Operations Management in the Sharing Economy: Essays on the Integrated Perspective of Item-sharing and Crowdshipping

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Chapter One

SYNOPSIS

1.1 Opportunities and challenges in the sharing economy

The sharing economy subsumes business models that provide services to a community as a whole rather than to an individual (Botsman and Rogers, 2011). These services can differ substantially in the needs they serve and their approach to do this, but it all comes down to the coordination of resources. For example, if there are two members of a sharing community who are of mutual benefit because one member provides the goods or services that are requested by another, finding and matching them renders a service. Another example for a service is to schedule consumers' requests to exclusively access common resources for a definite time span. Businesses that provide such services can gather substantial momentum from network effects as large sharing communities allow for plenty of opportunities to match supplies with requests and to offer a more diverse portfolio of goods for a common use. Estimated revenues for the sharing economy are already in the billions of dollars and they are expected to rise further (PricewaterhouseCoopers LLP, 2017; World Economic Forum, 2019a). The business models are classified into sharing concepts, based on what kind of resources are shared. While some concepts such as shared spaces (e.g. Airbnb, 2020) and shared mobility (e.g. Uber, 2020; Share Now, 2020) are very successful and/or popular already nowadays, others are developing rather slowly. This work aims to push and exploit the potential of such a concept, the so-called *item-sharing*. It is also analyzed in this context to what extent an integration with another concept, the so-called *crowdshipping*, can help item-sharing to attract and maintain an active consumer base that would allow to scale up operations.

Item-sharing offers consumers an on-demand access to items such as equipment for leisure activities, tools, or apparel (c.f. 'access-based consumption' in Bardhi and Eckhardt, 2012). These items are privately owned and they can be temporarily exchanged between members of a sharing community to serve other members' needs for them. Renting items may be more attractive than their purchase if consumers are only charged for the time the item is needed. This lowers the financial risk of item usage because the costs for an item's acquisition, maintenance, storage, and disposal become irrelevant. A typical example for a shared item is a drill. Given that a user rarely needs a drill and that he/she is interested in the result of using a drill and not in owning the drill itself, a purchase is hardly justified and a temporary access to a drill may be preferable. Moreover, a shared use of such rarely used tools allows for a better utilization of resources that leads to a more sustainable way of consumption. The sharing economy successfully promotes advantages like these and, by that, has initiated a fundamental shift in consumption behavior in which access is preferable to ownership (Rifkin, 2000; Böcker and Meelen, 2017).

Item-sharing is often understood as a peer-to-peer service, with an online platform as market place (Belk, 2014; Einav et al., 2015). The platform enables transactions between community members by establishing trust, providing a means of communication, and coordinating the information flow of supplies, requests, and payments. Its assets are the involved consumer base and the items being shared, and it generates profits by collecting transaction fees, see Erento (2020) or Zilok (2020) for examples. Despite being very scalable, a common problem of peer-to-peer item-sharing platforms is the asymmetry of supplies and requests, with people being reluctant to offer their expensive property to strangers (Barnes and Mattsson, 2016). Instead, they share rather common, affordable items for which the financial benefit of sharing over buying may be too low to consider an on-demand access advantageous. This is even more so if the costs and/or inconvenience that are associated with the reoccurring physical exchange of items are taken into account. The operations of such item exchanges are not at all managed by existing peer-to-peer item-sharing platforms so that potential consumers may be discouraged by the need to organize the transport themselves. Another interpretation of item-sharing is when traditional sales-based businesses also offer rental services to meet the changed consumption behavior of their customers (c.f. 'rental economy' in U.S. Chamber of Commerce, 2019; World Economic Forum, 2019b). These services blur the boundaries between sharing and renting but they enrich the supply of on-demand access offers in quality, variety, and availability of items from a consumer's perspective. However, they are designed as isolated applications to serve a niche market and they are usually not intended to increase in size to avoid a cannibalization of possibly more profitable sales-based businesses (Benjaafar and Hu, 2020). Thus, platform-based peer-to-peer item-sharing is only slowly increasing in popularity as it currently struggles with the capabilities to provide a reliable and convenient on-demand access to items on a large scale (Chasin et al., 2018; Taeuscher and Kietzmann, 2017).

The contribution of this work is to provide managerial insights into the potential of an upscaled peer-to-peer item-sharing. This may, for example, become relevant if peer-to-peer sharing networks and rental services by companies are united on a same platform, or if the public interest in item-sharing rises so that authorities and/or investors get involved (Agyeman et al., 2013; Choi and He, 2019). The following questions are therefore addressed by this thesis:

- How can optimization approaches support operational decisions of sharing platforms to improve overall performance?
- How does the availability of shared items affect the profitability and the degree of request fulfillment of a platform?
- Are there more service-oriented ways of exchanging items among consumers, either due to economies of density or through the integration with other concepts?
- Does sharing actually allow to mitigate the environmental impact of consumption?

These questions are addressed from an operations management perspective. The approach is to provide a decision support for the operational planning of platform operators so that consumers can be offered a more attractive item-sharing experience. To this end, the planning tries to effectively utilize all resources that are available in a sharing network, including the willingness of members to provide services for themselves and others (c.f. 'consumer involvement' Bardhi and Eckhardt, 2012). An example for such services is to transport items from their current locations to the locations where they are needed. This practice is referred to as *crowdshipping* and it is particularly efficient if the transports are conducted by members on trips they intend to take anyway (Barr and Wohl, 2013; DHL Trend Research, 2018). The research in this thesis analyzes to what extent crowdshipping may serve as a logistics concept for item-sharing so that also price-sensitive consumers can get their requested items delivered to their homes. As a platform increases in size, it becomes more complex to orchestrate the serving of requests with shared resources and the coordination of item exchanges between consumers. This planning challenge asks for new solution approaches and is addressed here with Operations Research techniques. The results of this work show that the logistics management of item-sharing networks constitutes an own research stream in the sharing economy literature with interesting insights for researchers and practitioners.

The remainder of this chapter is as follows. Section 1.2 provides an overview of related literature and points out the research gap this thesis aims to fill. The overall structure of the research that is conducted in the following chapters is outlined in Section 1.3. There, it is described that each chapter is a self-contained essay and it is explained how the research in these essays is related. Section 1.4 provides extended abstracts of the essays and Section 1.5 concludes this chapter with implications and possible directions for future research.

1.2 State of literature and research gap

The term 'sharing economy' is often exploited for marketing purposes in different contexts to benefit from its positive connotation of resource efficiency, sustainable consumption, and a sense of togetherness (c.f. 'sharewashing' in Hawlitschek et al., 2018). Therefore, a large body of literature on the sharing economy deals with proper definitions (Belk, 2014, 2010; Richardson, 2015), frameworks to capture the diversity of concepts (Lamberton and Rose, 2012; Cohen and Muñoz, 2016), and various analyses of factors that foster or inhibit growth of such businesses (Barnes and Mattsson, 2016; Botsman and Rogers, 2011). Further research on the sharing economy deals with designing access-based business models and analyzing implications of an intensive sharing (e.g. Hossain, 2020; Laukkanen and Tura, 2020; Benjaafar et al., 2019). This work is embedded in business research and it analyzes the potential of peer-to-peer item-sharing platforms to serve consumers' needs for items in a profitable, consumer-oriented, and sustainable way. The analyses are irrespective of who owns the shared items so that the results are also applicable to business-to-customer rental services.

Business research on the sharing economy concentrates on estimating, developing, and exploiting the market potential of access-based offers. To this end, marketing research investigates people's motivation for preferring access to ownership (Akbar and Hoffmann, 2018; Hamari et al., 2015; Böcker and Meelen, 2017) and develops unique selling propositions based on these findings (Baumeister et al., 2015; Schaefers et al., 2015; Kathan et al., 2016). The design of access-based offers and guidance on how to implement them can be derived from research on the business paradigms 'product-service systems' and 'servicization' (Tukker, 2015; Boehm and Thomas, 2013; Reim et al., 2015; Benjaafar and Hu, 2020). Their underlying idea is to focus more strongly on consumers' needs by selling the functionality of a product rather than selling the product itself. This essentially results in rental services that are very similar to the shared use of resources in item-sharing (c.f. 'use-oriented product-service systems'). Related literature addresses the benefit of a possibly higher market absorption potential through price differentiation, the threat of cannibalizing existing sales-based businesses, and environmental implications of a temporary provision of goods (Agrawal and Bellos, 2017; Örsdemir et al., 2019; Jiang and Tian, 2018). However, the results give only insights into the strategic positioning of item-sharing services but they do not address the operations management of serving requests with shared items. This thesis aims to fill this gap by developing concepts and decision support models for a better user experience with item-sharing.

Prominent examples for research on the operations management of businesses in the sharing economy are car sharing and bike sharing. An overview of relevant planning problems in these applications is provided by Ferrero et al. (2018) for car sharing and by Neumann Saavedra (2018) for bike sharing. In both cases, the shared resources are means of transport that immediately provide a service to those who access them. The problem in this context is that similarities in users' travel behavior leads to an imbalance in the spatial distribution of cars or bikes over time. Operations management research in these fields therefore focuses on improving the efficiency of costly relocation operations that are required to alleviate these imbalances. In contrast, the more general understanding of items in this thesis refers to items of very different types. Many of those first need to be transported to the location where they are requested to serve consumers' needs. Against this background, it is crucial to the acceptance of access-based offers that the exchange of shared items among consumers is efficient, particularly if items are requested multiple times. However, the physical exchange of single items between consumer locations necessitates last-mile transports that are known to be costly (Cleophas et al., 2019; Savelsbergh and Van Woensel, 2016). This asks for a completely new logistics concept for item-sharing, which is addressed in this thesis but not in the car- and bike-sharing literature. Moreover, the question whether to buy or rent items heavily depends on their price, usage frequency, and durability, among others.

The diversity of items in item-sharing provide a much broader spectrum with regard to these dimensions. This thesis is therefore the first to investigate the extent to which item-sharing is capable of a best possible serving of large-scale demands for items with a limited amount of items that are provided by the members of a sharing community.

The physical exchange of items in item-sharing is conducted by the consumers themselves or by other members of the sharing community. The latter idea, i.e. to have private drivers deliver packages instead of professional carriers, receives a lot of attention in the literature as the concept 'crowdshipping' (Archetti et al., 2016). This concept arouses the interest of researchers and practitioners because it allows for very efficient transportation if deliveries can be conducted along the trips the so-called crowdshippers intend to take anyway. The alternative interpretation according to which a company can flexibly draw on a fleet of self-employed drivers is neglected here (e.g. Amazon Flex, 2020). Research in the field of trip-dependent crowdshipping focuses on various aspects such as investigating crowdshippers' willingness to get involved in transportation services, integrating this willingness in existing operations, and increasing the acceptance of transportation services by non-professionals (Punel and Stathopoulos, 2017; Ta et al., 2018; Arslan et al., 2019; Devari et al., 2017; Le et al., 2019; Qi et al., 2018). Further insights into crowdshipping can be derived from research on the closely-related ride-sharing, in which people instead of packages are transported on existing trips (Agatz et al., 2011; Furuhata et al., 2013; Štiglic et al., 2016). Contrasting previous research, the pickup and drop-off locations of deliveries are not fixed if crowdshipping is embedded in an item-sharing context where the allocation of resources is subject to a platform's operations management. A setting like this opens up the opportunity to align delivery jobs with crowdshipping trips such that the execution of these jobs requires only minor additional effort by crowdshippers. This makes it more likely that transportation jobs are accepted by crowdshippers and that item exchanges in item-sharing can be facilitated through crowdshipping more often. To the best of the author's knowledge, the application of crowdshipping to support exchanges of items in item-sharing has not been investigated in the literature so far, despite being a promising approach to increase the potential of both concepts.

An often encountered methodological approach in sharing economy research is to provide empirical evidence of its relevance and its acceptance. This is done by asking consumers and crowdshippers regarding their attitude towards sharing activities, analyzing operations of existing item-sharing platforms, and conducting field tests to gain experience with crowdshipping (Punel et al., 2018; Paloheimo et al., 2015; Barr and Wohl, 2013). In contrast, theoretical research mainly deals with analytical studies. For example, equilibrium models are used to investigate interacting effects of sharing markets (e.g. Einav et al., 2015; Agrawal and Bellos, 2017; Örsdemir et al., 2019). The methodology used in this work is to apply Operations Research methods to provide decision support for the optimization problems faced by combined item-sharing and crowdshipping platforms. To this end, a mathematical program is formulated that describes the integrated problem of matching supplies and demands of items together with coordinating their transportation through crowdshipping. Such mathematical programs are then solved using standard solvers, customized solution algorithms, or heuristics. Eventually, these methods are evaluated in extensive computational experiments to analyze the resulting potentials of the investigated sharing concepts and to generate managerial insights.

1.3 Overview of contributions

This dissertation is a cumulative thesis where each of the following chapters is a self-contained manuscript. Figure 1.1 shows the structure of this work and how the involved manuscripts are interrelated. The common scope throughout this work is to analyze the integration of item-sharing and crowdshipping on a single platform. Integrated platforms like these do not exist in practice nowadays but they could be implemented at a rather low effort. This research therefore contributes to identifying the potential of such an integration for future reference. The approach is to develop decision support models for a platform's operations management and to derive managerial insights through what-if scenarios in simulated environments. Gains in profit and the improvement in consumer service are assessed quantitatively to provide practitioners with some guidance on crucial design elements of such integrated platforms.

