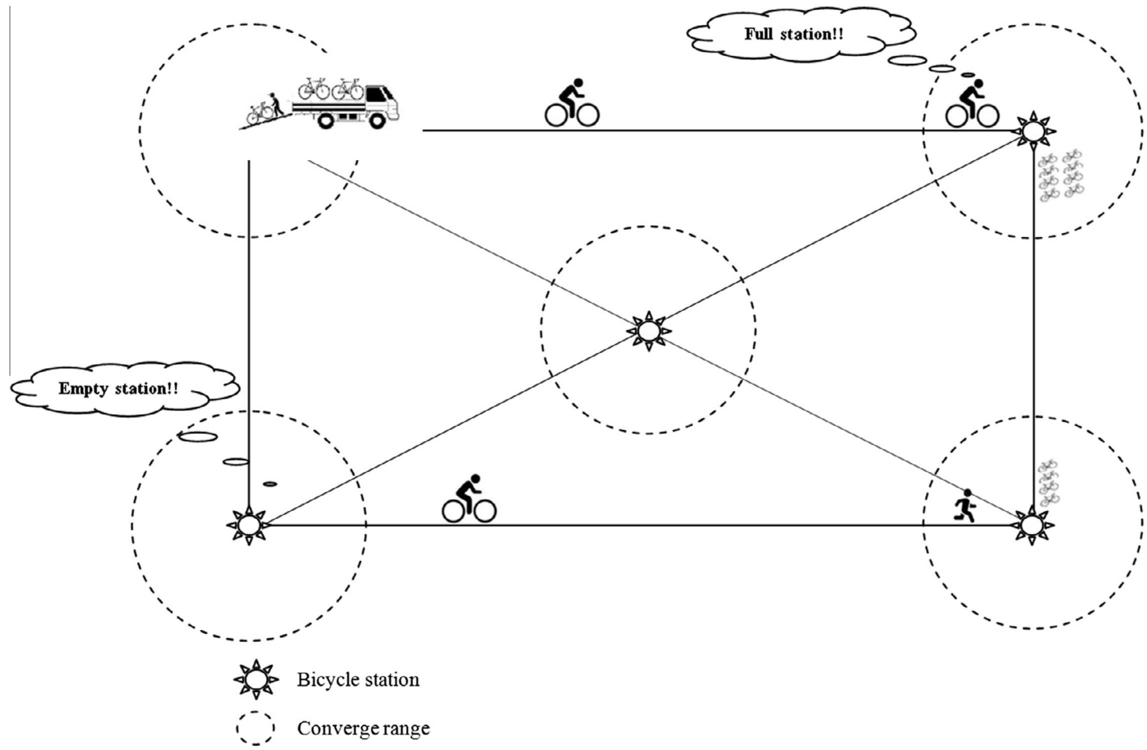

Fig. 1. Structure of bicycle sharing systems.

making tools are unavoidable. The recent momentum of such public transportation systems, as an ecological mobility system in dense cities, has not been followed by an intense research. In the following paragraph, we first give a short overview of different research areas concerning BSS, then, we focus on the operational level of decision making.

Most of the studies related to bicycle sharing systems in the literature have focused on their history and development (DeMaio, 2009; Shaheen, Guzman, & Zhang, 2010), promotional policies and safety issues (Aultman-Hall & Kaltenecker-Georgina, 1999; Martens, 2007). During these last years, we observe the emergence of a growing number of scientific articles which are investigating various issues in these systems including strategic and operational design.

1.1. Strategic design

Some works examine strategic planning aspects in BSS such as locations, network design and the capacities of stations for a strategic planning purpose. Vogel and Mattfeld (2010) present a suitable model to test the impact of dynamic positioning strategies on the performance of the system. Their model is efficient for strategic planning but not enough detailed to support balancing operations.

Indeed, some authors address the strategic decisions concerning capacities and locations of the bicycle stations. Shu, Chou, Liu, Teo, and Wang (2010) address the locations and stations' capacities issues. They develop practical model to predict the flow of bicycles and estimate the number of trips supported by the system given an initial allocation of bicycles and the number of attachment points needed for each station. In addition, they study the profitability of a periodic redistribution of bicycles. Lin and Yang (2011) develop a model to identify the number of bicycle stations and their locations as well as the network of bicycle paths. Their model takes into consideration the interest of both users and service providers. In their extended study, (Lin, Yang, & Chang, 2013) address a strategic design for BSS and take into account decisions on the bicycle stocks at stations. Martinez, Caetano, Tomas, and Cruz (2012) address the location and capacity issues. They propose a mixed integer program to determine the locations and the required number of bicycles.

Moreover, Dell'Olio, Ibeas, and Moura (2011) investigate the stations locations issue and develop a methodology for the design and implementation of bicycle-sharing systems. Their method is based on the estimation of demands for a given period considering the stations and the rental prices.

Other studies analyze bicycle temporal and geographical usage patterns (Kaltenbrunner, Meza, Grivolla, Codina, & Banchs, 2010) or system characteristics and usage patterns as presented by Nair and Miller-Hooks (2011), where they propose a MIP for the optimal configuration of shared mobility systems by determining the stations' locations and capacities as well vehicles inventories.

1.2. Operational design

At this level, the operating of systems with at least a minimum quality of service must be ensured with the aim of satisfying the maximum of users' demands and reducing the operational costs. Some studies are based on network data analysis and statistics for operational planning, i.e., predicting future demands of users, bicycles availability, as addressed in the works of Bordagaray, Ibeas, and dell'Olio (2012), Kadri, Labadi, and Kacem (2015), Kaltenbrunner et al. (2010) and Pucher, Buehler, and Seinen (2011).

Vogel, Greisera, and Mattfelda (2011) propose an approach based on the use of data mining for strategic and operational planning purpose. They show with a case study that data mining applied to operational data provides an overview on the typical usage patterns of BSS and is exploited for predicting user demands for a medium-term time. Other studies address the operational and management issues in BSS especially balancing activities between stations by means of vehicles, in order to balance bicycle stocks among the stations. The objective for any BSS service provider is to be able to meet the variable demands for bicycles as well free