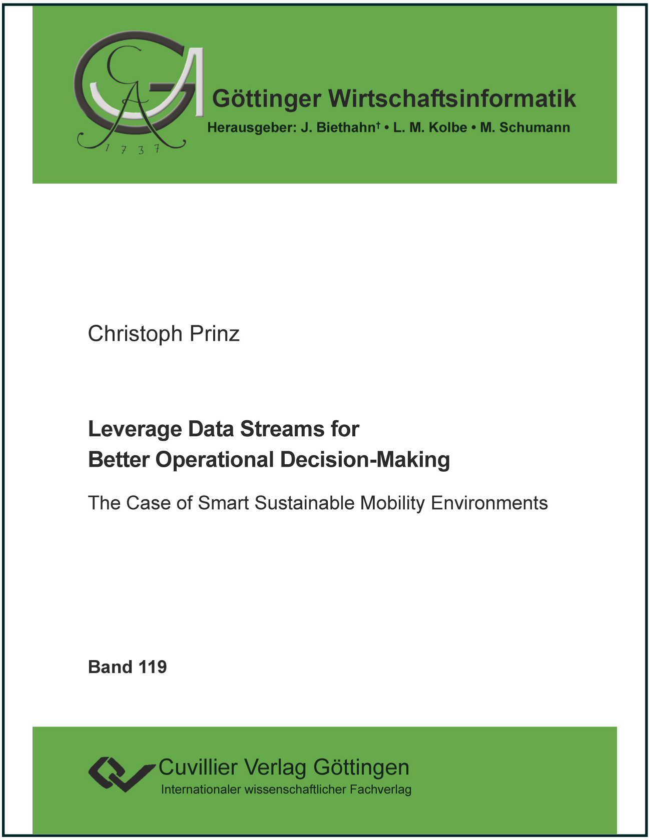
Christoph Prinz (Autor)

Leverage Data Streams for Better Operational Decision-Making

The Case of Smart Sustainable Mobility Environments



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A. Foundations

The first part of this dissertation is divided into two sections.

The following Section A.I motivates this dissertation with respect to current information systems (IS) research. Consequently, this section poses research gaps and questions and presents the structure, research positioning, and research design of this dissertation, followed by an overview of anticipated contributions.

The subsequent Section A.II provides this dissertation's research background and foundation. To this end, the importance of data-enabled IS for achieving smart sustainable mobility environments is discussed. Furthermore, an overview of related work to the topic of this dissertation is provided.

I. Introduction

This section introduces the research topic and agenda of this dissertation. The first Section A.I.1 exposes the research motivation and the relevance of the research. Next, the second Section A.I.2 highlights the derived research gaps and questions addressed in this dissertation. Subsequently, the dissertation's structure is presented (A.I.3), followed by the positioning (A.I.4) and design (A.I.5), as well as an overview of anticipated contributions (A.I.6).

I.1 Motivation

Mobility is one of the basic needs of every human being and builds an essential fundament of our globalized society. Transportation provides individuals with access to what they value and need to live their lives: work, education, vacation, leisure, meeting family and friends, and shopping (Follmer & Gruschwitz, 2019). The ability to choose from a wide range of mobility options is an achievement of technological progress and service innovation (Cledou et al., 2018). It fosters personal evolvement, a privilege to which we have become accustomed.

However, the mobility sector is held responsible for the arising problems related to the global phenomenon of climate change and urbanization (Chapman, 2007; United Nations, 2018). Most traditional transportation modes contribute to climate change, are wasteful with natural resources and space, and operate inefficiently due to a lack of coordination (Cheng et al., 2020). This inefficiency results in high societal costs caused by individual benefits of physical mobility (Bruun & Givoni, 2015). The technology stack of tomorrow's multimodal mobility system is just around the corner, enabling vehicles to be connected, autonomous, shared, and electric (Sperling, 2018). While this so-called "CASE" technology promises to tackle some of the aforementioned ubiquitous challenges, its uncoordinated implementation and global deployment can also lead to unintended consequences, such as increased demand for road-based transport due to improved cost competitiveness of shared vehicles, the rise of empty rides of autonomous vehicles, or the waste of clean energy in electric vehicles (Ketter et al., 2022). To counteract such unintended consequences, the socio-technical lens of IS research provides us with a platform to steer progress in technology and information technology (IT) in a direction that positively impacts individuals, businesses, and society (Sarker et al., 2019).