More precisely, the potential of item-sharing and the idea of a concept integration with crowdshipping are formally analyzed for a first time in Chapter 2. Chapter 3 addresses the planning of operations for scenarios in which crowdshippers offer to conduct multiple deliveries on their trips. Chapter 4 proposes and investigates the idea of transferring shared

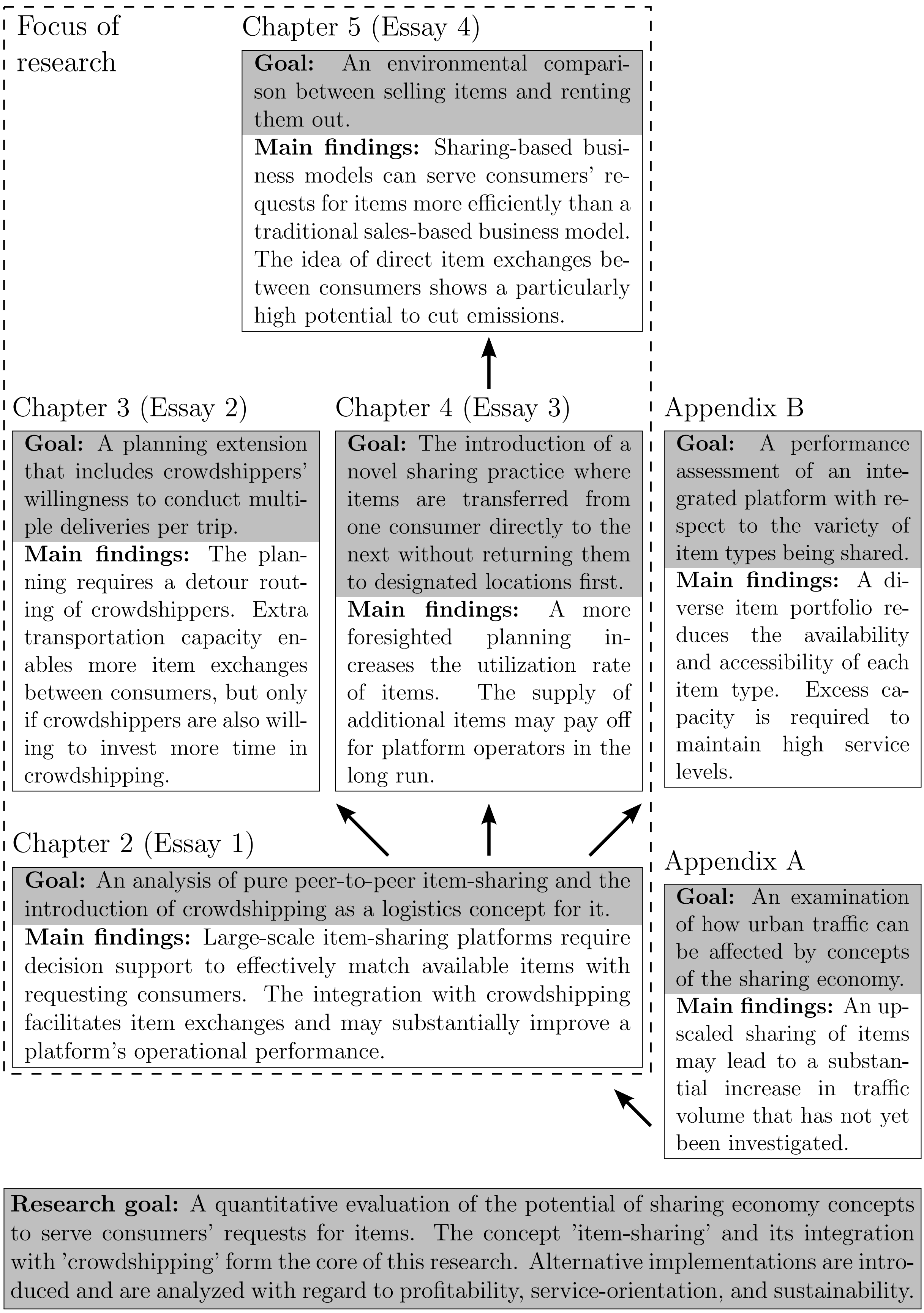

Figure 1.1: Goal and approach of this work.

items directly from one consumer to another without returning them to temporary storage locations in-between requests (so-called 'request chaining'). Chapter 5 concludes this work with an environmental comparison between alternative approaches of serving consumers' requests for items. We compare the selling of items with the traditional sharing of items via designated storage locations and the new item-sharing approach developed in Chapter 4. Additional minor studies on the sharing economy are outsourced to the appendix. Appendix A identifies research gaps at the interface between sharing economy, particularly item-sharing, and urban mobility. In Appendix B, the performance of a sharing platform is investigated for the case in which items of different types are shared.

The conceptual contribution of the essay in Chapter 2 is to investigate the extent to which crowdshipping can serve as a logistics concept for item-sharing. To this end, we integrate the operational planning of the two concepts. The research in Chapter 3 identifies circumstances in which the consideration of capacitated crowdshipping improves the operational performance of an integrated platform. The scope for incentivizing crowdshippers to accept the extra effort of conducting multiple deliveries is analyzed, too. Chapter 4 introduces an alternative interpretation of item-sharing. The main motivation for this sharing practice is to cut the transportation effort of exchanging items, but it also includes further advantages for platform operators and consumers. This research also analyzes how a platform's service can be improved by supplying additional items. The research in Chapter 5 challenges the public perception that a shared use of items is by default more environmentally friendly than a purchase. We determine types of items and sharing practices for which this is the case, based on emissions that are released during the production and transport of items. The sharing practice 'request chaining' effectively reduces consumption-based emissions since only a few items are required to achieve high service levels and the effort to exchange items is low.

The methodological contribution of the essay in Chapter 2 is to formulate the operational planning of an integrated platform as assignment problems. We also provide two heuristic solution approaches, one of which provides a very good compromise between computation time and solution quality. It is shown in Chapter 3 that the allocation of items and the coordination of transports increase in complexity as crowdshippers are more flexible and agree to conduct multiple deliveries per trip. We have developed an exact solution approach for this planning problem, which can also be turned into a heuristic. Also, this method proves to be considerably faster than previous assignment problem formulations for the case with single-capacitated crowdshipping. The concept 'request chaining' in Chapter 4 leads to interdependencies between assignment decisions in subsequent periods. A multi-period planning formulation is proposed that allows to substantially improve operational performance in comparison to a period-to-period planning with previous solution approaches. The mathematical program is also embedded in a rolling horizon framework to address dynamics regarding the appearance of members' announcements. The environmental comparison of alternative request-serving approaches in Chapter 5 is based on a framework that integrates analytical computations and case analyses. Altogether the contributions of this thesis provide models and methods for the operations management of integrated item-sharing and crowdshipping. These support platforms in various ways, e.g. by figuring out the required amounts of supplied items, the coordination and appropriate compensation of crowdshippers, the maximization of fulfilled demand, or the environmental analysis of their operations.

Table 1.1 provides an overview of the contributions. The list of authors for each contribution indicates that the research was conducted in collaboration with other researchers, particularly with my supervisor professor Frank Meisel. The professors Kjetil Fagerholt and Henrik Andersson from the Norwegian University of Science and Technology in Trondheim, Norway, joined for Essays 2 and 3. In general, I am the leading author in all four essays as I substantially contributed to all aspects of every essay. This includes but is not limited to laying out the research concepts, formulating and modeling the problems, implementing methods, conducting experiments, and writing the essays. Frank Meisel contributed to many of the above aspects in the essays he co-authored and, therefore, is always listed as second author. Kjetil Fagerholt and Henrik Andersson were mainly involved on a conceptual level by shaping the research focus and proofreading. Kjetil Fagerholt additionally provided methodological input for the design of solution methods. A breakdown of each author's individual contributions to an essay is provided in the authors' declaration at the end of the thesis. Table 1.1 also provides the publication status of each contribution and a quality assessment of the publishing journals. The essays in Chapters 2, 3, and 5 as well as the conference proceedings

Table 1.1: Overview of manuscripts in this thesis.

Chapter	Title	Authors	Publication status	JOURQUAL 3
2	The integration of item-sharing and crowdshipping: Can collaborative consumption be pushed by delivering through the crowd?	Behrend, M. and Meisel, F.	☑ *Transportation Research Part B: Methodological* 111 (2018), 227–243. DOI: https://doi.org/10.1016/j.trb.2018.02.017.	B
3	An exact solution method for the capacitated item-sharing and crowdshipping problem	Behrend, M., Meisel, F., Fagerholt, K., and Andersson, H.	☑ *European Journal of Operational Research* 279 (2019), 589–604. DOI: https://doi.org/10.1016/j.ejor.2019.05.026.	A
4	A multi-period analysis of the integrated item-sharing and crowdshipping problem	Behrend, M., Meisel, F., Fagerholt, K., and Andersson, H.	☐ Submitted to *European Journal of Operational Research.* In revision after a first round of reviewing.	A
5	Buying versus renting: On the environmental friendliness of item-sharing	Behrend, M.	☑ *Transportation Research Part D: Transport and Environment* 87 (2020), 102407. DOI: https://doi.org/10.1016/j.trd.2020.102407.	B
A	Sharing Economy im Kontext urbaner Mobilität	Behrend, M. und Meisel, F.	☑ *Innovative Produkte und Dienstleistungen in der Mobilität*, 2017, Springer Gabler, Wiesbaden, S. 335–346. DOI: https://doi.org/10.1007/978-3-658-18613-5_21.	
B	Heterogeneity of items in an integrated item-sharing and crowdshipping setting	Behrend, M. and Meisel, F.	☑ *Operations Research Proceedings 2018*, 2019, Springer International Publishing, pp. 269–275. DOI: https://doi.org/10.1007/978-3-030-18500-8_34.	D

in the Appendices A and B are published. Essay 3 has not yet been accepted but is currently revised after a first round of reviewing. The journal ranking JOURQUAL3 is provided by the German business research community (Verband der Hochschullehrer für Betriebswirtschaft e.V., 2015). It is based upon the judgement of its members and classifies journals as a leading scientific journal (A), an important and notable scientific journal (B), a renowned scientific journal (C), or as a scientific journal (D). There are no known conflicts of interest associated with these publications and there has been no significant financial support for this work that could have influenced its outcome. Also, none of this work is part of another dissertation.

1.4 Extended abstracts

1.4.1 Essay 1

The integration of item-sharing and crowdshipping: Can collaborative consumption be pushed by delivering through the crowd?

Moritz Behrend and Frank Meisel

Research objective: The need-based access to items in item-sharing necessitates frequent transports of small shipments between requesting consumers. Since there is currently no cost-efficient logistics concept available for such deliveries, consumers usually source the requested items themselves. Crowdshipping is a concept that allows for potentially efficient transports of small shipments as private people conduct deliveries on trips they would make anyway. The goal of this research is to analyze how crowdshipping can facilitate item exchanges in item-sharing if the two concepts are integrated on one platform. This analysis also quantifies the potential that may result from such a joint consideration of concepts.

Methods: An integrated platform consolidates announcements of supplies of items, requests for items, and crowdshipping trips. We employ mathematical optimization to support the operator of such a platform in assigning supplies to requests and, if applicable, also assigning a crowdshipper the task to conduct the delivery. To this end, we formulate assignment problems and we also propose two heuristics. The first heuristic approach is to decompose the problem into two subproblems and to solve them sequentially with the Hungarian method. The second approach is to represent all feasible matchings as vertices in a graph and to compose an operable plan by selecting a subset of those vertices through a graph-based heuristic. Eventually, the platform's potential is analyzed in a simulation study for Atlanta in the U.S. state of Georgia.

Results: Item-sharing exhibits strong economies of density. The integration with crowdshipping increases both profitability and service level of a platform. We consider two alternative ways of how crowdshipping can facilitate item exchanges between consumers. In a home delivery, a crowdshipper picks up an item from its current location and delivers it directly to a consumer's home. In a neighborhood delivery, the requested item is brought to the destination of a crowdshipper's trip from where it needs to be picked up by the requesting consumer himself/herself. The inclusion of home deliveries has the bigger effect on profit, particularly because of the extra service consumers may be willing to pay for. Neighborhood deliveries allow for further item exchanges as crowdshippers and consumers collaboratively conduct the transport. The planning complexity increases with every additionally considered delivery option and alternative solution methods are required to efficiently solve large scale problems. The proposed heuristics are fast and scalable. However, only the graph-based approach allows for an improved solution quality in comparison to the scenario without crowdshipping. A sensitivity analysis shows that home deliveries become less attractive if higher compensations must be paid to crowdshippers. Furthermore, a platform's operational performance substantially depends on the willingness of consumers and crowdshippers to invest time in item transports.

Conclusion: An effective operations management of item-sharing platforms shows great potential for serving consumers' requests with shared items, particularly in densely populated areas. The results further demonstrate that crowdshipping is a promising logistics concept to facilitate item exchanges.

1.4.2 Essay 2

An exact solution method for the capacitated item-sharing and crowdshipping problem

Moritz Behrend, Frank Meisel, Kjetil Fagerholt, and Henrik Andersson

Research objective: The benefit of a concept integration was investigated in Essay 1 based on scenarios where crowdshippers accept to conduct at most one delivery per trip. However, crowdshippers may also accept to conduct multiple deliveries when they want to get more involved in crowdshipping. The goal of this research is to quantify the potential of capacitated crowdshipping and to derive managerial insights on how a platform shall incentivize crowdshippers to improve operational performance.

Methods: Crowdshipping with more than one delivery per trip requires a routing of crowdshippers on their way from their origin to their destination via intermediate pick-up and drop-off locations. Such a 'detour routing' determines the travel time increase due to crowdshipping, which allows to respect crowdshippers' preferences when assigning delivery jobs to trips. Note that this is not possible if the solution methods of Essay 1 are simply generalized regarding the number of jobs that can be assigned to a trip. We propose a new exact solution method that supports the operational planning of a platform operator in two steps. First, a label setting algorithm determines feasible crowdshipping routes for each crowdshipper. Second, a set packing problem selects a combination of those routes that maximizes profit. The exact solution method can also be turned into a heuristic by altering the search for crowdshipping routes. The potential of capacitated crowdshipping is analyzed based on a simulated serving of item requests through an integrated sharing platform in Atlanta in the U.S. state of Georgia.

Results: The proposed method is much faster for the case of single-capacitated crowdshipping than the assignment problem formulations used in Essay 1. Furthermore, if crowdshippers accept to conduct multiple deliveries, higher profits are possible. However, the magnitude of this profit increase is strongly linked to crowdshipper's willingness to extent their trips since the execution of more deliveries also requires more detouring. As crowdshippers accept longer detours and offer to conduct multiple deliveries, the planning complexity increases substantially and the computational effort to solve problems to optimality becomes intractable. One approach to obtain a good but not necessarily optimal solution in this case is to simply plan with less crowdshipping flexibility. Alternatively, the search of the label setting algorithm can also be modified such that not all but only a subset of possible crowdshipping routes are considered. It is the combination of complexity reducing measures that makes the algorithm very versatile and powerful and that allows to obtain the highest profits in the experiments. A sensitivity analysis regarding the number of crowdshippers and their offered transportation capacity reveals a decreasing marginal benefit of every additional capacity unit used as more crowdshippers are available. Finally, we show that a deep integration of item-sharing and crowdshipping on a single platform is considerably more profitable than other degrees of collaboration between the two concepts.

Conclusion: The proposed combination of label setting algorithm and set packing problem is an exact and efficient method for the capacitated item-sharing and crowdshipping problem. A platform benefits from crowdshippers' additional flexibility to conduct multiple deliveries, but only if the crowdshippers are also willing to invest some time in transportation services. The scope for incentivizing crowdshippers to conduct more than one delivery is particularly high in settings where crowdshipping opportunities are rare.

1.4.3 Essay 3

A multi-period analysis of the integrated item-sharing and crowdshipping problem

Moritz Behrend, Frank Meisel, Kjetil Fagerholt, and Henrik Andersson

Research objective: Item-sharing is an inherently multi-periodic process as the same items are successively used by multiple consumers in the course of time. This contribution introduces the multi-period variant of the integrated item-sharing and crowdshipping problem. In this context, we propose the concept of 'request chaining' in which items are directly forwarded from one consumer to the next without returning the items to intermediate storage locations in-between two requests. This interpretation of item-sharing results in interdependencies between periods and it raises the question to what extent a more foresighted planning outperforms previously developed solution methods for a period-to-period decision making.

Methods: We propose a binary program that supports the operational planning of a platform operator in 'routing' items through a network of consumer locations over time. To this end, the program decides for every leg of an item's route which request to serve next and to whom to assign the responsibility of transport. As the considered time horizon increases in size, not all requests and crowdshipping trips may be available at each point of planning. We deal with these dynamics by embedding the binary program in a rolling horizon framework. This allows for an iterative decision making in which new requests are dynamically included in the planning once they become known. Potential benefits of a multi-period planning are analyzed and quantified based on a platform simulation that is similar to the one used in the previous studies.

Results: A platform with request chaining can substantially increase profits if the operational planning for the upcoming period also considers information of subsequent periods.

