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A modeling framework for the dynamic management of free-floating bike-sharing systems

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A B S T R A C T

Given the growing importance of bike-sharing systems nowadays, in this paper we suggest an alternative approach to mitigate the most crucial problem related to them: the imbalance of bicycles between zones owing to one-way trips. In particular, we focus on the emerging free-floating systems, where bikes can be delivered or picked-up almost everywhere in the network and not just at dedicated docking stations. We propose a new comprehensive dynamic bike redistribution methodology that starts from the prediction of the number and position of bikes over a system operating area and ends with a relocation Decision Support System. The relocation process is activated at constant gap times in order to carry out dynamic bike redistribution, mainly aimed at achieving a high degree of user satisfaction and keeping the vehicle repositioning costs as low as possible. An application to a test case study, together with a detailed sensitivity analysis, shows the effectiveness of the suggested novel methodology for the real-time management of the free-floating bike-sharing systems.

1. Introduction

Bike sharing systems (BSSs) offering a mobility service by means of public bikes available for shared use are becoming increasingly popular in urban environments. These shared systems provide city users with an alternative and more sustainable carbon-free mode of transportation (especially suited for short-distance trips), significantly reduce traffic congestion, air pollution, noise, and the need for parking in city centers, and support a greener growth of urban environments.

BSSs allow users to take a bike from a particular position in the network, use it for a journey, give it back closer to their destination, and pay either according to the time of usage or other specific pricing policies. Thanks to BSSs, it is possible to have access to those city areas that are not allowed to other kinds of vehicles and create an alternative connection with public transit networks. In the literature, it is possible to find different studies that suggest ways to enhance the efficiency of BSSs from tactical or strategical viewpoints. Some authors have investigated the optimal location of stations (García-Palomares et al., 2012; Martinez et al., 2012), the network design of bike lanes (Lin and Yang, 2011; Vogel and Mattfeld, 2011; Saharidis et al., 2014), and their capacity levels (Romero et al., 2012; Garcia-Gutierrez et al., 2014).

Despite their undeniable qualities, BSSs are mainly used for medium-short distances and for one-way trips. Such usage leads to an unbalanced distribution of bikes in time and space. This sometimes makes it impossible for users to find a bike when they want to

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start their journey, and/or the leave the bike at their preferred destinations due to full stations. Hence, aiming to increase the use of the system and user satisfaction, bike sharing service providers have to focus on the efficiency of rebalancing operations (Shui and Szeto, 2015; Li et al., 2016) and ensure that the number of bikes, as well as the number of free docking slots at each station, are periodically restored to predefined target values.

Essentially, there are two different relocation strategies: the user-based approach, where users are induced to leave their bike at a certain station in order to balance the global distribution of bikes; and the operator-based one, where the relocation process is performed by the BSS service staff.

The operator-based reallocation problem is known as a Pickup and Delivery Problem (PDP). The application of this optimization problem to BSSs has recently attracted the interest of many researchers and practitioners in this field. It can be modeled by a dynamic or a static approach (Chemla et al., 2013b). In the static version, which is usually performed during the night (when the system is closed, or the bike demand is very low), a snapshot of the number of bikes in each zone is considered and utilized to plan the redistribution. On the other hand, the dynamic relocation is performed during the day when the status of the system is rapidly changing and takes into account the real-time usage of the BSS. In the dynamic case, the relocation plan is strongly supported by forecasting techniques.

In the literature, it is more common to find authors dealing with a static approach (Raviv et al., 2013; Lu, 2016; Schuijbroek et al., 2017). They solve the problem by adopting different methods, such as an iterated tabu search (Ho and Szeto, 2014), a branch and bound algorithm (Kadri et al., 2016), an enhanced chemical reaction optimization such as the one proposed by Szeto et al., (2016), and the latest hybrid large neighborhood search by Ho and Szeto (2017). Often, they have studied static bike rebalancing benefit using methodologies like forecasting and inventory optimization (Chemla et al., 2013a; Dell'Amico et al., 2014; Forma et al., 2015; Erdoğan et al., 2015).