The Green IS research community has taken the responsibility to make a significant contribution in reducing emissions and mitigating the effects of global climate change and other environmental problems (Elliot, 2011; vom Brocke, Loos, et al., 2013). One strength of IS research is to observe, describe, and predict problems and behaviors using frameworks and theories (Banker & Kauffman, 2004; Gregor, 2006). However, the urgency to tackle global climate change also requires contributions in the form of design knowledge and utilitarian artifacts (vom Brocke, Watson, et al., 2013; vom Brocke & Seidel, 2012). Green IS research has generated such contributions with a special focus on organizational practices, hardware, behavioral nudging, smart devices, education, technology adoption, and mobility and sharing economy (Harnischmacher et al., 2020). Hence, pervasive sustainability effects are generated with sustainable hardware (first order), with artifacts directly influencing the sustainability of processes (second order), and with theories nudging behavioral change regarding sustainability (third order) (Köhler & Erdmann, 2004). A recent analysis highlights that the utility of such designs can be maxed by focusing on achieving measurable impact, extending the problem space beyond business processes and organizational contexts, establishing research in real-world scenarios, and investments in environmental education (Brendel, Chasin, et al., 2022).

The sharing economy made us rethink personal ownership's role and shape the next stage in the evolution of economies (Botsman & Rogers, 2011; Frey et al., 2019). Together with the technical achievement of CASE vehicles, the concept of shared ownership and consumption already positively impacts delivering a more sustainable mobility ecosystem (Ketter et al., 2022). This especially includes deployed service innovations of on-demand mobility like ride-sharing and hailing, and bike and scooter-sharing, which complement the current public transportation infrastructure (Shaheen et al., 2020). Nevertheless, the satisfaction of mobility requirements like family trips, the transport of bulky items, or trips to destinations with low population density often requires car-based journeys (Becker et al., 2017). Thus, carsharing services (CS) that provide individuals with short-term, self-service, and spontaneous access to a heterogenous fleet of electric cars are a cornerstone of a smart and sustainable mobility ecosystem (de Luca & Di Pace, 2015; Shaheen & Cohen, 2013).

Whenever individuals can rely on such an ecosystem, they are more willing to give up personal car ownership (Jochem et al., 2020; Martin & Shaheen, 2011a). The subsequent replacement of multiple privately owned cars by a few shared cars contributes fourfold to the fight against problems caused by urbanization and climate change. First, fewer parking spaces are required which means that these spots can be transformed into life-worthy areas enhancing communal coexistence (Tchervenkov et al., 2018). Second, rare resources are spared because fewer cars need to be produced. Third, deploying fleets powered by electric vehicles instead of fossil-fuel-powered private cars also reduces the emission of greenhouse gases (Liao & Correia, 2022). Fourth, the mode shifts from cars to alternatives like walking, biking, and public transport are accelerated, reducing the overall demand for car-based mobility. The reason for that is that individuals assess whether a car is required to fulfill a mobility task or more carefully when they do not have access to a privately owned car (Amatuni et al., 2020).

To foster this shift, researchers and practitioners developed business models for innovative vehicle-sharing service ideas (Remane et al., 2016). However, the basic requirement of vehicle availability significantly impacts the long-term success and establishment of those services as part of the mobility ecosystem (Nansubuga & Kowalkowski, 2021). From an operational perspective, this translates into the need to coordinate fleets in real-time tailored to short-term user demands (Ketter et al., 2022). Early generation shared vehicle systems offered access to vehicles on designated stations, where users had to make a reservation, including details like the pick-up and drop-off time and station (Cepolina et al., 2014). Based on this information and historical observations, the number of cars required to satisfy all requests could be determined straight-forward. However, customers have become more discerning, expecting access to heterogeneous fleets without needing a reservation, being dependent on stations, or underlaying the policy to drop off a vehicle at exactly the position where it was picked up (Golalikhani et al., 2021). Such requirements can be satisfied by introducing one-way free-floating shared vehicle systems. Due to the asynchronous character of demand and supply, operators must rebalance vehicles inside their systems to maintain vehicle availability tailored to spatiotemporal customer demand (Jorge & Correia, 2013; Wagner et al., 2014).