This is because a more foresighted long-term planning makes it less likely that items are assigned and delivered to remote request locations where they are temporarily inaccessible to others. Assignments like these occur frequently in a period-to-period planning for scenarios with only a few consumers and limited options to exchange items between them so that a multi-period planning is particularly beneficial in such cases. The planning complexity increases quickly as the considered time horizon is extended. In a dynamic setting with incomplete information, there are two essential parameters that affect the operational performance of a platform: the announcement lead-time, i.e. the number of periods separating the announcement of a request or trip and their realization, and the response lead-time, i.e. by how many periods the platform shall notify consumers and crowdshippers in advance about successful assignments. The results show that higher profits are possible if the difference between announcement lead-time and response lead-time allows for at least some periods of foresight in the planning. Eventually, we investigate how the number of available items affects the profitability of a sharing platform, given that this number can be controlled by the platform operator. The analysis is subject to consumers' rental duration and the width of the time window in which they want to be serviced. We observe the highest marginal profit per extra item for the scenario with long rental durations and a non-critical requesting behavior.

Conclusion: Request chaining is an efficient way of sharing items among consumers. Since already a few periods of look-ahead in the planning allows for a substantial improvement in service, consumers need to be sensitized to give a platform some time to plan their requests. Platform operators may consider providing additional items in a sharing network to increase both service and profits.

1.4.4 Essay 4

Buying versus renting: On the environmental friendliness of item-sharing

Moritz Behrend

Research objective: Item-sharing connotes efficiency and environmental friendliness as only a few, highly utilized items are required to serve demand. However, a shared use of items also necessitates frequent transports between consumers, which may counterbalance the positive environmental benefit of producing fewer items. Against this background, we compare the environmental impact of sales-based and sharing-based business models. The sustainability comparison is based on carbon dioxide equivalents (CO_2e) that are released during the production of items and their repeated transportation between consumers.

Methods: The traditional approach of selling items to consumers is compared to two item-sharing concepts, namely station-based sharing and free-floating sharing. In station-based sharing, items are made available at fixed stations from where they need to be picked up by consumers when requested and to which they need to be returned to after use. In free-floating sharing, items are directly transferred between consecutive consumers, meaning that a requesting consumer sources the item from the location where it was last used (see 'request chaining' in Essay 3). The comparison is conducted through a framework in which the performance of each approach is evaluated quantitatively in different dimensions. Essential performance measures are the degree of request fulfillment and the kilometric performance. The framework also allows to take into consideration that items need to be replaced at some point, either because of wear or obsolescence. Numerical experiments are based on simulations for a large metropolitan area.

Results: The analysis shows that considerably fewer items are required to serve total demand when items are shared rather than owned, particularly if the requests are evenly distributed over the time horizon. However, the repeated item transfers in item-sharing also require more traveling. The increase in kilometric performance is substantial for station-based sharing, moderate for free-floating sharing, and negligible if item exchanges in free-floating sharing are facilitated through crowdshipping. The environmental impact assessment of item production and transport shows that item-sharing is already the more environmentally friendly business model for items with comparably low life cycle emissions. Free-floating sharing is particularly emissions-efficient. The consideration of item-replacements due to wear or obsolescence affects the sustainability comparison of business models in different ways. While some degree of durability is required so that all requests can be served with a few shared items, the marginal environmental benefit of using particularly hard-wearing and/or long-lasting items in item-sharing decreases quickly. In contrast, items with particularly short lifetimes may better be shared than owned because less items need to be periodically replaced in this case.

Conclusion: Free-floating sharing has a great potential to cut the environmental impact of consumption. Already a few shared items allow for perfect service levels at a moderate increase of kilometric performance. Eventually, it needs to be decided for each individual item type whether selling or sharing is more emission efficient, subject to the consumers' requesting behavior, the emissions that are released during item production, and the item's durability and lifetime.

1.5 Implications and future research

A major implication of this work for future research is that the operations management of item-sharing platforms constitutes an own research domain, next to the well-studied operations management of other sharing economy concepts such as car sharing, bike sharing, or ride-sharing. This work lays the foundation for further analyses by providing benchmark results in the dimensions profit, service level, and environmental impact. The testing data is available online. Essay 1 shows that a well-designed operational coordination of supplies and requests in item-sharing networks increases overall satisfaction. The integration with crowdshipping is an effective measure to reduce the effort of exchanging items. The results in Essay 2 suggest that crowdshipping can become a more powerful logistics concept for item-sharing if crowdshippers can be assigned multiple deliveries per trip. The potential of a more sophisticated planning is, however, limited by the time crowdshippers are willing to invest on transportation services. In any case, the combination of a label setting algorithm and a set packing problem is a very efficient and versatile solution method to support a platform's operations management. The concept 'request chaining', introduced in Essay 3, certainly stimulates the way in which we think about sharing. It is also demonstrated that a more foresighted planning substantially improves operational performance in this context. The sensitivity analysis further suggests that the provision of additional items may pay off in the long run. Essay 4 indicates that item-sharing allows to effectively reduce the environmental impact of consumption. This holds for various types of items covering a wide range of carbon footprints. Free-floating sharing has the highest potential to provide a service-oriented and environmental friendly consumer experience.

Implications for practitioners are the following. Essay 1 demonstrates that it is crucial to a platform's performance to attract a critical mass of active consumers. To this end, Essays 3 and 4 suggest that it might also be necessary to extend a platform's business of merely coordinating other peoples' property by also providing items on its own. Already a few extra items per offered type substantially increase the achieved service levels and, therefore, improve overall user experience. The integration with item-sharing is deemed to be desirable in all essays. It might, however, be necessary to incentivize crowdshippers to put more effort into the transportation of items, as is discussed in Essay 2. The 'request chaining' concept in Essay 3 provides a very scalable interpretation of item-sharing. New items simply need to be 'fed into the system' where they circulate among consumers, and no further investments in infrastructure like storage capacity is needed. Moreover, the direct item transfers between consumers may help to increase the popularity of item-sharing. This is because an item can be obtained with substantially less effort in comparison to the traditional station-based sharing. Another appealing aspect may be the prospect of keeping an item beyond the booked planning period. Essay 4 shows that offering sharing services allows to substantially reduce consumption-related emissions, particularly for items with a medium to high carbon footprint.

Future research can extend the operational planning of item-sharing platforms in various directions. For example, there might be situations where multiple items are required at the same time by one member (e.g. a camping chair and a tent for a hiking holiday). In this case, the assignment decisions and item flows need to be synchronized to make sure that the member receives either all the required items or none of them. It might also be desirable that items are shared always between the same members of a large sharing network. Such a consistency in the planning could help to build up trust and strengthen relationships between people who are otherwise strangers to each other. The consideration of such aspects calls for the development of extended optimization models and algorithms. There are also various open questions regarding the implementation of sharing-based business models that require further investigation. For example, the pricing of rental services allows for alternative designs such as pay-per-use, subscription models, or a membership fee. Since these pricing schemes differ in their effect on the profitability of a platform and the requesting behavior of consumers, it is worthwhile to compare them. The concept 'request chaining' is substantially different from traditional sharing practices. Empirical research may analyze consumers' willingness to store items after use for some time. Legal responsibilities need to be addressed in this context, too, since direct item exchanges between consumers do no longer allow to inspect the items for damages right after every use. This makes it more difficult to protect the platform against vandalism, fraud, and theft. An upscaling of item-sharing also raises questions for society, economy, and environment. The sharing economy is often criticized for generating jobs with precarious working conditions and it remains to be analyzed whether this allegation also applies to item-sharing and crowdshipping. An economic implication is that manufacturing companies may lose sales if efficient sharing systems effectively reduce overall demand. In contrast, the cheap access to items may also increase consumption due to rebound effects, with possibly negative environmental consequences. Altogether, these topics open up a broad and interesting research area for which this work hopefully serves as a starting point.

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Chapter Two

THE INTEGRATION OF ITEM-SHARING AND CROWDSHIPPING: CAN COLLABORATIVE CONSUMPTION BE PUSHED BY DELIVERING THROUGH THE CROWD? (ESSAY 1)

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Abstract: Item-sharing and crowdshipping are two concepts of the sharing economy. In item-sharing, members of a sharing community can temporarily rent items such as tools or leisure equipment from one another. In crowdshipping, private drivers offer to execute delivery jobs for other people on trips they would make anyway. Since the peer-to-peer exchange in item-sharing involves repeated, inefficient 'last-mile' transports of small shipments, we investigate here whether the integration of item-sharing and crowdshipping has the potential to facilitate collaborative consumption. To this end, the decision making for an integrated item-sharing and crowdshipping platform is modeled. This platform matches supplies, requests, and planned trips of the community members. We develop mathematical models and heuristics for maximizing the platform's profit and the number of fulfilled requests. Our results quantify and confirm the substantial benefit of integrating item-sharing and crowdshipping.

Keywords: Sharing Economy, Item-sharing, Crowdshipping, Last-Mile Delivery, Home Delivery, Neighborhood Delivery

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Chapter Three

AN EXACT SOLUTION METHOD FOR THE CAPACITATED ITEM-SHARING AND CROWDSHIPPING PROBLEM (ESSAY 2)

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Abstract: The item-sharing and crowdshipping problem combines two concepts of the sharing economy, namely item-sharing and crowdshipping. Item-sharing is about renting items among members of a sharing community. Crowdshipping addresses the transportation of these items through private people on trips they make anyway. The considered problem is to decide (1.) which request for an item to fulfill through which of the supplied items and (2.) who is doing the transport of rented items from the supply-locations to the request-locations. We generalize this problem with regard to crowdshippers' capacity, meaning that each crowdshipper can transport a given number of items along his/her intended route. This results in a detour routing problem, where crowdshippers are routed through intermediate locations on the way from their actual origin location to their intended destination. We propose an exact solution method based on a set packing formulation for which a label setting procedure generates feasible crowdshipper routes a priori. We also describe how to derive a heuristic from the exact approach. Our experiments identify to what extend higher capacities of crowdshippers lead to more profitable routes and under which conditions a heuristic reduction of the method is required to cope with the complexity of the problem. We also show that the new exact method clearly outperforms procedures that were developed earlier for a setting where each crowdshipper can transport at most one single item.

Keywords: Sharing Economy, Item-sharing, Crowdshipping, Capacity, Label Setting

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Chapter Four

A MULTI-PERIOD ANALYSIS OF THE INTEGRATED ITEM-SHARING AND CROWDSHIPPING PROBLEM (ESSAY 3)

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Abstract: The integrated item-sharing and crowdshipping problem arises from the operational planning of sharing platforms that coordinate diverse services offered by individuals to peers. Item-sharing means to rent-out items whereas crowdshipping describes the willingness of private drivers to conduct deliveries on their planned trips. Integrating both concepts on a single platform can lead to higher profits and better service quality by transferring items through crowdshippers. We investigate a multi-period variant of the problem to facilitate more foresighted assignments of items to requests and crowdshippers. Thereby, items can be used to sequentially serve multiple requests without being returned to their initial locations. This so-called 'request chaining' cuts transportation effort and improves the availability of items to consumers. We present a binary program for the multi-period decision making that 'routes' the items though a network of requests. We also propose a rolling horizon approach for settings with incomplete information due to dynamically incoming announcements. Our experiments analyze the benefits of a more foresighted planning, subject to the length of the considered time horizon, the announcement lead-time of dynamically incoming requests and crowdshipping trips, and various types of requesting preferences. They show that a look-ahead in the planning is particularly useful for scenarios with few requests. We also derive managerial insights on the number of items that should be provided in such a community.

Keywords: Transportation, Sharing economy, Item-sharing, Crowdshipping, Multi-period planning

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4.1 Introduction

Platform-based business models in the sharing economy bring together members of a platform community who offer resources or services and members who request them (Botsman and Rogers, 2011). The business models are typically to coordinate announcements of offers and demands and to enable transactions. Prominent examples are item-sharing platforms for the sharing of members' resources (Erento, 2020; Zilok, 2020) and crowdshipping platforms for sharing transport services (Amazon Flex, 2020; Postmates, 2020; Deliv, 2020). In item-sharing, underutilized items such as tools (e.g. drills) or equipment for leisure activities (e.g. tents) are offered to be temporarily used by others. Such items might be privately owned and offered for the time they are not needed or they are provided by companies that intend to generate revenues through renting out items. In crowdshipping, people conduct deliveries on their own upcoming trips, which is seen as a novel opportunity for city logistics (Savelsbergh and Van Woensel, 2016; Cleophas et al., 2019). In recent studies, we have investigated the concept of integrating item-sharing and crowdshipping on a same platform (Behrend et al., 2019; Behrend and Meisel, 2018). The motivation is to increase the consumer experience through a full-service providing platform where desired items are provided *and* delivered. Current platforms do not offer such convenience and consumers need to pick up the rented items themselves. Experiments have shown that a platform's profitability and the service provided to consumers both benefit from such an integration already in the single-period setting that was assumed in this previous research. However, sharing items is an inherently multi-periodic process as each item can be used sequentially by multiple consumers. We therefore investigate in this paper the multi-period variant of the integrated item-sharing and crowdshipping problem.

More precisely, we consider an integrated platform that consolidates information about supplies of shared items and requests for them as well as transportation services offered by occasional drivers, so-called crowdshippers. Whether the items are privately-owned or company-owned is irrelevant for the following analysis. The goal is to use this information to satisfy the requests using the supplied items and to have the community members conduct the transportation of items. There are no additional vehicles at the platform's disposal so that the platform needs to orchestrate the allocation of items as well as the assignment of the resulting delivery jobs to community members in order to fulfill requests. A multi-period decision making allows to include future announcements early in the process, which hopefully supports a higher long-term performance by dealing with conflicting requests in a timely manner. Moreover, a better service can be offered to consumers by communicating fulfillment confirmations for requests several periods in advance. However, to achieve these benefits, the platform needs to collect announcements over a sufficiently long time span so that eligible matchings can be found. We therefore assume a non-urgent behavior of both consumers and crowdshippers who let the platform know some periods (e.g. days) in advance where and when an item is requested or transport services are offered, respectively.

To satisfy multiple requests sequentially with any given item, this item needs to be transferred to a requesting location and then needs to stay there for the desired rental duration before it is released by the served consumer and transferred to the next request. Releasing an item commonly implies that the item is returned to where it was previously sourced from. While this suggests a close control over the rent-out item, it results in (potentially unnecessary) shippings between (distant) locations. A more efficient procedure is to let the item stay with the currently served consumer and then to transfer it directly from there to the next request. Such direct transfers are suitable for all kinds of items that require only little maintenance like, for example, gaming consoles or other electronic gadgets. It allows for a very scalable business model as storage capacity is outsourced to consumers. We refer to the concept of transferring items multiple times directly from one request to the next as *request chaining*.

Recurrent transfers of an item from the location it was previously used to the location of the next request demands a careful planning. This is because consumers and crowdshippers conduct the transportation, but only if the effort to travel to the pick-up location and from there to the new request location is accepted. While the drop-off location of a delivery is an outcome of the decision in the current planning period, the pick-up location is an outcome of previous assignment decisions (i.e. previously fulfilled requests). Therefore, decisions in previous periods also affect who can be assigned an upcoming task of transferring an item to a subsequent request. Against this background, a multi-period planning is highly relevant as only the long-term evaluation of assignment decisions allows to have items circulate from one request to the next without getting stuck in remote locations from where they are less likely to be picked up again.

