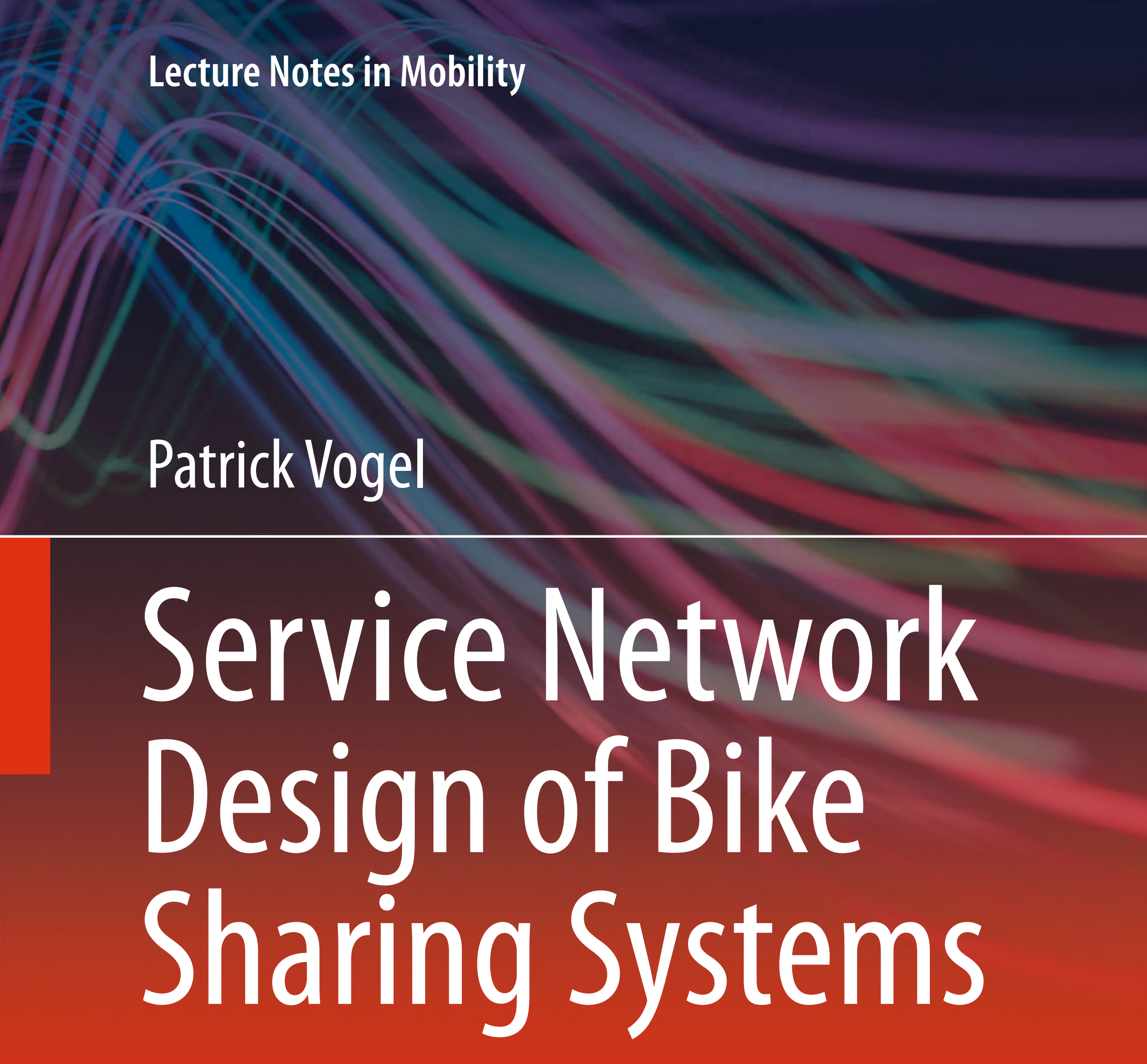

Lecture Notes in Mobility

Patrick Vogel

Service Network Design of Bike Sharing Systems

Analysis and Optimization

Springer

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Abbreviations

BSS	Bike sharing system
CBW	Citybike Wien
CP	Constraint-based programming
CSS	Car sharing system
DBI	Davies–Bouldin index
DI	Dunn index
DM	Data mining
EM	Expectation maximization
GRASP	Greedy randomized adaptive search
HM	Hybrid metaheuristic
I	Intuitive insert operator
IDA	Intelligent data analysis
IM	Information model
KDD	Knowledge discovery in databases
KM	K-means
KML	Keyhole markup language
LNS	Large neighborhood search
LP	Linear programming
MIP	Mixed-integer programming
OBIS	Optimizing Bike Sharing in European Cities
OD	Origin/destination
PDP	Pickup and delivery problem
R	Random insert operator
SI	Silhouette index
sIB	Sequential information bottleneck
SMS	Shared mobility system
SND	Service network design
SP	Swapping problem

