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Exact loading and unloading strategies for the static multi-vehicle bike repositioning problem

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A B S T R A C T

This study investigates a bike repositioning problem (BRP) that determines the routes of the repositioning vehicles and the loading and unloading quantities at each bike station to firstly minimize the positive deviation from the tolerance of total demand dissatisfaction (TDD) and then service time. The total demand dissatisfaction of a bike-sharing system in this study is defined as the sum of the difference between the bike deficiency and unloading quantity of each station in the system. Two service times are considered: the total service time and the maximum route duration of the fleet. To reduce the computation time to solve the loading and unloading sub-problem of the BRP, this study examines a novel set of loading and unloading strategies and further proves them to be optimal for a given route. This set of strategies is then embedded into an enhanced artificial bee colony algorithm to solve the BRP. The numerical results demonstrate that a larger fleet size may not lead to a lower total service time but can effectively lead to a lower maximum route duration at optimality. The results also illustrate the trade-offs between the two service times, between total demand dissatisfaction and total service time, and between the number of operating vehicles provided and the TDD. Moreover, the results demonstrate that the optimal values of the two service times can increase with the TDD and introducing an upper bound on one service time can reduce the optimal value of the other service time.

1. Introduction

Cycling has been widely recognized as an economical and environmentally friendly mode of transport. Particularly in overseas countries, citizens are very much encouraged to travel by cycling in short-distance so that the number of motorized trips can be reduced, with a view to reducing pollution from motorized vehicles. To make cycling more convenient and efficient, the concept of bike sharing was introduced to allow the rental use of bicycles at specified stations within a city and return at any other stations whenever a short-distance trip is required (Raviv et al., 2013). Whereas bike-sharing systems are commonly run by the public sector, they can also be run successfully overseas by commercial parties to gain revenue or by a public-private partnership. Bike sharing is currently very popular worldwide. As of 2 November 2017, public bike-sharing systems were available in about 1488 cities and included approximately 18,740,100 bicycles around the world (Meddin and DeMaio, 2017).

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The main challenge in operating a bike-sharing system is that the numbers of bikes required at some stations are often insufficient to satisfy the corresponding cycling demand. With a fixed number of bikes in the bike-sharing system, the operator always needs to transfer the bikes from bike surplus stations to bike deficient stations by trucks to reduce unsatisfied cycling demand. This problem is called a public bike repositioning problem (BRP), which determines optimal truck routes and the loading and unloading activities of the trucks, subject to various constraints including vehicle, station, and operational constraints. Because of its unique characteristics and practical importance, the BRP has attracted the interest of many researchers in recent years. The BRP can be modeled as either a static or dynamic optimization problem (Raviv et al., 2013). The static problem considers night-time scenarios where the demand is low or the system is closed, while the dynamic problem considers daytime scenarios that take real-time usage of the system into account. Table 1 has summarized the BRP publications according to the operational scenario, the number of operating trucks used, problem objectives, and whether loading and unloading time is considered in the travel time/cost in the objective function. In terms of operational scenarios, the vast majority of the BRP studies address the static problem but only a few studies have tackled the dynamic problem (Caggiani and Ottomanelli, 2012; Contardo et al., 2012; Kloimüllner et al., 2014; Regue and Recker, 2014; Brinkmann et al., 2015; Zhang et al., 2016; Shui and Szeto, 2017). In terms of the number of trucks used, both single and multiple vehicle problems are studied. In terms of formulations, multiple vehicle repositioning problems are straightforward extensions of single vehicle repositioning problems. However, it is more realistic to consider multiple vehicle repositioning problems for large-scale bike-sharing systems.

In terms of problem objectives, common components are (1) travel time or related measures such as travel distance or cost, and (2) total demand dissatisfaction (e.g., total number of users who fail to get a bike at stations) in a bike-sharing system, in the form of unmet demand, penalty cost, or the deviation from the target inventory level. Whereas the first one is the key concern of private operators, the second one is a societal benefit measure and should be included in the objective by the government as the operator. Ideally, the total demand dissatisfaction of a bike-sharing system should be zero. In practice, some tolerance may be allowed. Although total demand dissatisfaction is crucial in any public bike system from the perspective of the society, solely focusing on the total demand dissatisfaction of the system does not guarantee that the final service routes can have the lowest service time (including in-vehicle travel time and loading and unloading times). Loading and unloading times also contribute to the operation hours of truck drivers, which have financial implications for the operator. It is important to capture the loading and unloading times accurately to minimize the operation cost for the operator (even if the operator is the public sector) because the cost can be viewed as a negative benefit (or a negative profit), and hence minimizing the operation cost can be viewed as maximizing the benefit. However, most of the preceding studies that capture travel time in the objective function do not use *actual* loading and unloading times in the travel time calculation. Moreover, those studies that use the actual loading and unloading times in travel time calculation do not consider the total demand dissatisfaction of the system simultaneously. Furthermore, multiple optimal solutions with the same minimum total demand dissatisfaction may exist. Using service time minimization as a second priority level objective helps the operator choose a solution among those optimal solutions with respect to the first priority level objective.

To address these issues, this paper proposes a new repositioning problem that minimizes firstly the positive deviation from the tolerance of the total demand dissatisfaction (TDD) of the system and then the service time of the vehicles (including actual loading and unloading times). The total demand dissatisfaction of a bike-sharing system in this study is defined as the sum of the difference between the bike deficiency and unloading quantity of each station in the system. The predetermined parameter, TDD, is introduced into the first priority level objective function to allow a certain degree of bike deficiency in the system. Using this objective function allows us to derive and analyze simple loading and unloading strategies to determine *exact* pickup and drop-off quantities at each station. The service time of the vehicles required by the second priority level objective function is depicted by one of the two measures: the total service time and maximum route duration of all vehicles. The two measures result in two main models with their only difference in the measure used in the second priority level objective function.

It is noted that having too many excess bikes at some stations may result in inadequate parking spaces. To consider the space inventory required at each station for bike returns, unlike Nair and Miller-Hooks (2011) and Raviv et al. (2013) that implicitly considered and explicitly modeled the space inventory required in the penalty function and the level of service constraint respectively, this paper introduces a new approach to capture the target space inventory level (i.e., the number of slots reserved for parking) in the computation of the bike surplus and deficiency at each station.

To solve the proposed problem, the enhanced artificial bee colony (EABC) algorithm is used to determine vehicle routes and exact loading and unloading strategies are incorporated into the algorithm to determine pickup and delivery quantities at each station in each given route obtained from the algorithm. Based on the proposed solution method, test instances in the literature are used to illustrate the performance of the method and the properties of the problem.

To summarize, the main contributions of this study are the following:

1. We introduce the concept of the TDD and a new BRP that determines the vehicle routes and the loading and unloading quantities at each bike station to minimize first the positive deviation from TDD and then the total service time of all the vehicles; we also introduce the problem variant based on maximum route duration rather than total service time.
2. We propose and examine simple loading and unloading strategies and further prove them to be optimal solutions to the loading and unloading sub-problem. Using these strategies in the solution process avoids the need of solving the time-consuming loading and unloading sub-problem as a linear program or maximum flow problem in each iteration