In this context, the main contributions of this paper are summarized as follows:

- We introduce the multi-period item-sharing and crowdshipping problem in which items are directly transferred from recently served consumers to those waiting to be served next, thereby omitting inefficient returns of items to initial supply locations.
- We present a mathematical optimization model that decides on the requests to serve taking into account the limited willingness of consumers and crowdshippers for transporting items.
- We propose a rolling horizon approach to support a joint decision making in settings with incomplete information due to announcements that occur in the course of time.
- We conduct comprehensive experiments to generate managerial insights on the profitability of the platform depending on the quantity of available items and the requesting behavior of consumers.

The remainder of the paper is organized as follows. In Section 4.2, we discuss related literature and point out the research gap in further detail. A formal problem description and the mathematical optimization model are presented in Section 4.3. In Section 4.4, we explain how to embed this model in a rolling horizon approach. The numerical experiments are subject of Section 4.5. Section 4.6 concludes the paper.

4.2 Related literature

Request-chaining, i.e. the sequential assignment of items to different request locations, bears close resemblance to classical routing problems where vehicles instead of items need to visit a sequence of locations (Laporte, 2009; Toth and Vigo, 2014). The literature in this field considers a vast number of problem extensions, some of which are relevant to the problem at hand. For example, if too few items are available to fulfill all requests, the selection of requests-to-be-satisfied becomes part of the planning. This characteristic is referred to in the routing literature as routing with profits (Feillet et al., 2005), selective routing (Laporte and Martello, 1990), or orienteering problem (Gunawan et al., 2016; Vansteenwegen et al., 2011). Also home delivery planning under limited transport capacities, restricted time windows, and route-dependent profitability involves decisions on which requests to serve (Campbell and Savelsbergh, 2005). Another relevant problem extension is the so-called open routing where vehicles' routes do not start and end at a predefined location (Schrage, 1981). Many contributions are available that deal with one or several of these mentioned extensions (e.g. Lalla-Ruiz et al., 2016; Souffriau et al., 2013; Archetti et al., 2015). In contrast to the routing of vehicles, the routing of items does, however, also require to assign a means of transport for every leg of an item's route, thereby adding an additional aspect to the problem.

Transportation by means of crowdshipping has gained in popularity over the years. An empirical-driven stream of the crowdshipping literature analyzes crowdshippers' motivation to conduct deliveries and senders' motivation to commission non-professional drivers with the transportation of goods. Prominent reasons for individuals to get involved in crowdshipping are economic incentives, a strong community spirit, or adding an additional purpose to their individual traveling for environmental reasons (Miller et al., 2017; Böcker and Meelen, 2017). Senders prospect for cheap and fast deliveries through crowdshippers but their expectations are subdued by concerns regarding unreliable individuals and the physical integrity of the shipped goods (Punel and Stathopoulos, 2017; Punel et al., 2018).

Another stream of the crowdshipping literature addresses the operational planning of assigning delivery jobs to crowdshippers. Several papers assess the benefits that commercial carriers can obtain from outsourcing delivery tasks to crowdshippers, despite compensating them for their detouring. Archetti et al. (2016) consider a single-echelon distribution through company-owned vehicles that is enhanced through crowdshippers. Wang et al. (2016) describe a two-echelon distribution where goods are transshipped from company-owned vehicles to crowdshippers so that the time-consuming final leg of deliveries can be parallelized. Qi et al. (2018) also address a two-echelon distribution, where the availability of crowdshippers depends on the amount of compensations paid. The mentioned papers assign delivery jobs to crowdshippers for single periods and assume that actual delivery times are negotiated between the involved parties themselves. The subsequent papers also respect time windows in the planning. Arslan et al. (2019) and Chen et al. (2018) consider a single-echelon distribution, Kafle et al. (2017) a two-echelon distribution, and Dahle et al. (2019) a pick-up and delivery setting, to name a few. The dynamics of successively incoming crowdshipping announcements is only addressed in Arslan et al. (2019) and tackled by a rolling horizon framework. Further static and dynamic approaches can be found in the literature on ride-sharing where people instead of freight are carried on existing trips (see Furuhata et al. (2013) for a general review and Agatz et al. (2012) for a review on dynamic approaches). The contributions differ from the setting considered in our paper in several regards. First, origin and destination locations of shipments are fixed and given in the mentioned papers. However, they are part of the planning when crowdshipping is integrated with item-sharing because delivery jobs are an outcome of the matching of supplied items with requests to serve. Second, in our approach, deciding on crowdshipping assignments of one period impacts delivery tasks in later periods. This necessitates a multi-period perspective, which contrasts existing papers that consider single-period problems. Furthermore, we include the option that crowdshippers can collaborate with the designated recipients in conducting deliveries whereas the transportation in the mentioned papers is solely conducted by the crowdshippers.

Research regarding item-sharing mostly addresses how to tailor business models to fit the needs of access-oriented consumers. Corresponding papers of Reim et al. (2015), Tukker (2015), and Boehm and Thomas (2013) discuss best practices on contract design, marketing strategies, and collaboration management for so-called 'use-oriented product service systems'. The recent publication by Benjaafar et al. (2019) contributes to this by assessing the benefit of peer-to-peer item sharing subject to cost of ownership, rental price, item usage, and expected wear and tear using equilibrium models. To the best of our knowledge, the concept of request chaining has not yet been investigated in this context although it may reduce the inconvenience of handling and transporting rented items. Request chaining may therefore foster the popularity of item-sharing.

Research on the integration of item-sharing and crowdshipping on a single platform has started recently. Behrend and Meisel (2018) propose an assignment problem to coordinate the item transfers with respect to consumers' and crowdshippers' preferences for a single period. Numerical results for a simulated sharing platform in Atlanta, Georgia, have shown that the availability of crowdshippers allows to significantly increase the profitability of the platform due to a better consumer service and more satisfied requests. These results were obtained for a setting with homogeneous items and crowdshippers who agree to conduct maximum one delivery job per trip. It was shown in Behrend and Meisel (2019) that this setting can be extended easily to handle heterogeneous items by adding compatibility constraints to the model. In Behrend et al. (2019), a capacitated version of the problem was investigated where crowdshippers accept multiple delivery jobs per trip. The resulting increase of transportation capacity allows to provide a slightly better service at a considerably higher planning complexity. This is because the extension requires solving a detour routing problem as the mere assignment of delivery jobs to trips cannot respect a crowdshipper's travel time limit for the modified trip. All mentioned papers consider a single-period setting. Theoretically, this one-time decision making can be applied in a multi-period setting by iteratively generating solutions based on inputs that are outcomes of past decision makings. This is typically done in a rolling horizon framework where an optimization model is solved at different points in time, always with the most up-to-date information and in such a way that the sequential decision making forms a consistent solution (Boysen et al., 2019). However, considering only the information about requests and trips of the next period in such a framework while ignoring future announcements is likely to result in a poor platform performance in the long run. We therefore investigate in this paper a multi-period planning that includes upcoming but already known requests early in the decision process to allow for a more foresighted planning. We compare this approach with the myopic planning in our experimental study.

4.3 The multi-period item-sharing and crowdshipping problem

4.3.1 Problem definition and notation

We consider a multi-period planning problem of a sharing platform that assigns supplied items to requests. There are no designated storage locations to which the items need to be returned to after use so that a request location that is served in some period turns into a supply location once the associated consumer releases the item. Transfers of items from one location to another can be conducted in three so-called *transfer modes*: (a) the item is either collected by the requesting consumer himself/herself (*self-sourcing*), (b) the item is delivered by a crowdshipper directly to the consumer (*home delivery*), or (c) the item is taken by the crowdshipper to the destination of its own trip and is collected from there by the consumer (*neighborhood delivery*). The three transfer options allow to flexibly share the burden of transporting an item among a crowdshipper and a requesting consumer.

The planning is based on periods, with each period being one day. Consequently, consumers announce their requests for items based on days. Crowdshippers announce the day at which they conduct a trip that might be used for a delivery. This planning granularity is sufficient to coordinate requests where consumers hold items for days or even weeks. The precise scheduling that coordinates the item transfers among the involved parties within a period is beyond the scope of this paper. We assume that these parties will bilaterally negotiate actual pick-up and delivery times once the platform tells them on which day the transfer is to be conducted. Furthermore, for reasons of simplicity, we consider here just one type of items to be shared, although the presented approach can easily be adapted to the case with heterogeneous items. Also, since we focus in this paper on multi-period planning, we consider unit capacity for crowdshippers as higher capacities result only in minor gains but come at a much higher planning complexity (Behrend et al., 2019).

The most relevant notation that is used for modeling the problem is summarized in Table 4.1. The set of considered periods is referred to as $\mathcal{P}$. We denote by $\mathcal{S}$ the set of requests that have been served in previous periods and that hold an item at the beginning of the planning horizon. The open requests for items form the set $\mathcal{R}$. A request $i \in \mathcal{R}$ corresponds to a consumer's need for one item. The platform knows the specific location where the item needs to be delivered to and the so-called rental duration s_i, i.e. the number of periods the consumer wants to hold the item. Furthermore, the consumer's preference regarding the beginning of the rental is expressed by a service time window $[e_i, e_i + f_i)$, where e_i is the earliest period to receive the item and f_i is the width of the time window. For example, $f = 1$ means that a consumer requests an item in the very period e_i, i.e. time window $[e_i, e_i]$, and $f = 2$ means that a request can be served either in period e_i or $e_i + 1$. Once an item is transferred to a requesting location, a consumer has exclusive access to it

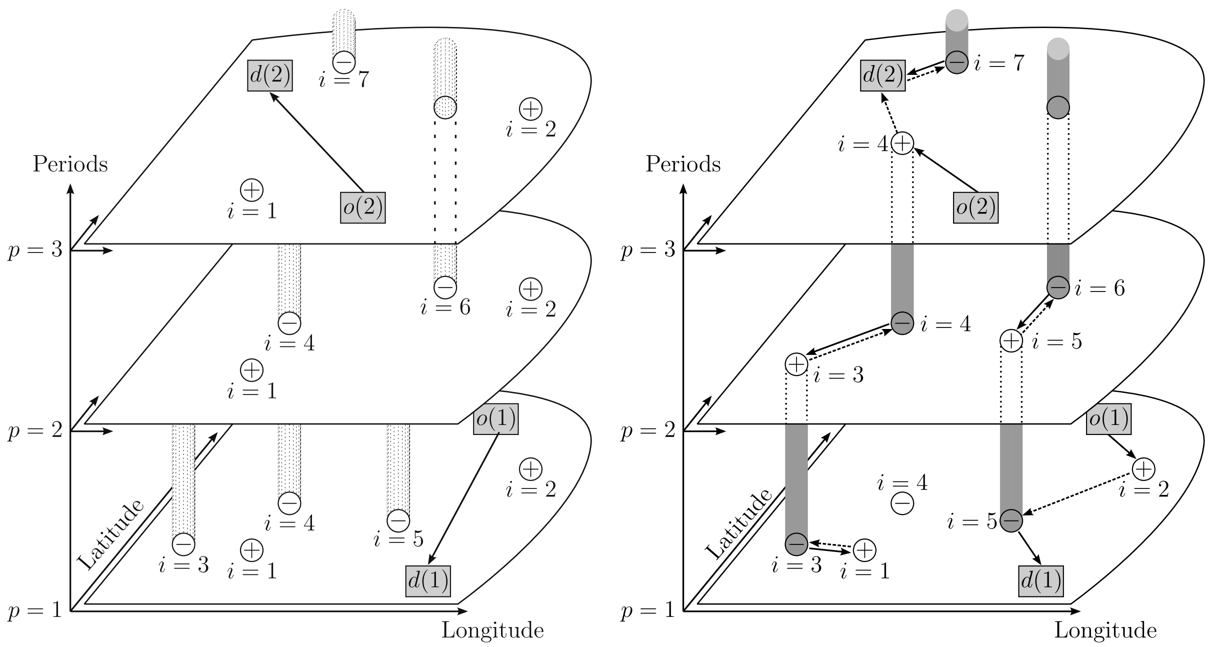
Table 4.1: Notation used.

Sets:	
$\mathcal{P}$	Periods.
$\mathcal{S}$	Requests holding an item initially, i.e. supply locations.
$\mathcal{R}$	Open requests.
$\mathcal{K}$	Trips of crowdshippers.
Parameters:	
s_i	Rental duration of request $i \in \mathcal{R}$.
e_i	Earliest period for serving request $i \in \mathcal{R}$.
f_i	Width of service time window of request $i \in \mathcal{R}$.
ρ_i	Release period of request $i \in \mathcal{S} \cup \mathcal{R}$.
g_k	Traveling period of crowdshipping trip $k \in \mathcal{K}$.
r_{ij}^{ssrc}	Profit if an item is transferred from a request $i \in \mathcal{S} \cup \mathcal{R}$ to a request $j \in R$ through self-sourcing.
r_{ijk}^{crowd}	Profit if an item is transferred from a request $i \in \mathcal{S} \cup \mathcal{R}$ to a request $j \in \mathcal{R}$ through crowdshipping on trip $k \in \mathcal{K}$.
Variables:	
x_{ijp}	1 if request $j \in \mathcal{R}$ is served with the item at location $i \in \mathcal{S} \cup \mathcal{R}$ in period $p \in \mathcal{P}$ through self-sourcing, 0 otherwise.
y_{ijk}	1 if crowdshipper $k \in \mathcal{K}$ is used to transfer the item at location $i \in \mathcal{S} \cup \mathcal{R}$ to request $j \in \mathcal{R}$, 0 otherwise.

for the rental duration s_i. Therefore, the item can first be assigned to other requests as of a so-called release period ρ_i. The release period for yet unsatisfied requests $i \in \mathcal{R}$ is an outcome of the planning as it is subject to the start of the service. It is, however, known for all former requests $\mathcal{S}$ that have been served in previous periods and currently hold an item. The set of crowdshipping trips is denoted $\mathcal{K}$. Each trip $k \in \mathcal{K}$ is associated with an origin location $o(k)$ and a destination location $d(k)$. The traveling period of trip k is denoted g_k, with $g_k \in \mathcal{P}$.

We illustrate the problem setting in Figure 4.1a. This figure shows information available to the platform for the three periods $\mathcal{P} = \{1, 2, 3\}$ in a time-expanded graph. In the first period $p = 1$, former requests $\mathcal{S} = \{1, 2\}$ each hold one item (see vertices marked with '+' in the bottom layer of Figure 4.1a). These items are released in period $p = 1$ (i.e. $\rho_1 = \rho_2 = 1$) and can therefore be assigned to other requests right away. If they are not assigned to a request in this period, they remain at their current location and can be assigned to other requests in later periods. There are five yet unsatisfied requests $\mathcal{R} = \{3, 4, 5, 6, 7\}$ (vertices labelled '$-$' in Figure 4.1). The requests vary with respect to their service time windows and their rental duration. For example, request $i = 3$ requires an item only for period $p = 1$ ($s_3 = 1, e_3 = 1, f_3 = 1$), whereas request $i = 4$ also requires an item for one period but is flexible with regard to the beginning of the rental ($e_4 = 1,\ f_4 = 2$). Thus, $i = 4$ can be

(a) An exemplary problem setting. (b) An exemplary solution.



⊕: Released item. ⊖: Item request. $o(k)$ Origin of trip. $d(k)$: Destination of trip.