Research developed frameworks, algorithms, and decision support systems (DSS) to solve strategic, tactical, and operational decision problems associated with vehicle relocations in CS (Illgen & Höck, 2019) and micromobility sharing based on scooters and e-bikes (Boufidis et al., 2020; Caggiani et al., 2018; Nath & Rambha, 2019; Si et al., 2019). The overarching determinant for operational efficiency and effectiveness is the precision of the underlying demand forecasts (Wu & Xu, 2022). Especially the rising availability of data streams from vehicles and users provides an abundance of information to be leveraged to tackle operational challenges in the context of a smart sustainable mobility system (Ketter et al., 2022).

Leveraging those data streams further to enhance the service quality of shared vehicle offerings constitutes a challenge that shares characteristics with what Hevner et al. (2004) call a “wicked problem”. For example, the requirements for service operation can be seen as unstable since they are highly dependent on the environment (e.g., regulations, competition, overall mobility service quality, demand uncertainty) and may change over time. Furthermore, there are complex interactions between the problem of increasing vehicle availability and its solution, especially since subcomponents often influence or constraint each other. For example, vehicles that are currently relocated are not available for rental and thus reduce availability for a short time. Also, the significant influence of operational constraints like the nature of catchment areas, available staff, and available parking spots must be considered.

This dissertation takes a problem-oriented perspective on the phenomenon of smart sustainable mobility environments by designing data-driven decision support to tackle the operational challenges of shared fleet providers. To this end, this dissertation aims to address unresolved problems with utilitarian design, solution-oriented process guidance, and applicable phenomena knowledge. It presents new insights on demand-supply management in the sharing economy, allowing research to theorize and providing practice with ready-to-implement artifacts in form of frameworks, algorithms, and DSS.

I.2 Research Gap and Research Questions

This dissertation aims to contribute to a smart sustainability mobility ecosystem by exploring potentials for increasing the availability of shared vehicle fleets. This is achieved by generating design knowledge on the IS-enabled development process of vehicle operation modes and a spatiotemporal customer demand model.

The first step of this research endeavor is to understand the problem context and to evaluate whether existing solutions are suitable to address all aspects of the problem. Researchers developed frameworks, algorithms, and DSS to solve strategic, tactical, and operational decision problems associated with providing shared vehicle fleets (Illgen & Höck, 2019). Existing literature reviews such as those from Brendel & Kolbe (2022), Ferrero et al. (2017), Golalikhani et al. (2021), Illgen & Höck (2019), Jorge & Correia (2013), and Wu & Xu (2022) structure such research and synthesize findings on a general and universal level. Since this dissertation aims to tackle the operational challenge of vehicle relocations to improve vehicle availability, a knowledge base that provides a holistic view of vehicle relocation algorithms is required. Consequently, this dissertation answers the following research question (RQ) to investigate available design knowledge on vehicle relocation algorithms:

RQ1: What is the status quo of vehicle relocation algorithm research?

Simulations provide a cost-efficient solution to represent operational services comprehensively and to track the impact that systemic factors and business constraints have on system behavior when such factors and constraints change (Alfian et al., 2017). Consequently, they are applied to advance further design knowledge on system operation modes, including vehicle relocation algorithms. Researchers typically develop such simulations from scratch and adapted them to specific research contexts and showcases. Hence, no standardized and IS-supported method enabling a utility-driven design process based on simulations exists. This dissertation answers the following RQ to address the subsequent risk of researchers spending resources on developing disposable software instead of making research contributions:

RQ2: How can information systems enable the development and evaluation of operation modes?

