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A time-space network flow approach to dynamic repositioning in bicycle sharing systems

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ABSTRACT

Faced with increasing population density, rising traffic congestion, and the resulting upsurge in carbon emissions, several urban metropolitan areas have instituted public bicycle sharing system as a viable alternative mode of transportation to complement existing long-distance bus- and metro- transit systems. A pressing issue that needs to be addressed in bike sharing systems is the accrued imbalance of bicycles between commuter demands and inventory levels at stations. To overcome this issue, a commonly employed strategy is to reposition bicycles during off-peak periods (typically at night) when no new user arrivals are expected. However, when such an imbalance occurs during day-time peak hours, such a passive strategy would result in lower resource utilization rates. To overcome this drawback, in this study, we propose a dynamic bicycle repositioning methodology that considers inventory level forecasting, user arrivals forecasting, bicycle repositioning, and vehicle routing in a unified manner. A multi-commodity time-space network flow model is presented, which results in an underlying complex nonlinear optimization problem. This problem is then reformulated into an equivalent mixed-integer problem using a model transformation approach and a novel heuristic algorithm is proposed to efficiently solve this model. Specifically, the first stage involves solving the linear relaxation of the MIP model, and a set covering problem is subsequently solved in the second stage to assign routes to the repositioning vehicles. The proposed methodology is evaluated using standard test-bed instances from the literature, and our numerical results reveal that the heuristic algorithm can achieve a significant reduction in rejected user requests when compared to existing methods, while yet expending only minimal computational effort.

1. Introduction

In recent years, many metropolitan areas have invested in sustainable public transportation systems to stem the rising tide of traffic congestion and the associated increase in harmful carbon emissions. One such green initiative is *bicycle sharing systems*, which have risen to prominence over the last decade. According to a report commissioned by the Land Transport

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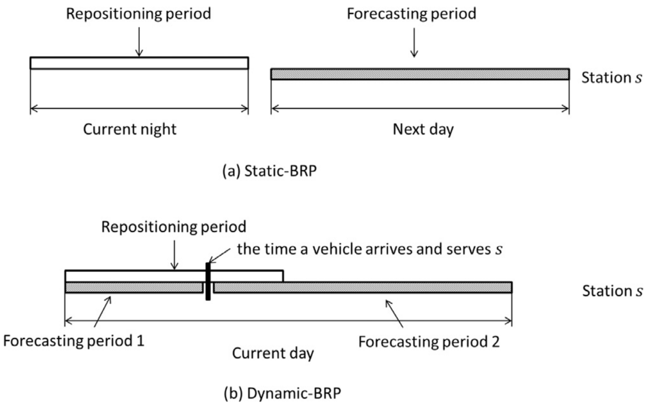

Fig. 1. The repositioning period and forecasting period for the dynamic-BRP.[1]

Authority (LTA) of Singapore, nearly 78 major cities world-wide have deployed bike sharing systems, with Europe leading the way, closely followed by Canada and Asia (Midgley, 2009). A typical bicycle sharing operation comprises the following three resource components: (i) a set of *bicycles*, which can be rented by commuters for a (fixed) price; (ii) a set of *stations* or *depots*, from where a bicycle can be picked-up or dropped-off; (iii) a fleet of *repositioning vehicles* (usually trucks) that are used to transport bicycles from one location to another. From a user perspective, such bicycle sharing options have predominantly been used as an alternative (mostly) one-way transportation mode for short journeys, and serve to complement existing long-distance public transportation modes, such as bus- and metro-transit systems.

In order to guarantee high levels of service quality and increased resource utilization rates, it is necessary to monitor and replenish the inventory level at each station, by periodically repositioning bicycles from one station to another. Such bicycle repositioning activities are usually performed at night, when no pick-ups/drop-offs are anticipated (Raviv et al., 2013; Dell'Amico et al., 2014; Forma et al., 2015), thereby resulting in a *static bicycle repositioning problem* (*static-BRP*). In the literature, there are a bundle of methodologies proposed for the static-BRP (Benchimol et al., 2011; Schuijbroek et al., 2013; Chemla et al., 2013; Raviv et al., 2013; Papazek et al., 2013; Schuijbroek et al., 2013; Di Gaspero et al., 2013; Dell'Amico et al., 2014; Ho and Szeto, 2014; Erdogan et al., 2015; Di Gaspero et al., 2016; Dell'Amico et al., 2016; Li et al., 2016; Szeto et al., 2016; Ho and Szeto, 2017). However, given the growing user demand, scheduling repositioning activities exclusively at night cannot sufficiently adjust the inventory level of stations during the day. This leads to an acute imbalance between pick-ups and drop-offs, and at stations where this phenomenon is most prevalent, a significant proportion of pick-up/drop-off requests will likely be rejected, thereby resulting in severe underutilization rates. Furthermore, it also discourages passengers from adopting bike sharing as an alternative mode of transportation, leading to adverse social and environmental impacts. Therefore, there is a pressing need to mitigate this inevitable accrued imbalance between inventory levels and commuter demand expectations at bicycle stations during regular operational hours.

Repositioning bicycles periodically during day-time operational hours is an option to counteract this phenomenon, as the inventory levels at bicycle stations can be rebalanced by using the forecasts of inventory levels (Raviv and Kolka, 2013; Shu et al., 2013; Schuijbroek et al., 2013) and rental/return requests (Barth and Todd, 1999; Cheu et al., 2006; Kek et al., 2009; Froehlich et al., 2009; Kaltenbrunner et al., 2010; Caggiani and Ottomanelli, 2012; de Chardon and Caruso, 2015; Borgnat et al., 2011; Caggiani and Ottomanelli, 2013), thereby resulting in a *dynamic bicycle repositioning problem* (*dynamic-BRP*). The main objective of the dynamic-BRP is to determine the optimal inventory levels that need to be maintained at each bicycle station such that *user dissatisfaction* is minimized. The user dissatisfaction is defined as the expected number of commuter requests (both rentals and returns) that will be rejected in a future time period due to the lack of available bicycles or empty docks (Raviv and Kolka, 2013). For either the static-BRP or the dynamic-BRP, three key components are user dissatisfaction estimating, bicycle repositioning and vehicle routing. For the static-BRP, the user dissatisfaction is first estimated and then the bicycle repositioning and vehicle routing are solved. However, the situation is much difficult in the dynamic case as the repositioning period and the forecasting period are overlapped (see Fig. 1). It consequently leads to a result that the estimation of the user dissatisfaction should be performed simultaneously when making the bicycle repositioning and vehicle routing decisions. Meanwhile, the forecasting information in the dynamic-BRP is *time dependent* and a repositioning solution needs to be generated relatively quickly; otherwise, the forecasted information might not accurately reflect the actual scenarios at a bicycle station.

The challenges that arise in the dynamic-BRP necessitate dedicated and efficient methodologies. However, considering the complexity of fully integrating three key components (namely, the user dissatisfaction estimating, the bicycle repositioning and the vehicle routing), several partially integrated or sequential solution methodologies of the dynamic-BRP are proposed

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[1] The repositioning period is a time-window in which all repositioning operations need to be completed while the forecasting period is a time-window in which the number of rejected requests is forecasted.