Figure 4.1: A time-expanded graph representation of the considered problem.

satisfied by assigning it an item either in $p = 1$ or in $p = 2$. The example also involves two crowdshipping trips $\mathcal{K} = \{1, 2\}$, each represented by a pair of an origin vertex $o(k)$ and a destination vertex $d(k)$ together with a connecting arc. Trip $k = 1$ is announced for period $p = 1$ ($g_1 = 1$) and trip $k = 2$ for $p = 3$ ($g_2 = 3$).

Figure 4.1b shows an exemplary solution to the problem that allows to satisfy all requests in $\mathcal{R}$. The item that is initially with consumer $i = 1$ is used by consumer $i = 3$ in period $p = 1$, followed by consumers $i = 4$ and $i = 7$ in $p = 2$ and $p = 3$, respectively. The other item is first used by consumer $i = 5$ in $p = 1$ before it is transferred to and used by request $i = 6$. The item transfer between $i = 1$ and $i = 3$ is an example for self-sourcing where consumer $i = 3$ himself/herself picks up the item from $i = 1$ by making the round trip $3 - 1 - 3$ in $p = 1$. An example for a home delivery is the detouring of trip $k = 1$ in $p = 1$ to deliver the item from $i = 2$ directly to $i = 5$. An example for a neighborhood delivery is the collaborative effort of the crowdshipper on trip $k = 2$ and consumer $i = 7$ to transfer the item from $i = 4$ to $i = 7$ via $d(2)$ in period $p = 3$.

The considered objective of the platform is to maximize profit. It collects payments for satisfying requests and it compensates crowdshippers for their detouring. We employ a remuneration scheme in which consumers' payments grow linearly in the rental duration s_j by rate r^{var}. The revenue from assigning consumer j the item previously used by $i \in \mathcal{S} \cup \mathcal{R}$, together with the task to self-source it, is denoted by r_{ij}^{ssrc} and computed by $r_{ij}^{\text{ssrc}} = s_j \cdot r^{\text{var}}$. For technical reasons, we set $r_{ij}^{\text{ssrc}} = -\infty$ if the supply location i is so far from j that the consumer refuses a self-sourcing, i.e. the assignment is forbidden in the optimization model. In a neighborhood delivery, consumers also need to pick up the items themselves, only this time from the destination of a trip $k \in \mathcal{K}$. We denote the corresponding revenue by r_{jk}^{nbrhd}. We further assume that the increased service of a home delivery of the item is valued by a consumer in terms of a fix extra payment r^{fix}. Accordingly, satisfying a request $j \in \mathcal{R}$ through a home delivery effects a revenue $r_j^{\text{home}} = s_j \cdot r^{\text{var}} + r^{\text{fix}}$.

The compensation for crowdshippers' additional travel time in excess of the duration of their original trip increases at a constant rate c^{dtr} per minute of detouring. Let c_{ijk}^{home} be the compensation the platform needs to pay to crowdshipper $k \in \mathcal{K}$ for a home delivery that incurs a detour via the locations $i \in \mathcal{S} \cup \mathcal{R}$ and $j \in \mathcal{R}$. We set $c_{ijk}^{\text{home}} = \infty$ if the assignment is infeasible as it exceeds the crowdshippers willingness for detouring. Similarly, we denote by c_{ik}^{nbrhd} the compensation for detouring only via location $i \in \mathcal{S} \cup \mathcal{R}$ on trip $k \in \mathcal{K}$ in case of a neighborhood delivery, where $c_{ik}^{\text{nbrhd}} = \infty$ is set for infeasible assignments due to excessive detouring. The profit from transferring an item from request $i \in \mathcal{S} \cup \mathcal{R}$ to request $j \in \mathcal{R}$ by crowdshipping trip $k \in \mathcal{K}$ is then defined as

$$r_{ijk}^{\text{crowd}} = \max\left\{r_j^{\text{home}} - c_{ijk}^{\text{home}};\ r_{jk}^{\text{nbrhd}} - c_{ik}^{\text{nbrhd}}\right\}. \tag{4.1}$$

Note that although crowdshipping implies either a home delivery or a neighborhood delivery, only the most profitable, feasible transfer mode will be considered by a profit-oriented platform, which is reflected by the max-function in Equation (4.1). We assume that consumers accept whatever transfer mode the platform chooses. The approach could be extended easily by a specific value r_j^{fix} for consumer j to express individual preferences for home deliveries or neighborhood deliveries. If, in Equation (4.1), neither home delivery nor neighborhood delivery is feasible for this combination of i, j and k, r_{ijk}^{crowd} takes value $-\infty$. The described preprocessing is without loss of optimality for the subsequent decision making.

4.3.2 Mathematical model

We present a binary program for the multi-period item-sharing and crowdshipping problem ($MPICP$). The request chaining, i.e. the coordination of ongoing item transfers between requests, is explicitly modeled through the decision variables. Consumers' and crowdshippers' willingness to get involved in item transfers is addressed implicitly by defining variables only for those item transfers that are feasible.

Let x_{ijp} be a binary variable indicating by $x_{ijp} = 1$ that request $j \in \mathcal{R}$ is served through the item at location $i \in \mathcal{S} \cup \mathcal{R}$ in period $p \in \mathcal{P}$ via self-sourcing, $x_{ijp} = 0$ otherwise. Let y_{ijk} be a binary variable indicating by $y_{ijk} = 1$ that crowdshipper $k \in \mathcal{K}$ is used to transfer the item at location $i \in \mathcal{S} \cup \mathcal{R}$ to request $j \in \mathcal{R}$, $y_{ijk} = 0$ otherwise. The corresponding period for the transfer is inferred from the traveling period g_k of crowdshipper trip k. The transfer mode (home delivery or neighborhood delivery) is the more profitable one as determined in the preprocessing by Equation (4.1).

The following tuple-set $\mathcal{A}$ contains all those (i, j, p)-combinations for which a transfer by self-sourcing is actually feasible, i.e. for which variable x_{ijp} needs to be created.

$$\begin{aligned}\mathcal{A} = \{(i, j, p) \quad &\forall i \in \mathcal{S} \cup \mathcal{R}, j \in \mathcal{R}, p \in \mathcal{P} \mid i \neq j \;\wedge\; \rho_i \leqslant p \;\wedge \\ &e_j \leqslant p < e_j + f_j \;\wedge\; r_{ij}^{\text{ssrc}} \neq -\infty\}.\end{aligned} \tag{4.2}$$

Here, item transfers can originate from locations of initially satisfied requests $i \in \mathcal{S}$ or open requests $i \in \mathcal{R}$ but only for serving open requests $j \in \mathcal{R}$ with $i \neq j$. Moreover, according to Equation (4.2), a transfer from i to j in period p can take place only if consumer i releases the item no later than period p (i.e. $\rho_i \leqslant p$), if period p falls into the service time window of request j (i.e. $e_j \leqslant p < e_j + f_j$), and if self-sourcing is not prohibited due to a too large distance between i and j (i.e. $r_{ij}^{\text{ssrc}} \neq -\infty$).

Similarly, the following tuple-set $\mathcal{B}$ contains all (i, j, k)-combinations for which crowdshipping is an option for transferring the item, i.e. for which variable y_{ijk} needs to be created.

$$\begin{aligned}\mathcal{B} = \{(i, j, k) \quad &\forall i \in \mathcal{S} \cup \mathcal{R}, j \in \mathcal{R}, k \in \mathcal{K} \mid i \neq j \;\wedge\; \rho_i \leqslant g_k \;\wedge \\ &e_j \leqslant g_k < e_j + f_j \;\wedge\; r_{ijk}^{\text{crowd}} \neq -\infty\}.\end{aligned} \tag{4.3}$$

The main difference of the definition of set $\mathcal{B}$ compared to $\mathcal{A}$ is that the travel period g_k of crowdshipper k determines exactly the period in which an item can be transferred. Note that by excluding infeasible assignments with prohibitively high penalty costs ($-\infty$) we still include unprofitable assignments, i.e. where the compensation is higher than the received payment. Such item transfers may pay off in terms of higher total profit in later periods when further (nearby) requests are satisfied by this item.

The corresponding BIP model for the $MPICP(\mathcal{S}, \mathcal{R}, \mathcal{K}, \mathcal{A}, \mathcal{B})$ reads as follows:

$$\text{maximize } Z = \sum_{(i,j,p)\in\mathcal{A}} r_{ij}^{\text{ssrc}} \cdot x_{ijp} + \sum_{(i,j,k)\in\mathcal{B}} r_{ijk}^{\text{crowd}} \cdot y_{ijk} \tag{4.4}$$

subject to

$$\sum_{(i,j,p)\in\mathcal{A}} x_{ijp} + \sum_{(i,j,k)\in\mathcal{B}} y_{ijk} \leqslant 1 \qquad \forall i \in \mathcal{S} \cup \mathcal{R} \tag{4.5}$$

$$\sum_{(i,j,p)\in\mathcal{A}} x_{ijp} + \sum_{(i,j,k)\in\mathcal{B}} y_{ijk} \leqslant 1 \qquad \forall j \in \mathcal{R} \tag{4.6}$$

$$\sum_{\substack{(j,i,p')\in \\ \{\mathcal{A}|p'\leqslant p-s_i\}}} x_{jip'} + \sum_{\substack{(j,i,k)\in \\ \{\mathcal{B}|g_k\leqslant p-s_i\}}} y_{jik} \geqslant \sum_{(i,j,p)\in\mathcal{A}} x_{ijp} + \sum_{\substack{(i,j,k)\in \\ \{\mathcal{B}|g_k=p\}}} y_{ijk} \qquad \forall i \in \mathcal{R}, p \in \mathcal{P} \tag{4.7}$$

$$\sum_{(i,j,k)\in\mathcal{B}} y_{ijk} \leqslant 1 \qquad \forall k \in \mathcal{K} \tag{4.8}$$

$$x_{ijp} \in \{0,1\} \qquad \forall (i,j,p) \in \mathcal{A} \tag{4.9}$$

$$y_{ijk} \in \{0,1\} \qquad \forall (i,j,k) \in \mathcal{B} \tag{4.10}$$

Objective (4.4) maximizes the platform's profit. Constraints (4.5) state that an item at location i can be transferred at most once to another request location. This holds for locations that initially hold an item at the beginning of the first period ($i \in \mathcal{S}$) as well as for open request locations ($i \in \mathcal{R}$). Conversely, an open request location can maximum receive one item according to Constraints (4.6). Constraints (4.7) are the balance constraints for open request $i \in \mathcal{R}$. They enforce that if request i is served, the item stays at this location at least for the rental duration s_i. In other words, an item can be taken from i and be brought to some other request in period p (right-hand side of Constraint (4.7)) only if it was transferred to i in period $p - s_i$ or earlier (left-hand side of Constraint (4.7)). The sets of feasible self-sourcing options ($\mathcal{A}$) and crowdshipping options ($\mathcal{B}$) are filtered accordingly in these constraints. Note that Constraints (4.6) and (4.7) are stated only for open requests in set $\mathcal{R}$ as already satisfied requests in $\mathcal{S}$ only serve as supply locations that provide items initially.

A crowdshipper can be used for at most one item transfer according to Constraints (4.8). Finally, the domains of the decision variables are defined in Constraints (4.9) and (4.10).

4.4 Rolling horizon approach

In the following, we propose a planning framework to address the dynamic variant of the multi-period item-sharing and crowdshipping problem. In this variant, requests and crowdshipping trips are unknown beforehand and announced to the system in the course of time. In Section 4.4.1, we describe the iterative procedure of planning at discrete points in time, each time based on the most up-to-date information. In Section 4.4.2, we present alternative commitment strategies for fixing decisions that belong to future planning periods. An illustrative example is provided in Section 4.4.3.

4.4.1 Planning framework

Let $t \in \mathcal{P}$ be the *upcoming period* at the beginning of which the platform has to decide on the requests to serve in this period. We denote by τ the width of the planning horizon, i.e. the number of periods that are included in the decision making. In other words, for given t and τ, an *active planning horizon* $\mathcal{P}'$ is defined consisting of periods $\{t, \ldots, t + \tau - 1\}$. We assume here that only the assignment decisions for period t are communicated to the users of the sharing-platform and that the assignments for the following periods $\mathcal{P}' \backslash \{t\}$ are considered tentative and not published yet. With higher values for τ, the optimization model looks further ahead and, therefore, suggests more foresighted assignments for period t. However, the available data becomes less complete the further we look into the future, as new requests may appear that have not been announced yet. We model the dynamics of request announcements by an *announcement lead-time* α. This lead time describes how many periods prior to the earliest rental period a consumer notifies the platform of his/her request. Thus, a request i with a service time window $[e_i, e_i + f_i)$ becomes known to the platform in period $e_i - \alpha$. Although individual announcement lead-times can easily be modeled, we assume for reasons of simplicity identical lead-times for all requests. Subject to t, τ, and α, we identify the subset of *active requests* $\mathcal{R}' \subseteq \mathcal{R}$ that are relevant for the current planning by

$$\mathcal{R}' = \{i \in \mathcal{R} \mid e_i - \alpha < t \wedge e_i < t + \tau \wedge t < e_i + f_i\}. \tag{4.11}$$

According to Equation (4.11), a request is active if it is known to the platform, if its time window starts before the end of the active planning horizon, and if the service time window has not yet ended in period t. We also assume that crowdshippers announce their trips α periods prior to their traveling period g_k. The subset of *active trips* $\mathcal{K}' \subseteq \mathcal{K}$ that are relevant for the current planning is defined as

$$\mathcal{K}' = \{k \in \mathcal{K} \mid g_k - \alpha < t \wedge g_k \in \mathcal{P}'\}. \tag{4.12}$$

This set is composed of trips that are already announced and whose traveling period is within the active planning horizon. We use the notation $MPICP(\mathcal{S}, \mathcal{R}', \mathcal{K}', \mathcal{A}, \mathcal{B})$ to indicate that the $MPICP$ is solved based on the active requests and active trips.

An iterative planning in combination with request chaining causes dependencies of decisions in subsequent periods. The rolling horizon approach therefore requires to include decisions made in period t (i.e. from the solution of the $MPICP$) as input for the subsequent planning in the next period. We therefore update the sets $\mathcal{S}$ and $\mathcal{R}$ as items are moved to keep track of the items' locations and the requests yet-to-be-served, respectively. Furthermore, for a newly satisfied request i that enters set $\mathcal{S}$ in period t, we set the release period to $\rho_i = t + s_i$. Finally, we denote by Π the profit that the platform accumulated right up to the beginning of period t, including all revenues and compensations from earlier periods. After the decision making of period t has been done, Π is updated by adding those revenues and compensations that belong to the newly implemented decisions of this particular period. Note that Π denotes the total profit that the platform realized so far, whereas the objective function value Z of the $MPICP$ denotes the prospective profit over all periods in the currently active planning horizon $\mathcal{P}'$.

The whole procedure conducted by the platform in period t is described in Algorithm 1. It takes as input the planning horizon (τ), the profit accumulated so far (Π), the set of initial supply locations ($\mathcal{S}$), the set of open requests ($\mathcal{R}$), and the set of trips ($\mathcal{K}$). The algorithm returns the updated profit Π, the updated set $\mathcal{S}$ of locations that hold items at the end of period t, and the remaining open requests ($\mathcal{R}$). In lines $1-3$, the algorithm identifies the

Algorithm 1: Period transition algorithm.