Customers expect that shared vehicles are available for short-term usage, self-service, and spontaneous occupation and drop-off (de Luca & Di Pace, 2015). Operators of fleets where vehicles are freely distributed over a service area have no definite information on when and where a customer demands a vehicle and when and where a rented vehicle will be available again. Since most of the research considers such information as given (Brendel & Kolbe, 2022), available design knowledge is not feasible to solve the problem of vehicle availability. The remaining core challenge is to understand and model customer demand predictors that can be utilized as input for vehicle relocation decision support. Hence, this dissertation is guided by the following question, to seamlessly provide vehicle supply for spatiotemporal demand in free-floating fleets:

RQ3: How can spatiotemporal demand be modeled to enhance operational decision-making?

Three sub-RQ are motivated and derived to specify this overarching RQ further.

With the emergence of CASE vehicles, ubiquitous spatiotemporal data streams from vehicle fleets have become available (Ketter et al., 2022). Merging them with empirically analyzed determinants for users' preferences to use a concrete mobility option provides an abundance of information to be leveraged to develop accurate demand forecasts (de Luca & Di Pace, 2015). Although finding hyperparameters for feasible machine learning (ML) algorithms has been part of some initial investigations (e.g., Cagliero et al., 2019; Cocca et al., 2020; Li et al., 2021), such baseline models have not been integrated into purposeful IT artifacts concerned with solving the prevailing business problem of vehicle relocations. To this end, this dissertation answers the first sub-RQ of RQ3, to demonstrate economic value and derive managerial implications of a subsequent data-driven vehicle relocation algorithm:

RQ3.1: How should data-driven vehicle relocations be designed to increase the business value of shared vehicle fleets?

Whenever research integrated demand models in vehicle relocation strategies (e.g., Cagliero et al., 2019; Cocca et al., 2020; Herrmann et al., 2014; Nair & Miller-Hooks, 2011; Repoux et al., 2015; Schulte & Voß, 2015a; Weikl & Bogenberger, 2015; Yu et al., 2020), such models were trained against historical demand data. However, historical booking data represent a biased and skewed version of the true demand distribution since censoring issues occur when demand surpasses available vehicle supply (Gammelli, Rodrigues, et al., 2020). Hardt & Bogenberger (2020) are the first to propose an unconstraining routine for demand patterns by assuming that demand follows an empirical distribution function, which must be known in advance. However, knowing the distribution function in advance is not feasible in practice. Hence, this dissertation answers the second sub-RQ of RQ3, aiming to develop a data-driven, nonparametric, and practical approach for the modeling of training data:

RQ3.2: How can censored demand data be unconstrained in the context of shared vehicle fleets?

The catchment area of vehicles inside the fleet must be understood, to assess whether the current system supply can satisfy an individual's trip demand. By far, most studies implicitly or explicitly assume that shared vehicles have circular catchment areas, i.e., they are perfectly accessible and equally attractive to all starting points within a fixed radius (e.g., Banerjee et al., 2020; Cao et al., 2019; Çelebi et al., 2018; Nikiforiadis et al., 2021). The evaluation of whether a vehicle relocation is effective depends on the assumed vehicle catchment area. This dissertation answers the third sub-RQ of RQ3, to enable such understanding of real-world customer choice behavior:

RQ3.3: What is the situational size, shape, and nature of pedestrian catchment areas of shared vehicles?

