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Anticipatory service network design of bike sharing systems

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Abstract

Today's conurbations suffer from inefficiency in transportation systems. Bike sharing systems (BSS) combine the advantages of public and private transportation to better exploit the given transportation infrastructure. They provide bikes for short-term trips at automated rental stations. However, spatio-temporal variation of bike rentals leads to imbalances in the distribution of bikes, causing full or empty stations in the course of the day. Ensuring the reliable provision of bike and free bike racks is crucial for the viability of these systems. On the tactical planning level, target fill levels of bikes at stations are determined to provide reliability in service. On the operational planning level, the BSS operator relocates bikes in vehicles among stations based on target fill levels. A recent approach in tactical service network design (SND) anticipates relocation operations of BSS by means of a dynamic transportation model yielding the required demand of relocation services (RS). A RS is described by pickup and return station, time period, and the number of relocated bikes. RS represent the design decision for implementing a service between two stations in each period for each day of the system operation. The output of the SND model are the time-dependent target fill levels at stations and the set of cost-efficient RS to facilitate these target fill levels. However, the existing approach neglects the sequence of RS into tours, thus leading to a weak anticipation of operational decisions. We extend an existing SND approach by including the concept of service tours (ST). RS are sequenced in ST which start and end at the depot. Experiments shows that the ST obtained by the extended SND yield a stronger anticipation of operational decisions.

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1. Introduction

In recent years, shared mobility systems (SMS) have been proposed to tackle the critical problems of metropolises, e.g., traffic congestion and high air pollution. In this context, bike sharing systems (BSS) have emerged as a flexible and sustainable means of shared mobility. BSS combine the advantages of public and private transportation to better exploit the given transportation infrastructure.

BSS offer bike rentals through automated rental stations. Each rental station provides a limited number of bikes and free bike racks for users. Free-of-charge short-term trips are usually offered to motivate the usage of the bike fleet (Büttner and Petersen, 2011). However, the acceptance of BSS depends on the service level of the system, i.e., the

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successful provision of bikes and free bike racks when demanded (Shaheen et al., 2010). Rentals at empty stations, as well as return of bikes at full stations are not possible. Due to spatio-temporal demand variation in combination with one-way-trips, providing suitable bike fill levels at each station during the day is challenging.

On the tactical planning level, target fill levels need to be determined for each station through the course of the day, to allow rentals and returns when demanded. Due to the limited capacity of stations, high fill levels increase rental probability but decrease return probability and vice versa. On the operational planning level, the BSS operator relocates bikes among stations based on target fill levels. Hence, a vehicle fleet starts tours from the depot, carries out a sequence of relocation operations, and returns to the depot. Relocation operations and fill levels are interdependent since bike relocations are required to compensate inadequate fill levels. However, relocation operations result in significant costs, affecting the viability of BSS (Büttner and Petersen, 2011). Neglecting information on the relocation operations in the tactical planning level leads to suboptimal decisions on fill levels. Therefore, anticipation of operational decisions is required.

Vogel et al. (2015) proposed a service network design (SND) approach to cover tactical planning issues of BSS. Relocation operations are anticipated by a computationally tractable dynamic transportation model yielding relocation services (RS). RS represent the design decision for implementing a service between two stations in a period of the day of the system operation, e.g., a workday. In addition, demand scenarios are obtained as input for the SND by a data analysis approach. Thus, typical demand flows between stations are obtained in terms of time-dependent origin-destination (OD) matrices. In the remind of this paper, we refer to the SND approach proposed by Vogel et al. (2015) as SND-RS.

However, SND-RS does not sequence the RS into tours. Information about empty trips of vehicles are neglected, leading to a weak anticipation of operational decisions. Therefore, we extend the SND-RS, adding the concept of service tours (ST), which leads to a stronger anticipation of operational decisions. In this work, the new SND approach is called SND-ST.

The remainder of this paper is organized as follows. Recent tactical planning approaches for SMS, including the SND-RS and their drawbacks, are discussed Section 2. The SND-ST and its MIP formulation are subject of Section 3. In Section 4, SND-RS and SND-ST are compared with regard to the fill levels and their operational anticipation. Computational experiments show that both SND approaches obtain similar fill levels as tactical decisions whereas the SND-ST yields extended information in terms of the requirements to manage the vehicle fleet though the ST. Finally, conclusions and future work are presented in Section 5.

2. Service network design of bike sharing systems

The literature has mainly focused on the strategic and operational planning for SMS. However, literature on tactical planning is scarce. We present approaches which consider anticipation of operational decisions in the tactical planning level. Correia and Antunes (2012) present three MIP formulations to maximize the total daily profit of one-way car sharing systems. In particular, revenue of trips paid by clients, costs of the depot, maintenance and depreciation of vehicles, and costs of dynamic vehicle relocations are taken into account. Cars are repositioned during the night to reset initial fill levels. This approach is validated by simulation techniques (Jorge et al., 2012). Sayarshad et al. (2012) maximize profit in BSS though a LP formulation yielding the minimum number of bikes that minimizes unmet demand, unutilized bikes, and relocation operations. Boyacı et al. (2015) introduce an optimization framework for car sharing systems which aims at maximizing their revenue. A MIP formulation considers an imaginary hub station to reduce the complexity that relocation operation involves in the MIP. Regarding tactical planning without anticipation of operational decisions, different approaches are presented by George and Xia (2011); Raviv and Kolka (2013); Cepolina and Farina (2012); Schuijbroek et al. (2013); Shu et al. (2013). Recent researches do not sufficiently cover the integration of the tactical and operational planning level. Furthermore, most optimization approaches are intractable for medium and large scale problems. Therefore, Vogel et al. (2015) propose the SND-SR yielding main tactical issues in addition with a suitable anticipation of operational decisions.

The SND-RS follows the work of Crainic (2000) and Wieberneit (2008) in freight transportation since this field covers most of BSS characteristics. The optimization model takes the form of a MIP which determines target fill levels at each bike station and time point minimizing the expected cost of RS while ensuring a predefined service