Input: t, τ, Π, $\mathcal{S}$, $\mathcal{R}$, $\mathcal{K}$;
Output: Π, $\mathcal{S}$, $\mathcal{R}$;

1 $\mathcal{P}' \leftarrow \{t, \ldots, t+\tau-1\}$;
2 $\mathcal{R}' \leftarrow \{i \in \mathcal{R} \mid e_i - \alpha < t \wedge e_i < t+\tau \wedge t < e_i + f_i\}$;
3 $\mathcal{K}' \leftarrow \{k \in \mathcal{K} \mid g_k - \alpha < t \wedge g_k \in \mathcal{P}'\}$;

`// Determine feasible transfer combinations.`

4 $\rho_i \leftarrow \max\{e_i, t\} + s_i \quad \forall i \in \mathcal{R}'$;
5 $\mathcal{A} \leftarrow \{(i,j,p) \quad \forall i \in \mathcal{S} \cup \mathcal{R}', j \in \mathcal{R}', p \in P' \mid i \neq j \;\wedge\; \rho_i \leqslant p \;\wedge\; e_j \leqslant p < e_j + f_j \;\wedge\; r_{ij}^{\text{ssrc}} \neq -\infty\}$;
6 $\mathcal{B} \leftarrow \{(i,j,k) \quad \forall i \in \mathcal{S} \cup \mathcal{R}', j \in \mathcal{R}', k \in \mathcal{K}' \mid i \neq j \;\wedge\; \rho_i \leqslant g_k \;\wedge\; e_j \leqslant g_k < e_j + f_j \;\wedge\; r_{ijk}^{\text{crowd}} \neq -\infty\}$;

`// Solve optimization problem.`

7 $x, y \leftarrow MPICP(\mathcal{S}, \mathcal{R}', \mathcal{K}', \mathcal{A}, \mathcal{B})$;

`// Extract and implement item transfers for period` t.

8 $\mathcal{A}^* \leftarrow \{(i,j,p) \in \mathcal{A} \mid p = t \wedge x_{ijp} = 1\}$;
9 $\mathcal{B}^* \leftarrow \{(i,j,k) \in \mathcal{B} \mid g_k = t \wedge y_{ijk} = 1\}$;
10 $\Pi \leftarrow \Pi + \sum_{(i,j,p) \in \mathcal{A}^*} r_{ij}^{\text{ssrc}} + \sum_{(i,j,k) \in \mathcal{B}^*} r_{ijk}^{\text{crowd}}$;
11 $\mathcal{S}^+ \leftarrow \{j \in \mathcal{R}' \mid \exists i \in \mathcal{S}$ such that $(i,j,t) \in \mathcal{A}^* \vee \exists i \in \mathcal{S}, k \in \mathcal{K}'$ such that $(i,j,k) \in \mathcal{B}^*\}$;
12 $\mathcal{S}^- \leftarrow \{i \in \mathcal{S} \mid \exists j \in \mathcal{R}'$ such that $(i,j,t) \in \mathcal{A}^* \vee \exists j \in \mathcal{R}', k \in \mathcal{K}'$ such that $(i,j,k) \in \mathcal{B}^*\}$;
13 $\mathcal{S} \leftarrow \mathcal{S} \backslash \mathcal{S}^- \cup \mathcal{S}^+$;
14 $\mathcal{R} \leftarrow \mathcal{R} \backslash \mathcal{S}^+$;
15 **return** Π, $\mathcal{S}$, $\mathcal{R}$;

active planning horizon $\mathcal{P}'$, the active requests $\mathcal{R}'$, and the active trips $\mathcal{K}'$. It then derives feasible transfer combinations $\mathcal{A}$ and $\mathcal{B}$ based on these active sets in lines $4-6$, as described in Section 4.3.2. Since the release period ρ_i of yet unsatisfied requests $i \in \mathcal{R}'$ is required for the definition of these sets but unknown so far, it is set to its theoretical minimum, i.e. to the earliest possible release period, in line 4. Next, the $MPICP$ is solved and the decision variables for successful item-transfers through self-sourcing (x) and crowdshipping (y) are retrieved, see line 7. The decisions for period t are implemented in lines $8-14$. Here, $\mathcal{A}^*$ denotes the set of self-sourcings to conduct in period t and $\mathcal{B}^*$ denotes the set of crowdshipping transfers in that period. The platform's profit Π is then updated by adding the associated profits of the new assignments, see line 10. The locations of items at the end of period t are identified in lines $11-13$. To this end, we define temporary sets for those requests that received an item in t ($\mathcal{S}^+$) and that sent out an item in t ($\mathcal{S}^-$). We use them to update set $\mathcal{S}$ in line 13. Finally, the algorithm updates set $\mathcal{R}$ in line 14.

4.4.2 Commitment strategy

The process described in Section 4.4.1 provides a platform maximum flexibility as it commits itself only to the plan for the upcoming period t whereas all assignments for later periods are tentative and might be changed in a subsequent planning. While this commitment strategy allows for very profitable decisions that are based on most up-to-date information, consumers and crowdshippers are merely notified on short notice (i.e. at the beginning of period t) whether their demand can be met or their crowdshipping service is required, respectively. To increase the quality of the platform's services and, thus, the user experience, we extend the proposed framework such that assignments related to future periods can also be fixed and be communicated to members further in advance. This results in an overlap between decisions in different iterations of the planning as assignments made in previous periods need to be kept fixed in following planning iterations to ensure that they are put into practice as already communicated to the platform users.

Let β be the desired *response lead-time* of the consumers and crowdshippers, i.e. the number of periods the platform shall notify them in advance about successful assignments. For reasons of simplicity, the response lead-time is assumed to be identical for all community members. It is defined on the interval $0 \leqslant \beta \leqslant \alpha - 1$, where $\beta = 0$ means that the members desire no advanced notification (like in Section 4.4.1) whereas $\beta = \alpha - 1$ implies that members expect a notification about whether or not their request will be served right in the period after they announced it.

The overlap of decisions in consecutive planning iterations asks for modifications to both Algorithm 1 and the model in Section 4.3.2. Let $\bar{\mathcal{A}} \subseteq \mathcal{A}$ be the subset of self-sourcings that must be implemented in period $t+1$ and beyond under a given response lead-time β. It is defined as

$$\bar{\mathcal{A}} = \{(i, j, p) \in \mathcal{A} \mid x_{ijp} = 1 \ \wedge \ t + 1 \leqslant p \leqslant t + \beta\}. \tag{4.13}$$

According to Equation (4.13), $\bar{\mathcal{A}}$ contains those assignments that are selected by the $MPICP$ while planning for t but that decide on item transfers in future periods up to $t+\beta$. Thus, if a request is notified when the respective assignment first enters set $\bar{\mathcal{A}}$, the associated consumer knows β periods in advance that his/her request is satisfied and where he/she needs to pick-up the assigned item. Likewise, we denote by $\bar{\mathcal{B}}$ the subset of fixed crowdshippings for period

$t + 1$ and beyond, which is defined as

$$\bar{\mathcal{B}} = \{(i,j,k) \in \mathcal{B} \mid y_{ijk} = 1 \ \wedge \ t+1 \leqslant g_k \leqslant t+\beta\}. \tag{4.14}$$

The travel period g_k of crowdshipping trip k determines the period of the item transfer in Equation (4.14) and the transfer mode depends on which transfer mode is selected in the preprocessing. The sets $\bar{\mathcal{A}}$ and $\bar{\mathcal{B}}$ are additional inputs in Algorithm 1 that are updated after solving the $MPICP$ in line 7. The updated sets are then returned by the algorithm as additional outputs such that they are respected in subsequent planning iterations. Finally, we augment the optimization model $MPICP$ such that it respects the new inputs $\bar{\mathcal{A}}$ and $\bar{\mathcal{B}}$ by adding the following constraints to enforce fixed self-sourcings

$$x_{ijp} = 1 \quad \forall (i,j,p) \in \bar{\mathcal{A}} \tag{4.15}$$

and the following constraints to enforce fixed crowdshippings

$$y_{ijk} = 1 \quad \forall (i,j,k) \in \bar{\mathcal{B}}. \tag{4.16}$$

To exclude from the decision making those item transfers for which a response cannot be communicated timely, we furthermore restrict arc sets $\mathcal{A}$ and $\mathcal{B}$ that control the generation of x- and y-variables. This is done by adding the following criterion to the definition of arc set $\mathcal{A}$ in line 5 of Algorithm 1 and in Equation (4.2):

$$p \geqslant t + \beta. \tag{4.17}$$

Similarly, we further restrict arc set $\mathcal{B}$ in line 6 of Algorithm 1 and in Equation (4.3) by adding

$$g_k \geqslant t + \beta. \tag{4.18}$$

The criteria (4.17) and (4.18) imply that item transfers are only feasible if they address periods that are at least β periods beyond the current planning period t.

4.4.3 An illustrative example

We illustrate the dynamic planning of a platform as described in Sections 4.4.1 and 4.4.2 based on an example with three requests where a decision making is required at the beginning of period $t = 4$. Figure 4.2 presents request-dependent parameters and provides a time-space visualization of the problem setting. In this visualization, alternative assignment decisions

Requests				Service plan
i	s_i	e_i	f_i	
1	1	3	1	
2	2	4	2	
3	1	4	1	

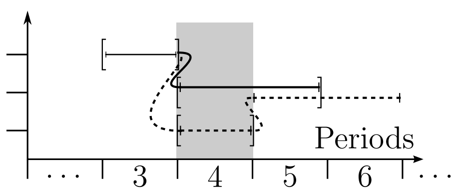


Figure 4.2: Exemplary planning problem for period $t = 4$ ($\mathcal{S} = \{1\}$, $\mathcal{R} = \{2, 3\}$).

are depicted as item paths (solid and dotted) to ease the reading. Request $i = 1$ currently holds an item ($\mathcal{S} = \{1\}$) and releases it in $p = 4$ ($e_1 + s_1 = \rho_1 = 4$). This item can be assigned to one of the yet unsatisfied requests $i = 2$ or $i = 3$ ($\mathcal{R} = \{2, 3\}$) as both of them request an item in that period ($e_2 = e_3 = 4$) and accept to self-source it from the location of $i = 1$, which is assumed here. Request $i = 2$ is flexible regarding the beginning of the rental ($f_2 = 2$) and requires the item for two periods ($s_2 = 2$) whereas request $i = 3$ is less flexible ($f_3 = 1$) and asks for a shorter rental duration ($s_3 = 1$). Table 4.2a shows relevant information of Algorithm 1 for a setting with short announcement lead-times ($\alpha = 1$) and no response lead-time ($\beta = 0$), subject to the planning horizon. For $\tau = 1$, $i = 2$ and $i = 3$ are mutually exclusive and the platform assigns the item to $i = 2$ in $p = 4$ to maximize profit ($Z = s_2 \cdot r^{\text{var}} = 2 \cdot r^{\text{var}}$), due to the higher rental duration of that request. The corresponding assignment $(1, 2, 4) \in \mathcal{A}^*$ is communicated right away and consumer $i = 2$ puts the planning into practice by self-sourcing the item from $i = 1$ in $p = t = 4$. Payments from served requests are always collected for the complete rental duration so that the platform's profit (Π) increases by $2 \cdot r^{\text{var}}$. Moreover, the item's current location is updated for future reference by replacing request 1 with request 2 in the set $\mathcal{S}$ and by setting the release period to $\rho_2 = t + s_2 = 4 + 2$. This solution is depicted by the solid item path in Figure 4.2.

For a horizon of $\tau = 2$ periods, the planning can take advantage of the long service time window of $i = 2$ so that the item is first assigned to $i = 3$ in $p = 4$ and afterwards taken from $i = 3$ to serve $i = 2$ in period $p = 5$, see dotted item path in Figure 4.2. Note that only the transfer from $i = 1$ to $i = 3$ in period $p = 4$ is communicated ($(1, 3, 4) \in \mathcal{A}^*$) and that payments are collected for this assignment only ($\Pi = \Pi + s_3 \cdot r^{\text{var}} = \Pi + 1 \cdot r^{\text{var}}$). The assignment of the same item to $i = 2$ in $p = 5$ is only tentative ($\bar{\mathcal{A}} = \varnothing$). It can be

(a) $\alpha = 1$, $\beta = 0$.

τ	Z	$\mathcal{A}^*$	$\bar{\mathcal{A}}$	Π	$\mathcal{S}$
1	$2 \cdot r^{\text{var}}$	$(1,2,4)$	$\varnothing$	$\Pi + 2 \cdot r^{\text{var}}$	$\{2\}$
≥ 2	$3 \cdot r^{\text{var}}$	$(1,3,4)$	$\varnothing$	$\Pi + 1 \cdot r^{\text{var}}$	$\{3\}$

(b) $\alpha = 2$, $\beta = 1$.

τ	Z	$\mathcal{A}^*$	$\bar{\mathcal{A}}$	Π	$\mathcal{S}$
1	0	$\varnothing$	$\varnothing$	Π	$\{1\}$
2	$2 \cdot r^{\text{var}}$	$(1,2,4)$	$\varnothing$	$\Pi + 2 \cdot r^{\text{var}}$	$\{2\}$
≥ 3	$3 \cdot r^{\text{var}}$	$(1,3,4)$	$(3,2,5)$	$\Pi + 1 \cdot r^{\text{var}}$	$\{3\}$

Table 4.2: Assignment decisions subject to lead-times (α, β) and planning horizon (τ).

revised if new requests for items appear later on that are more profitable. Otherwise, the same assignment can still be communicated to consumer $i = 2$ at the beginning of period $p = 5$ as no response lead-time $(\beta = 0)$ is requested.

Table 4.2b shows results for a setting in which requests are announced two periods in advance $(\alpha = 2)$ and consumers expect a response one period prior to the beginning of the rental $(\beta = 1)$. In such a situation, no profit can be collected $(Z = 0)$ for $\tau \leqslant \beta$ as assignments cannot be communicated sufficiently far in advance, see the first row in Table 4.2b. The platform consequently needs to adjust the planning horizon to the requested response lead-time of its consumers. For $\tau = 2$, requests $i = 2$ and $i = 3$ are mutually exclusive again as the platform needs to communicate a decision for $p = 4$ while planning for $t = 3$. Here, the platform chooses request $i = 2$ to maximize its profit. For $\tau \geqslant 3$, the platform assigns the item to $i = 3$ in $p = 4$ and sends it from there to request $i = 2$ in period $p = 5$. This time, the assignment from $i = 3$ to $i = 2$ is no longer tentative as the platform needs to notify $i = 2$ one period in advance $(\beta = 1)$. The assignment $(3, 2, 5)$ therefore enters set $\bar{\mathcal{A}}$ to enforce the already communicated item transfer in the subsequent decision making at the beginning of $p = 5$ $(\bar{\mathcal{A}} = \{(3, 2, 5)\})$.

4.5 Numerical experiments

4.5.1 Experimental setting

We test the proposed planning approach by simulating the operations of an integrated item-sharing and crowdshipping platform in the metropolitan area of Atlanta in the US state of Georgia. We chose Atlanta as it represents a typical metropolitan region with a dense street network of different kind of roads, i.e. from small living streets to highways connecting the city center and surrounding suburbs. Data from this region was already used in the experiments of Behrend and Meisel (2018) and Behrend et al. (2019). The following experiments are based on ten instances, each with 1500 request locations, 1500 origins and 1500 destinations of crowdshipping trips uniformly distributed within an area of 900 km^2 around the city center. This allows to simulate up to 30 requests and 30 crowdshipping trips per period over an horizon of 50 periods. For this purpose, we assign earliest serving periods e_i uniformly to the requests as well as traveling periods g_k to the trips. Simulations of smaller scale are derived by considering only subsets of those requests and trips, such that results are comparable across various problem sizes and time horizons. In the following, we refer to consumers' requests and crowdshippers' trips jointly as *announcements* and vary their numbers together. Thus, an instance with an announcement rate of 10 means that 10 requests and 10 trips are announced per period. The number of available items (i.e. the cardinality of set $\mathcal{S}$) is given as a further input to a problem. We assign the initially available items to request locations randomly.