Solutions to a dynamic public bike sharing balancing problem have been proposed at first by Contardo et al., (2012), who suggested a mathematical formulation on a space–time network, and after that by Caggiani and Ottomanelli (2012 and 2013), Benarbia et al. (2013) and Vogel et al. (2014). Regue and Recker (2014) proposed a novel approach, that results proactive instead of reactive, as the bike redistribution occurs before inefficiencies are observed, increasing system performance and, potentially, customer satisfaction; they used the outputs of a machine learning technique to decompose the inventory and the routing problem. Some other works (Pfrommer et al., 2014; Fricker and Gast, 2016) have examined incentive policies aimed at encouraging users to return bikes to the locations that need bikes. Shui and Szeto (2017) proposed a dynamic bike repositioning problem that simultaneously minimizes the total unmet demand of the bike-sharing system and the fuel and CO_2 emission cost of the repositioning vehicle. The solution method is based on an Artificial Bee Colony algorithm.

In recent years, innovative systems for the management of bike sharing, called Free-Floating Bike Sharing Systems (FFBSSs), are gradually showing up. At the beginning they have only been applied to medium-small areas or pilot projects; however, particularly during the last two years, they have started to be implemented in many large cities in China, England, Netherlands, and other countries. In FFBSSs, users can lock shared bikes to an ordinary bike rack or to any pole, removing the concept of fixed stations, and avoiding the necessity of docking stations and kiosk machines (Pal and Zhang, 2017) with relevant physical and information communication technology infrastructures.

The position of the available bikes is identified through a satellite receiver located on each bicycle, or by means of users' smartphones (using the smartphone for locking/unlocking the bike's smart lock, the bicycle location is transmitted to the central system). Users can detect a bike through web or mobile applications. More information on how these systems work can be found on websites of FFBSSs providers such as SocialBicycle (SoBi).

The main advantages that make FFBSSs more attractive than the current BSSs generations are twofold: (1) reduced system start-up costs and (2) the possibility to find and leave the bike almost anywhere as long as it is a location accessible to all users and within the served area. For FFBSSs, the problem of full stations does not exist, since bikes can be dropped off almost everywhere and the number of ordinary racks that could be installed is very high, thanks to their low acquisition, installation and maintenance costs. However, as in BSSs, bike distribution can be unbalanced in time and space and there is no guarantee of finding a free bike near the origin of the desired trip. Furthermore, as bikes are scattered across the territory (because of the opportunity to leave the bike anywhere) and their positions may change during the day and from day to day, the relocation process of these systems is even more challenging than that of the traditional BSSs.

To the best of our knowledge, there are only four recent papers on FFBSSs. Reiss and Bogenberger (2015 and 2016) have proposed GPS-data analyses of FFBSS with the suggestion of a relocation strategy and a validation method to show the effects of rebalancing operations through the application of their proposed methods on Munich's FFBSS. Pal and Zhang (2017) have presented a hybrid nested large neighborhood search with variable neighborhood descent algorithm to solve a static rebalancing problem. Caggiani et al. (2017b) proposed a methodology for the strategic design of FFBSS whose facilities could be allocated in the territory according to spatial and social equity principles.

In this paper, we propose a new, comprehensive, dynamic, and operator-based bike redistribution methodology that starts from the prediction of the number and position of bikes over an FFBSS operating area and ends with a Decision Support System (DSS) for the relocation process. The DSS is activated at constant gap times during the day in order to carry out dynamic bike redistribution, mainly aimed at achieving a high degree of user satisfaction and keeping the costs of repositioning operations as low as possible. As a matter of fact, it is important to point out that maximizing customer satisfaction is one fundamental contribution to the maximization of profitability for a company: a greater user satisfaction implies the system being used more intensively from any user. Moreover, satisfied customers may recommend the service to other possible customers, increasing the potential for additional revenue and profit, and playing an important part in shaping attitudes towards the company and the service.