SSE	Sum of squared error
T	Time-shift operator
UTPS	Urban transportation planning systems
VNS	Variable neighborhood search
VRP	Vehicle routing problem

Symbols

B	Number of trips in the bike sharing system
$B_{s_i,t}$	Number of bikes at station s_i in time period t
b	Number of bikes in the bike sharing system
$B_{s_i}^{-}$	Number of daily rentals at station s_i
$\beta_{c_j,t}^{-}$	Temporal rental activity of cluster c_j
$B_{s_i}^{+}$	Number of daily returns at station s_i
$\beta_{c_j,t}^{+}$	Temporal return activity of cluster c_j
br_{s_i}	Number of bike racks at station s_i
C	Set of temporal activity clusters
c_z	Temporal activity cluster z
ch_t	Average handling cost of one relocated bike in time period t
$\mathrm{ct}_{s_i s_j}$	Average transportation cost of one relocated bike between stations s_i and s_j
cm	Recourse cost for missing bikes and missing bike racks
d	Desired number of trips
$d_{s_i s_j}$	Distance between stations s_i and s_j
δ	Cost savings measure
$f_{s_i s_j,t}$	Bike flow between stations s_i and s_j in time period t
$f_{s_i c_j,t}^{-}$	Rental bike flows between station s_i and cluster c_j in time period t
$f_{s_i c_j,t}^{+}$	Return bike flows between station s_i and cluster c_j in time period t
$f_{s_i s_j,t}^{-}$	Rental bike flows between stations s_i and s_j in time period t
$f_{s_i s_j,t}^{+}$	Return bike flows between stations s_i and s_j in time period t
γ	Clustering
I	Intuitive insert operator
$\kappa_{c_i c_j,t}$	Intercluster distribution between clusters c_i and c_j in time period t
l	Lot size, defining the capacity of the relocation truck
$\lambda_{s_i s_k}$	Intracluster distribution between stations s_i and s_k
K^p	Neighborhood in iteration p
N	Set of bike stations

$\mathrm{MB}_{s_i,t}$	Number of missing bikes at station s_i in time period t
$\mathrm{MBR}_{s_i,t}$	Number of missing bikes' racks at station s_i in time period t
o	Observed number of trips
P_K	Subproblem defined by neighborhood K^p
p	Iteration in the hybrid metaheuristic
$\mathrm{pb}_{s_i,t}$	Proportion of returned bikes that are available for rental at station s_i in time period t
$\mathrm{pbr}_{s_i,t}$	Proportion of rented bikes that are available for return at station s_i in time period t
R	Random insert operator
$R_{s_i s_j,t}$	Number of relocated bikes between stations s_i and s_j in time period t
$\mathrm{RS}_{s_i s_j,t}$	Relocation service between stations s_i and s_j in time period t
$\mathrm{RS}^{\mathrm{free}}_{s_i s_j,t}$	Set of free relocation services
$\mathrm{RS}^{\mathrm{fix}}_{s_i s_j,t}$	Set of fixed relocation services
S^0	Initial solution
S^p	Optimal solution of subproblem in iteration p
s_i	Bike station i
$\mathrm{sb}_{s_i,t}$	Bike safety buffer at station s_i in time period t
$\mathrm{sbr}_{s_i,t}$	Bike rack safety buffer at station s_i in time period t
T	Set of time periods
τ	Threshold
ur	Usage rate

Chapter 1
Introduction

The main contribution of this work is introducing the notion of service network design (SND) for tactical planning of bike sharing systems (BSS). Therefore, an integrated approach of data analysis and mathematical optimization is pursued to provide input data and support decisions on SND. By introducing the notion of SND to BSS, this work aims to show the usefulness and benefit of tactical planning for shared mobility systems (SMS).