In the default scenario, $|\mathcal{S}| = 20$ items are available as of the first period. The rental duration of all requests is one period ($s_i = 1 \ \forall i \in \mathcal{R}$) and items need to be provided directly in period e_i to serve a request ($f_i = 1 \ \forall i \in \mathcal{R}$). Fastest routes between locations are generated with the Open Source Routing Machine (Open Source Routing Machine, 2020) and are based on the actual road network as provided by Open Street Maps (Geofabrik GmbH, 2020). Consumers self-source items if the round trip to pick-up the item at its current location does not exceed 10 minutes. Crowdshippers accept detours if they do not exceed their original trip duration by more than 30%. In the instance data, the original trip durations of crowdshippers are on average 24.7 minutes with a standard deviation of 8.4. Rental fees and compensation rates are as in Behrend and Meisel (2018). The platform collects a fee of $r^{\text{var}} = \$10$ per rental period of a satisfied request and an additional one-time fee of $r^{\text{fix}} = \$5$ if the item is delivered through a home delivery. Furthermore, it compensates crowdshippers with $c^{\text{dtr}} = \$0.5$ per minute of detouring. All test instance data, including locations of requests and trips as well as travel times for self-sourcing and crowdshipping, is available online at http://dx.doi.org/10.17632/d9zc7knxdz.3.

All experiments are conducted on a computer with 3.4 GHz and 16 GB RAM. We solve the $MPICP$ using Gurobi 7.5 . The rolling horizon approach is implemented in Java 8.0.

4.5.2 Short-sighted versus long-term planning

The first experiment analyzes the improvement of profits that can be obtained by an integrated item-sharing and crowdshipping platform through a more foresighted planning. To this end, we compare the two planning approaches proposed in this paper. The first approach is a *period-to-period planning* that is represented by the rolling horizon approach described in Section 4.4 with a planning horizon of $\tau = 1$. Decisions are based on the announcements for the upcoming period only and they are fixed when moving from one period to the next. The second approach is to solve the *multi-period model* from Section 4.3.2 to optimality where all announcements are considered jointly to derive optimal assignment decisions for the whole time horizon. In both settings, we assume perfect information where all announcements are known beforehand. We solve both settings for each of the ten instances with announcement rates of 10, 20, and 30, and for time horizons of $|\mathcal{P}| = 5$, 10, 15, and 20 periods.

Table 4.3 reports for both approaches the platform's accumulated profit at the end of the time horizon, the overall computation time required for the problem solving, and the total number of decision variables involved in the problems. The last column "Δ Profit" shows the relative improvement of profit between the period-to-period planning and the multi-period planning. All reported values are averages over ten instances with an announcement rate and a planning horizon as shown in the first two columns of the table. Since there are $|\mathcal{S}| = 20$ items available in all instances considered here, supply of items and requests for items are in equilibrium for an announcement rate of 20. Scenarios with an announcement rate of 10 experience an oversupply of available items. Scenarios with an announcement rate of 30 express settings with a shortage of available items.

In Table 4.3, we observe consistently higher profits for the multi-period planning and, therefore, strictly positive values in the "Δ Profit" column. While this result is expected, a more detailed comparison of these results reveals that the foresighted planning is particularly advantageous in scenarios with few requests. For example, the relative profit increase over 20 periods is 23% with an announcement rate of 10 but only 14% for an announcement rate of 30. This is explained as follows. Under few announcements, request locations are further apart from each other and less crowdshipping trips are available so that fewer options exist to feasibly retrieve an item from one location once that it has been delivered there. This

Table 4.3: Comparison of extreme planning approaches based on different problem sizes.

Announcement rate	Time horizon	Period-to-Period Planning			Multi-Period Planning			Δ Profit
		Profit	CPU [sec]	Variables	Profit	CPU [sec]	Variables	
10	5	253	0.1	132	276	0.1	265	9 %
	10	490	0.1	245	566	0.1	826	16 %
	15	714	0.1	365	852	1.2	1785	19 %
	20	924	0.1	466	1133	3.7	2833	23 %
20	5	549	0.1	458	606	0.2	1395	10 %
	10	1113	0.1	892	1273	5.8	4893	14 %
	15	1660	0.1	1370	1945	28.5	11052	17 %
	20	2196	0.1	1755	2596	73.0	18275	18 %
30	5	816	0.1	1034	888	1.5	3628	9 %
	10	1673	0.1	2094	1871	30.5	14485	12 %
	15	2524	0.1	3255	2861	351.1	33425	13 %
	20	3341	0.1	4238	3816	2253.4	57420	14 %

can cause items getting stuck in remote locations. A more foresighted planning evaluates assignments in the long run and, therefore, decides to serve requests at those locations from where the items can also be transferred to other request locations in later periods. As more announcements are considered, more transfer options exist and the selection of requests to satisfy is less decisive. Nevertheless, the advantage of a foresighted planning is still substantial in the scenarios with an announcement rate of 30 and increases with the time horizon.

Regarding the solvability of the problems, we observe that the computation times of the multi-period planning quickly increase with longer time horizons. For example, under an announcement rate of 30, the average runtime of the multi-period planning increases from 1.5 seconds per instance for a planning horizon of 5 periods to 30.5 seconds for 10 periods and 2253.4 seconds for 20 periods. In contrast, the period-to-period planning is easy to solve and scalable. The computation time is negligible for all scenarios and the number of decision variables increases almost linearly with the time horizon. Note, however, that the multi-period planning already results in a substantial profit increase for scenarios with small time horizons at only slightly higher computation times. A good compromise therefore could be an iterative planning procedure with at least some foresight.

4.5.3 Dynamic arrival of announcements

The second experiment addresses scenarios with incomplete information in which requests and trips are not known beforehand but are dynamically announced to the platform. For this purpose, we vary the announcement lead-time (α) as well as the response lead-time (β) to analyze their effect on the profitability of the platform. The planning horizon is assumed to be equivalent to the announcement lead-time ($\tau = \alpha$) in all experiments so that all known information is always included in the planning. As such, we also implicitly investigate the effect of different planning horizons as it makes no difference whether the planning cannot or does not include information from more distant periods.

Each bar plot in Figure 4.3 shows the platform's accumulated profit after 50 periods for different announcement lead-times α, each averaged over ten instances. A row-wise comparison of plots shows the effect of more announcements, from 10 requests and trips per period at the top, to 20 in the middle row, to 30 at the bottom. A column-wise comparison addresses the effect of higher response lead-times. Here, we consider no notification in advance ($\beta = 0$) for the plots on the left, notification one period in advance ($\beta = 1$) for the middle plots, and notification two periods in advance ($\beta = 2$) for the plots on the right. The brightest bars for $\alpha = 1$ in the left-most plots ($\beta = 0$) represent the same profits as obtained in the period-to-period planning in Table 4.3, this time for an extended time horizon of 50 periods. We increase the announcement lead time up to $\alpha = 10$ (darkest bar) to investigate the additional profit that can be obtained if announcements are available to the platform several periods in advance.

We first consider the scenario with an announcement rate of 10 and no prior notification ($\beta = 0$), i.e. the upper left plot in Figure 4.3. We observe a difference in accumulated profits subject to the announcement lead time α. The profit gap between the farthest foresight ($\alpha = 10$, darkest bar) and a period-to-period planning ($\alpha = 1$, brightest bar) is \$612 (27.2%). The profit of the multi-period planning in Table 4.3 with announcement rate 10 and time horizon 20 is, in turn, 1.2% higher, compared over a time horizon of 20 periods and adjusted for end-of-horizon effects. As more announcements per period are considered, the advantage of a more foresighted planning becomes less pronounced. For example, for an announcement rate of 30 and $\beta = 0$, the bars for $\alpha \geqslant 3$ are almost equally high, meaning that the additional foresight does not add much value to the planning. Still, a look-ahead of $\alpha = 3$ is 13.6% better than no foresight at all ($\alpha = 1$).

As the response lead-time for consumers and crowdshippers increases from left to right,

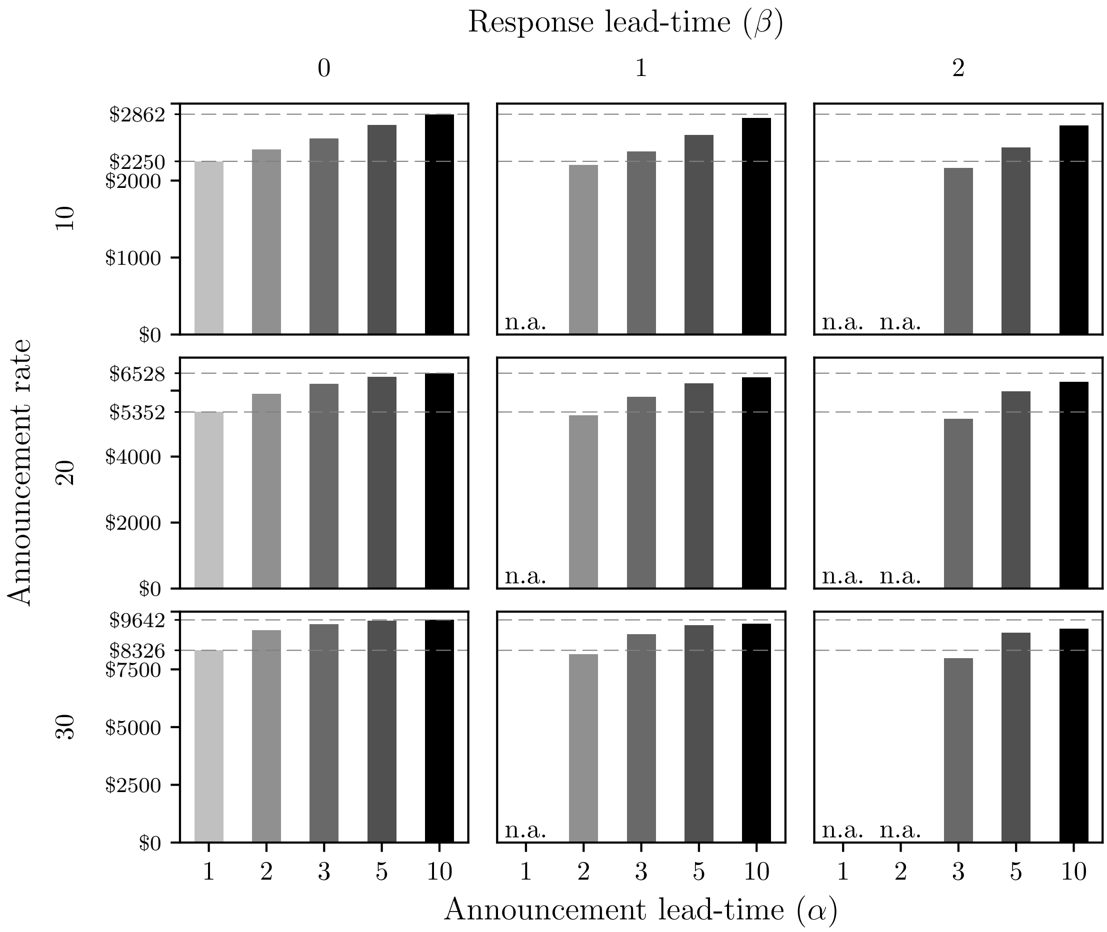


Figure 4.3: Accumulated profit of a platform over 50 periods in a dynamic setting.

fewer bars are visible in each subplot as a too short-sighted planning does not allow for sufficient prior notification and no profit can be collected. $\alpha > 1$ is required for scenarios with $\beta = 1$ so that $\alpha = 1$ (brightest bar) is missing in the plots of the second and third column. By looking at the individual bars in the plots, we observe a rightwards shift with increasing response lead-time where the bars of small α almost replace those for larger α. For example, in the scenarios with an announcement rate of 30 the platform accumulates \$8326 for $\alpha = 1$ and $\beta = 0$, \$8140 for $\alpha = 2$ and $\beta = 1$, and \$7965 for $\alpha = 3$ and $\beta = 2$ (compare heights of left-most bars in the plots of the last row). The similarity of the values imply that a loss of profit as a result of committing to a plan earlier can almost be compensated by planning even further in advance. The small differences that remain can be ascribed to profit losses at the beginning of the simulation when the requests in the first period(s) cannot be notified timely. Since this difference becomes negligibly small as the simulation continues, we conclude that higher response lead-times merely have an effect on the profitability of a platform as long as the announcement lead-times increase at the same rate. In the end, the community members themselves decide on the announcement lead-time and response lead-time. The platform therefore needs to raise their awareness for the benefit of including information for multiple periods into the planning. Not only is this in the interest of the platform, the community members also benefit as more requests can be served and more trips can be assigned a delivery job.

4.5.4 Sensitivity analysis

In the third experiment, we conduct a sensitivity analysis regarding the effect of different requesting behaviors as defined by the rental duration and the width of the service time window. Items may be used longer or consumers may be more flexible in when to use the requested item. This provides managerial insights for platform operators that are interested in adjusting the number of available items to increase profits and/or the provided service.

Table 4.4 presents the combinations of rental durations s and widths of service time windows f that we consider in this experiment. The comma-separated values are uniformly distributed among all requests in each scenario. A "short/critical" requesting behavior refers to the default setting. In contrast, the "long" rental durations address scenarios in which the items are one to three periods in use. Furthermore, requests are "non-critical" if they can be served in one out of up to three consecutive periods. We simulate a dynamic setting with an announcement rate of 20. The planning is based on the rolling horizon approach with $\tau = 3$, $\alpha = 3$, and $\beta = 0$. The number of available items varies from $|\mathcal{S}| = 20$ (default setting) up to $|\mathcal{S}| = 100$. Requests in $\mathcal{S}$ are assumed to be served one period before the beginning of the time horizon $\mathcal{P}$. Their rental duration is sampled from the same parameter combinations as all the other requests so that the items are released dynamically in the course of time.

Figure 4.4 shows the average accumulated profits after 50 periods, subject to the number of available items and the requesting behavior. We observe substantially higher profits for scenarios with long rental durations (solid graphs) under each number of available items. The platform benefits here from higher profits per served request. Conversely, it cannot offset lower profits per served short-term request through more transfers. With more items,

Table 4.4: Parameter combinations for different types of requesting behavior.