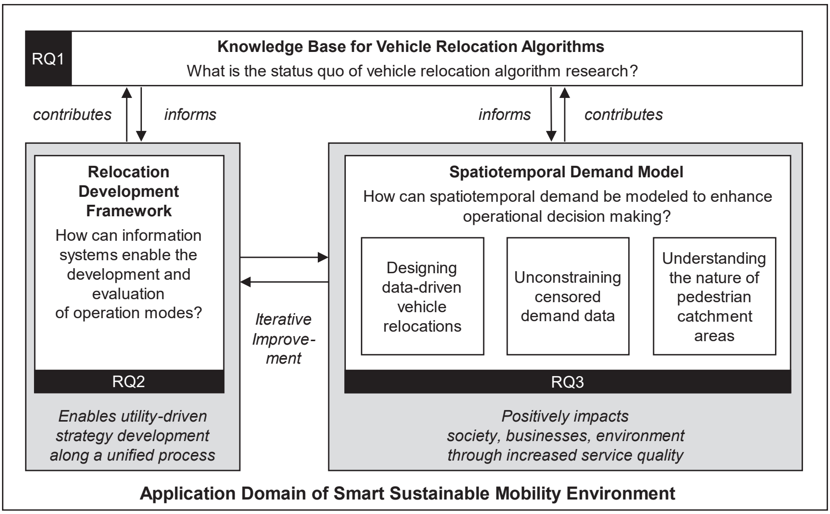

Figure 1: Research Overview

Figure 1 illustrates the RQ and their interdependencies. Answering RQ1 ensures that answering RQ2 and RQ3 is rigorously embedded into the existing knowledge base. The subsequent design of the relocation development framework (RQ2) is utilized to develop and evaluate the spatiotemporal demand model (RQ3). Within the design cycles associated with RQ3, the initial artifact design is iteratively improved. The utility of all designs addressed in RQ2, RQ3, and sub-questions contribute to the overall knowledge base on vehicle relocation algorithms.

I.3 Structure of the Dissertation

This cumulative dissertation comprises three parts: Part A provides the groundwork, Part B addresses the subsequent RQ, and Part C concludes and generalizes the resulting findings. An overview of the according structure is presented in Figure 2 and will be described as follows.

Part A provides the motivation and foundations of this dissertation by providing a frame with an introduction (A.I) and research background (A.II). The introduction first motivates the research endeavor (A.I.1) and derives guiding RQ to close identified research gaps (A.I.2). The structure of this dissertation is presented (A.I.3) before the subsequent research position (A.I.4), research design (A.I.5) and the anticipated contributions (A.I.6) are delineated. To complete the introduction, the research background is introduced (A.II.1, A.II.2, A.II.3), followed by an analysis of related work (A.III).

Part B represents the core of this cumulative dissertation by presenting five separate studies performed to answer the motivated RQ. An overview of how the studies contribute to the RQ and where they have been published is provided in Table 1.

Part C highlights the contributions of this dissertation and discusses results and generalization potential. First, it provides an overview of the findings of the performed studies (C.I) and their synthesis and generalization in form of a design theory (C.II). Building on this, implications for research, practice and society are discussed (C.III). Final remarks on limitations and opportunities for future research are made followed by a summary of the research project as whole (C.IV). This dissertation is closed with an overview of the author’s individual study contributions, further published studies, and the author’s CV (Appendix).