Traditional public and private modes of transportation are limited in dealing with increasing urban population and demand for mobility. The attitude towards established urban mobility concepts is changing, new technology is developing, and new concepts of sustainable and likewise flexible but affordable mobility are desired. Shared mobility systems (SMS) combine the advantages of public and private transportation satisfying those expectations. In particular, bike sharing as a recently successful concept of shared mobility becomes increasingly popular. Bike sharing systems (BSS) facilitate automated provision of bikes for short-term one-way trips. Positive effects such as better exploitation of given transportation infrastructure, reduction of pollution, and increase in health pave the way for the rapidly growing spread of BSS.

Crucial for the acceptance of bike sharing is the cost-efficient provision of reliable service. Users demand bikes for rentals and bike racks for returns at bike stations and points in time for their trips. High variation of user demand affects the provision of service. The dynamic nature of mobility results in imbalances in the spatiotemporal distribution of bikes among bike stations. Operators of BSS thus have to intervene in the system by operational relocation of bikes from full to empty stations which is usually associated with high cost. Operational planning of relocation requires fill levels of bikes at stations.

To this end, this work proposes a tactical planning approach by means of SND to determine fills levels. In particular, output of SND are time-dependent target fill levels of bikes at stations ensuring the availability of free bikes and bike racks. The tactical planning perspective requires both aggregation of operational demand and anticipation of operational decisions in order to avoid suboptimal fill levels. Core of

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this work is to determine a suitable aggregation and anticipation. SND of bike sharing is lacking attention in the scientific community so far. Thus, a novel integrated approach of intelligent data analysis (IDA) and mathematical optimization is developed to design the service network of BSS.

IDA models trip purposes based on operational trip data. Information systems in BSS record each trip resulting in extensive amounts of data. Recorded trip data only reflect individual observations of mobility and background information on trips, e.g., the trip purpose, are not available. For tactical planning, modeling the general mobility behavior is required in order to represent typical demand for the medium-term planning horizon adequately. In particular, IDA yields a spatiotemporal information model (IM) representing trip purposes. In combination with approaches from the field of urban transportation planning, trip purposes allow for the generation of different scenarios of bike flows serving as input for tactical planning. An exemplary scenario comprises hourly bike flows on a typical working day in the high season represented by 24 time-dependent origin/destination (OD) matrices.

Mathematical optimization supports decisions for a cost-efficient design of the service network. From the tactical planning perspective, SND deals with the optimal allocation of bikes to stations. The resulting target fill levels serve as direct input for operational planning of relocation tours. In addition, due to the tactical planning scope, suitable anticipation of relocation is required to avoid suboptimal decisions on fill levels. Operational planning involves computational challenging construction of relocation tours to transport bikes from full to empty stations. In contrast to constructing relocation tours, relocation is anticipated by means of a dynamic transportation model. The dynamic transportation model yields the set of relocation services required to maintain the target fill levels. Relocation services are described by the pickup and return station, time period and the number of relocated bikes.

The main contribution of this work is to apply the notion of SND from the field of freight transportation to BSS. This implies the motivation of SND, the provision of input data for optimization by means of an IM and formulation of a suitable SND optimization model anticipating relocation operations. In addition, the SND approach has to be applied and evaluated in order to show its usefulness and benefit. Consequentially, the structure of content is divided into four parts (c.f. Table 1.1). Part I outlines the problem description. First, the concept of bike sharing in the context of urban mobility is presented. Second, tactical SND as one of the logistical challenges in BSS is defined. An integrated approach of IDA and mathematical optimization for SND is pursued. Therefore, Part II presents how IDA yields insights into the mobility behavior in BSS, models trip purposes, and supports generating scenarios of bike flows by means of an IM. Optimization models and solution approaches addressing the SND are developed in Part III. Both the IM and optimization model are evaluated in a case study based on the real-world BSS Citybike Wien. Part IV draws a conclusion on SND of BSS and gives an outlook on potential future research.

Table 1.1 Structure of content

1. Introduction
Part I: Problem description
2. Bike sharing in the context of urban mobility 3. Service network design as a logistical challenge in the reliable provision of service in bike sharing systems
Part II: Intelligent data analysis
4. Determination of typical bike flows 5. Case study: Generation of typical bike flows for Citybike Wien
Part III: Optimization
6. Service network design of bike sharing systems 7. Case study: Service network design of Citybike Wien
Part IV: Conclusion
8. Conclusions and outlook
Bibliography

In particular, the individual chapters take on the following subjects:

Problem Description (Part I)
Part I motivates and defines SND of BSS. Chapter 2 summarizes mobility trends based on today's urban transportation challenges. In this context, bike sharing as a concept of shared mobility is introduced. Shared mobility, in particular bike sharing, differs from traditional modes of transportation. Bike sharing combines benefits of private and public transportation to satisfy recent trends in mobility needs of urban population. Especially the characteristics of BSS contributing to their success are outlined. Chapter 3 illustrates logistical challenges in the reliable provision of service in BSS implied by their special characteristics. Ensuring service occurs on different planning levels known from the field of freight transportation whereas this work focuses on tactical SND. Thus, the scope of SND of BSS is defined and existing literature related to the analysis and optimization of SMS is discussed. Finally, a conceptual framework is developed highlighting the integration of IDA and optimization for SND of BSS.