Requesting behavior	Rental duration (s)	Service time window (f)
short/critical	1	1
short/non-critical	1	1,2,3
long/critical	1,2,3	1
long/non-critical	1,2,3	1,2,3

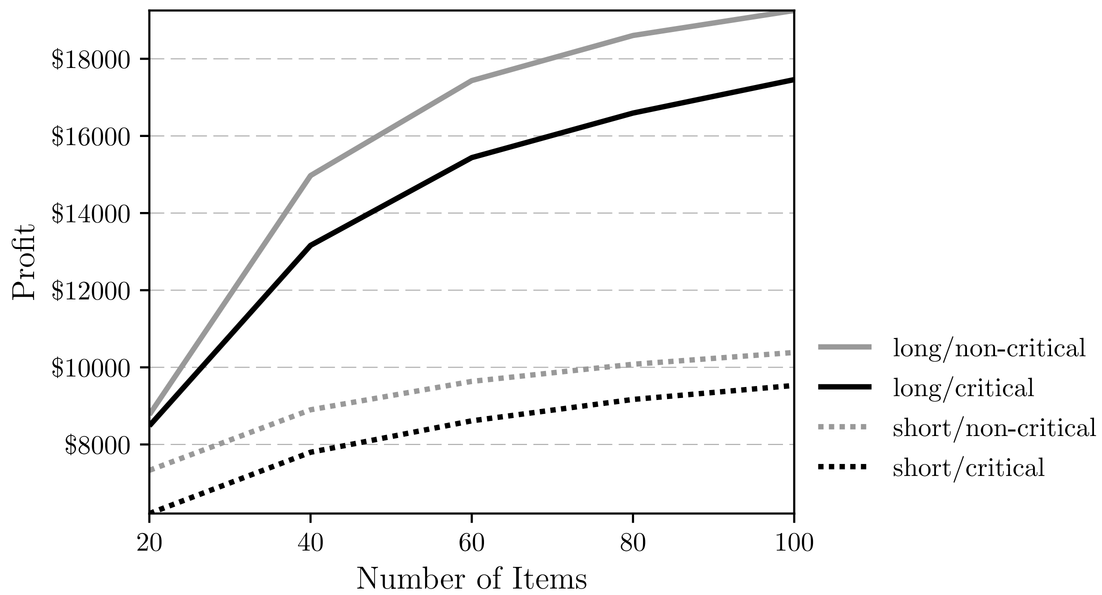


Figure 4.4: Accumulated profits after 50 periods.

profits increase in both cases at a decreasing rate. The marginal profits per additional item are particularly high for long rentals and between 20 to 40 items, implying a significant lack of supply in these settings. Investments in the provision of new items pay off here the most. The decision to adjust the number of available items may also be reasonable in other cases, subject to investment costs, revenues from rentals, and the longevity of the items. Regarding the width of the service time windows, we see that the planning can take advantage of serving consumers who are more flexible. The graphs for scenarios with non-critical behavior (bright) are always above those with time-critical requests (dark). The profit increase due to a more flexible planning ranges between 10% and 20% in all scenarios, except for those with a significant lack of supply. This could be used when establishing price mechanisms in practice.

Table 4.5 shows steady-state per-period performance measures of the platform for the investigated scenarios. The reported means (and standard deviations) express the per-period

Table 4.5: Steady-state performance analysis subject to requesting behavior and item supply.

Requesting behavior	$\|\mathcal{S}\|$	Profit (Platform)		Profit (Item)		Utilization rate [%]	Service rate [%]
		μ	σ	μ	σ		
short/critical	20	124.2	21.5	6.2	1.1	55.8	55.8
	40	156.0 (+26%)	23.4	3.9	0.6	35.3	70.6
	60	172.3 (+39%)	22.1	2.9	0.4	25.7	77.2
	80	183.3 (+48%)	20.7	2.3	0.3	20.3	81.3
	100	190.6 (+54%)	19.8	1.9	0.2	16.8	83.8
short/non-critical	20	146.6	23.4	7.3	1.2	66.2	66.2
	40	178.0 (+21%)	26.4	4.4	0.7	40.3	80.6
	60	192.7 (+32%)	28.1	3.2	0.5	28.7	86.0
	80	201.6 (+38%)	28.7	2.5	0.4	22.1	88.6
	100	207.7 (+42%)	29.8	2.1	0.3	18.0	90.1
long/critical	20	169.6	42.0	8.5	2.1	79.0	38.5
	40	263.2 (+55%)	46.4	6.6	1.2	62.3	58.9
	60	308.8 (+82%)	46.0	5.1	0.8	48.6	71.1
	80	331.9 (+96%)	44.4	4.1	0.6	38.8	76.9
	100	349.2 (+106%)	42.2	3.5	0.4	32.5	80.9
long/non-critical	20	175.4	49.4	8.8	2.5	80.4	42.0
	40	299.4 (+71%)	71.8	7.5	1.8	70.2	65.9
	60	348.7 (+99%)	75.5	5.8	1.3	54.4	78.7
	80	372.1 (+112%)	78.3	4.7	1.0	43.2	85.0
	100	385.1 (+120%)	75.5	3.9	0.8	35.4	87.9

values for the realized profit, the items in use, and the number of served requests across all periods and instances. Profits are shown for the platform in total and per item, where the latter is simply the total profit divided by the number of available items. The percentage of items in use (utilization rate) and the ratio of requests served (service rate) provide additional non-monetary information.

The results quantify the benefits of supplying additional items subject to the requesting behavior. The profit increases range from 42% (short/non-critical) to 120% (long/non-critical) if 100 instead of 20 items are made available. Fluctuations in profit seem to depend less on the number of available items but more on the type of requesting behavior. We observe high fluctuations for long rental durations and particularly high ones in case of long/non-critical. This is for two reasons. First, the fee for the entire duration is collected always in the first period of use. Second, wider and overlapping service time windows allow to serve more than 20 requests in a period if sufficient items exist ($|\mathcal{S}| \geqslant 40$). The profit per item per period is a critical indicator to identify a break-even point up until which the investment in further items pays off. In case of long/non-critical, this profit decreases from

\$8.8, a high value given that the variable rental fee is r^{ssrc} = \$10, down to \$3.9 as more items are provided. In the latter case, each item is used less, which is also reflected in a decline in the average utilization rate from 80% to 35%. Still, the additional items allow to serve more requests and, by that, help to provide an attractive service where almost 90% of requests can be served. This high service-quality may be crucial to attract new consumers to the platform in the long run. A platform operator is therefore advised to provide some oversupply subject to the rental duration and the flexibility with which the requests can be served.

4.6 Conclusions

We have investigated the multi-period item-sharing and crowdshipping problem with request chaining, where shared items remain at the requesting locations after use and are transferred directly from there to other locations in the following periods to be used by others. This results in dependencies between decisions in succeeding periods and, therefore, calls for a multi-period approach that creates sequences of item transfers with many served consumers per item over time. We have proposed a binary programming model that "routes" items through a network of requests while assigning the task of transportation for every leg of an item's route to the receiving consumer and/or an available crowdshipper. The objective is to maximize profit subject to service requirements of consumers and crowdshippers. We show how to embed the mathematical program in a rolling horizon framework to support the iterative decision making for scenarios with dynamically arriving announcements. Here, the planning for each period depends on the number of future periods for which information is included in the decision making and how far in advance consumers and crowdshippers want to receive a final response from the platform.

In our numerical experiments, we have simulated a platform for a large metropolitan area. The results show that the simultaneous consideration of all upcoming announcements in the multi-period planning allows for a substantial improvement in comparison with a period-by-period planning that only considers announcements for the next period. The increase in profit is up to 23% for large time horizons of 20 periods. The approach is shown to be particularly useful in case only few requests exist. In a dynamic setting where requests and trips are announced to the platform in the course of time, we observe that the advantage of being notified earlier balances out with the number of periods the platform needs to communicate reliable assignments in advance. Eventually, we tested various rental preferences of consumers to reveal what actions platform operators can take to improve the profitability and the service level of their platform. This helps, for example, to identify the amount of items that should be supplied on the platform.

Future research may focus on analyzing the environmental benefit of sharing items multiple times in comparison with each consumer buying an item individually. Also, modeling item-sharers and crowdshippers in greater detail raises questions from the field of consumer behavior. For example, it might be investigated how the platform performs if consumers are not willing to store items after use for a (too) long time or if community members communicate with each other so that rejecting requests negatively influences the number of announcements in future periods.

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Chapter Five

BUYING VERSUS RENTING: ON THE ENVIRONMENTAL FRIENDLINESS OF ITEM-SHARING (ESSAY 4)

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Abstract: Item-sharing is a concept of the sharing economy where items such as tools or leisure equipment are made available to a community and are accessed need-based. This allows to serve demand with a few highly utilized items, which is why item-sharing connotes resource efficiency and environmental friendliness. However, a shared use also necessitates to (repeatedly) transport single items between consecutive consumers. This kind of transports are relatively inefficient and may significantly affect the environmental efficiency of item-sharing. We investigate to what extent a few shared items allow to serve demand and under which circumstances the environmental benefit of providing fewer items is larger than the negative effects of a higher transportation effort. To this end, we develop a business model comparison framework to analyze and compare alternative ways of serving requests regarding the degree of request fulfillment and the emissions that are released during item production and transport. Our comparison includes variants of a traditional sales-based approach and two types of item-sharing in which items are either exchanged via stations or transferred directly from one consumer to another. We show by simulation studies for a large metropolitan area that item-sharing with direct transfers has a great emissions-cutting potential and that it becomes even more efficient if item exchanges are facilitated through so-called crowdshippers who offer to conduct transports on trips they would make anyway. The low environmental impact of item-sharing is further demonstrated in experiments with different requesting behaviors, various emission rates, and item replacements due to wear and obsolescence.

Keywords: Sharing economy, Item-sharing, Business models, Urban transportation, Emissions, Crowdshipping

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Appendix A

SHARING ECONOMY IM KONTEXT URBANER MOBILITÄT

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Abstract: In diesem Beitrag werden Konzepte aus dem Bereich der Sharing Economy dahingehend untersucht, welche Herausforderungen aber auch welche Lösungsansätze sie für die urbane Mobilität darstellen. Damit greifen wir eine Thematik auf, die in den letzten Jahren deutlich an Dynamik gewonnen hat. Im Zentrum des Sharings steht der Austausch von Ressourcen zwischen Mitgliedern einer Gemeinschaft. Als Ressource sind zum Beispiel Gegenstände wie Werkzeuge oder Fahrzeuge, aber auch Räumlichkeiten und Wissen zu nennen. Die Größe einer Tauschgemeinschaft korreliert aufgrund von Netzwerkeffekten positiv mit dem Nutzen, den jedes Mitglied aus dessen Mitgliedschaft zieht. Um Konzepten der Sharing Economy die Attraktivität zu verleihen, die zu deren Durchsetzung erforderlich ist, bedarf es folglich einer kritischen Masse an Mitgliedern. Es ist anzunehmen, dass diese besonders in Ballungszentren erreicht wird, sodass dort, als Alternative zum käuflichem Erwerb und alleinigem Konsum, der bedarfsgerechte Bezug von Tauschobjekten an Bedeutung gewinnt. Die Sharing Economy hat damit das Potenzial, das Konsumverhalten großer Bevölkerungsteile nachhaltig zu verändern, woraus ebenfalls erhebliche Folgen für den Personen- und Güterverkehr resultieren werden. Welche Aspekte der Sharing Economy zu einer zusätzlichen Be- oder Entlastung der ohnehin schon ausgelasteten innerstädtischen Verkehrsinfrastrukturen führen, soll in diesem Beitrag geklärt werden. Dazu werden zunächst verschiedene Konzepte der Sharing Economy diskutiert und die für die urbane Mobilität relevanten Teilaspekte identifiziert. Daran anschließend wird eine Taxonomie der Herausforderungen und Lösungen der Sharing Economy im Kontext urbaner Mobilität entwickelt. Hieraus leiten wir neue Forschungsbedarfe an den Schnittstellen zwischen Sharing Economy und urbaner Mobilität ab.

Keywords: Sharing Economy, Urbane Mobilität, City Logistics

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Appendix B

HETEROGENEITY OF ITEMS IN AN INTEGRATED ITEM-SHARING AND CROWDSHIPPING SETTING

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Abstract: We consider the operational planning of a platform that integrates two concepts of the sharing economy, namely item-sharing and crowdshipping. In item-sharing, members of a community can temporarily rent items from one another (peer-to-peer). Crowdshipping is an innovative means of transportation where private drivers execute delivery jobs along their intended trips. It has been shown by Behrend and Meisel (2018) that this integration leads to a number of assignment problems, whose optimal solution allows to increase a platform's profit and the level of service provided to item-sharing consumers. However, this result has only been evaluated for scenarios with homogeneous items so far. Since item-sharing platforms usually serve as a market place for a wide range of products we investigate here how this finding is effected when heterogeneous items are considered. Our results show that integrating crowdshipping with item-sharing becomes even more relevant in a setting with heterogeneous items.

Keywords: Sharing economy, Item-sharing, Crowdshipping

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AUTHORS' CONTRIBUTION STATEMENT

The contribution of each individual author to the essays in the Chapters 2, 3, and 4 is differentiated with respect to the widely used Contributor Roles Taxonomy *CRediT*. See https://casrai.org/credit/ for an explanation of the categories. The ranking indicates a relative contribution with ① being the highest.

The breakdown of each authors' contributions to the first essay '*The integration of item-sharing and crowdshipping: Can collaborative consumption be pushed by delivering through the crowd?*' is as follows:

Category	M. Behrend	F. Meisel
Conceptualization	①	①
Methodology	①	②
Software & Validation	①	
Investigation	①	②
Writing - Original Draft	①	
Writing - Review Editing	①	②
Visualization	①	

31.03.2020 .... 31.03.2020 ....

Date Date

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Moritz Behrend Frank Meisel

The breakdown of each authors' contributions to the second essay '*An exact solution method for the capacitated item-sharing and crowdshipping problem*' is as follows:

Category	M. Behrend	F. Meisel	K. Fagerholt	H. Andersson
Conceptualization	①	②	③	③
Methodology	①	②	②	②
Software & Validation	①			
Investigation	①	②	③	
Writing - Original Draft	①	②		
Writing - Review Editing	①	②	③	③
Visualization	①			

31.03.2020	31.03.2020	31.03.2020	31.03.2020
Date	Date	Date	Date
Moritz Behrend	Frank Meisel	Kjetil Fagerholt	Henrik Andersson

The breakdown of each authors' contributions to the third essay '*A multi-period analysis of the integrated item-sharing and crowdshipping problem*' is as follows:

Category	M. Behrend	F. Meisel	K. Fagerholt	H. Andersson
Conceptualization	①	②	②	②
Methodology	①	②	③	③
Software & Validation	①			
Investigation	①	②	③	
Writing - Original Draft	①	②		
Writing - Review Editing	①	②	③	③
Visualization	①			

31.03.2020	31.03.2020	31.03.2020	31.03.2020
Date	Date	Date	Date
Moritz Behrend	Frank Meisel	Kjetil Fagerholt	Henrik Andersson

ERKLÄRUNG ZUM SELBSTÄNDIGEN VERFASSEN DER ARBEIT

Ich erkläre hiermit, dass ich meine Doktorarbeit „Operations Management in the Sharing Economy: Essays on the Integrated Perspective of Item-sharing and Crowdshipping“ selbstständig und ohne fremde Hilfe angefertigt habe und dass ich als Koautor maßgeblich zu den weiteren Fachartikeln beigetragen habe. Alle von anderen Autoren wörtlich übernommenen Stellen, wie auch die sich an die Gedanken anderer Autoren eng anlehnenden Ausführungen der aufgeführten Beiträge wurden besonders gekennzeichnet und die Quellen nach den mir angegebenen Richtlinien zitiert.

Kiel, 08.12.2020	
Ort, Datum	Unterschrift Moritz Behrend