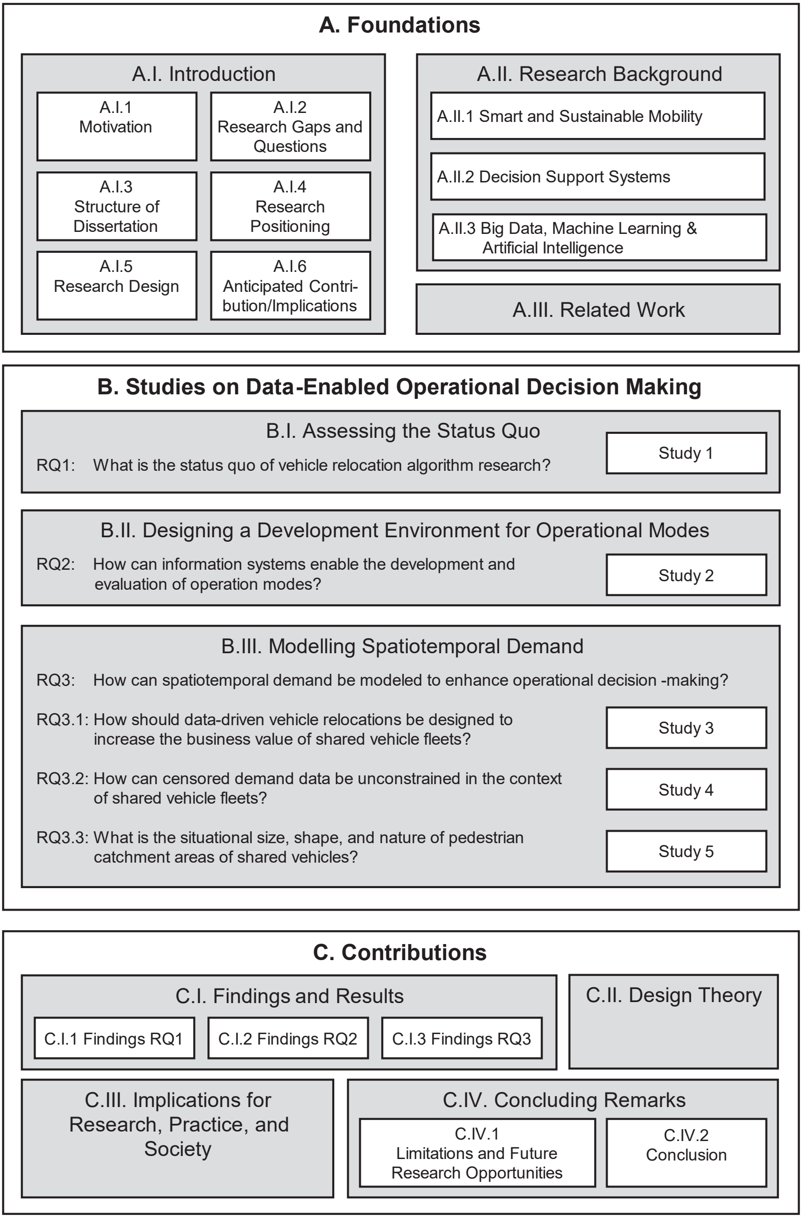

Figure 2: Structure of this Dissertation

Table 1: Overview of Studies Included in this Dissertation

Study	RQ	Section	Title	Outlet	Ranking	Status	Main Contribution
#1	1	B.I.	Archetypes of Carsharing Relocation Algorithms: A Perspective on Problem Space, Solution Space, and Evaluation	Journal: Journal of Decision Systems	B	Submitted	• Holistic overview of the current knowledge base of carsharing relocation algorithms • Derivation of prevailing research gaps
#2	2	B.II.	CASSI: Designing a Simulation Environment for Vehicle Relocation in Carsharing	Journal: AIS Transactions on Human-Computer Interaction	-	Published[1]	• Proposition of a unified research process to design vehicle operation modes • Provision of IS support for this process
#3	3.1	B.III.	Increasing the Business Value of Free-Floating Carsharing Fleets By Applying Machine Learning-based Relocations	Conference: ECIS 2020	B	Published	• Design of a data-driven relocation strategy for free-floating systems • Increased vehicle acceptance and decreased relocation efforts
#4	3.2	B.III.	"Now You Can See Me!" – Unconstraining Demand for Effective Service Operation: The Case of Vehicle Relocation in Free-Floating Carsharing	Journal: IEEE Transaction on Engineering Management	B	Submitted	• Design of a demand-unconstraining method of carsharing demand • Provision of a strategy to generate valid training data
#5	3.3	B.III.	How Far are You Gonna Go? Understanding Pedestrian Catchment Areas in Shared Mobility Systems	Conference: ICIS 2021	A	Published	• Investigation of shape and nature of shared vehicle catchment areas

I.4 Research Positioning

In general, research can be defined as an activity to gain an understanding of a phenomenon, whereas a phenomenon is typically a set of behaviors of some entities (Vaishnavi & Kuechler, 2004). The community of IS researchers thereby focuses on "electronic computation, the storage, manipulation and transmission of digital data, the specification of computer-based algorithms to support decision making, and the creation of systems that link people, business processes, firms, industries, and markets" (Banker & Kauffman, 2004, p. 281). Due to the prevailing emphasis on the socio-technical aspects

[1] Previous version published at ECIS 2020 (VHB B)