Intelligent Data Analysis (Part II)
Different scenarios of bike demand serve as input for SND. Scenarios refer to typical bike flows in the form of time-dependent OD matrices. The required information is derived from the aggregation of observed trips in combination with well-known urban transportation planning approaches. Chapter 4 presents an IM that abstracts from observed trip data by means of IDA. Based on cluster analysis, trip purposes are determined and represented by spatiotemporal distributions of trips. These distributions allow for the generation of different bike demand scenarios. Determining trip purposes from a vast amount of trip data is not trivial. Thus, required IDA techniques are presented. Chapter 5 puts the IM into practice for the BSS Citybike Wien. Spatial and temporal characteristics of trips are explored, trip purposes are determined, and scenarios of typical bike flows are

generated. In accordance with the findings of Citybike Wien, typical bike flows for artificial instances of BSS are generated. These flows serve as input for the case study of SND in Part III.

Optimization (Part III)

SND occurs by means of a mathematical optimization model and solution methods. Chapter 6 proposes a mixed-integer programming (MIP) formulation aiming at cost-efficient balancing of bikes to stations while ensuring a predefined service level for different scenarios of bike demand. Operational relocation decisions are anticipated by a dynamic transportation model yielding relocation services. In particular, decisions comprise time-dependent target fill levels of bikes at stations and expected relocation. Target fill levels ensure the provision of service depending on the time of the day for a given scenario. Determined relocation services yield the expected costs of relocation to maintain the target fill levels. The MIP formulation is computational challenging for real-world instances due to a large number of binary variables for relocation services. Thus, a heuristic solution method is required. Recently, hybrid metaheuristics (HM) have shown good performance to solve challenging optimization problems. This work proposes a HM based on large neighborhood search (LNS) guided by a fix-and-optimize strategy combined with exact solution methods provided by commercial solvers. In Chap. 7, computational experiments show the usefulness and benefit of SND based on Citybike Wien. In particular, target fill levels are determined according to different scenarios of bike demand. Furthermore, spatiotemporal characteristics of relocation services are provided, which can support operators of BSS in the planning and implementation of relocation services.

Conclusion (Part IV)

Chapter 8 summarizes the introduced SND approach and discusses future extensions and directions of research.

Part I
Problem Description

Chapter 2
Bike Sharing in the Context of Urban Mobility

The trend of growing interest in alternative urban transportation modes continues. Today's urban transportation infrastructure is often used to capacity and thus suffers from inefficiency. There is need for innovative and sustainable mobility to better use existing infrastructure. Moreover, new mobility concepts should satisfy the requirements of recently changing mobility needs of people while ensuring the viability of urban transportation and living. In this domain, SMS such as BSS or car sharing systems (CSS) have become more and more popular in recent years offering vehicles for collaborative use. Despite the great popularity, a common definition distinguishing shared mobility from traditional transportation services is lacking. However, understanding the characteristics of SMS and mobility behavior of users is essential in order to support the reliable provision of service. In particular, modeling mobility behavior in SMS requires a thorough understanding of mobility itself.

Consequently, bike sharing as a concept of shared mobility is presented and classified within the context of urban transportation and mobility (cf. Fig. 2.1). Therefore, basic definitions of mobility and urban transportation as well as urban transportation challenges are presented (Sect. 2.1). Current trends and drivers of new mobility concepts alleviating addressed urban transportation challenges are discussed. These drivers pave the way for new mobility concepts such as SMS, in particular, bike sharing (Sect. 2.2). Provision of service relies on the understanding of user's mobility needs. Thus, a definition of shared mobility from a user's perspective is given. Based on the definition, business models of SMS are discussed each standing out due to different characteristics. The planning, implementation, and operation of SMS requires considering the individual characteristics of these systems. The functionality of BSS is described accordingly and general guidelines on the planning, implementation, and operation of BSS are outlined.

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