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ORIGINAL PAPER

On the benefit of combining car rental and car sharing

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Abstract

Car rental and car sharing are two established mobility concepts which traditionally have been offered by specialized providers. Presumably to increase utilization and profitability, most recently, car rental providers began to offer car sharing in addition, and vice versa. To assess and quantify benefits and drawbacks of combining both into a single mobility concept with one common fleet, we consider such combined systems on an aggregate level, replicating demand patterns and rentals throughout a typical week. Our systematic approach reflects that, depending on a provider's status quo, different business practices exist, for example with regard to the applied revenue management approaches. Methodologically, our analyses base on mathematical optimization. We propose several models that consider the different business practices and degrees to which the respective new mobility concept is offered. To support mobility providers in their strategic decision-making, we derive managerial insights based on numerical studies that use real-life data.

Keywords Shared mobility · Car rental · Car sharing · Availability control · Pricing · Optimization

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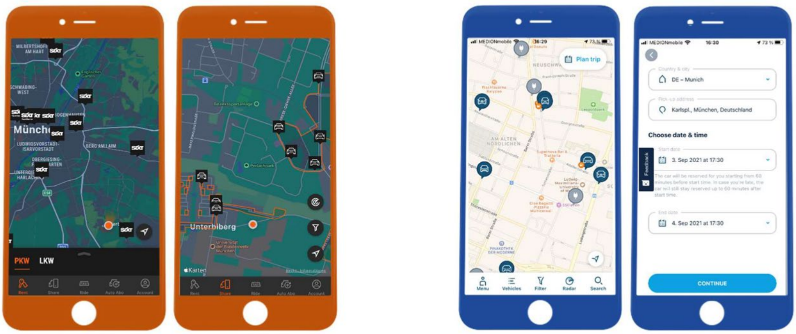
1 Introduction

Car rental and car sharing are two well-established mobility concepts that allow users to rent a vehicle for a limited period of time. Historically, one of the biggest differences between traditional car rental (CR) and traditional free-floating car sharing (CS) that we focus on in this work concerns the duration of the rentals. While CR rentals typically last between 1 and 7 days, rentals in traditional free-floating CS only last several minutes. As part of the two mega trends *urbanization* and *sharing economies*, both concepts are considered to play a decisive role in future sustainable urban mobility (Shaheen et al. 2019; Oliver Wyman Forum 2022), because they allow individual motorized mobility without requiring users to own a vehicle.

While CR and CS have traditionally been offered by different providers, this clear distinction has blurred in recent years. On the one hand, traditional CR providers like Sixt—one of the world's largest CR providers (Euromonitor International 2023)—have begun to additionally offer short-term rentals that resemble traditional CS on a service called "Sixt Share" (Fig. 1a). On the other hand, traditional CS providers like Share Now—Europe's largest CS provider (Statista 2023)—have begun to additionally offer long-term rentals with prior reservation and vehicle delivery, which resemble traditional CR (Fig. 1b). In this work, we consider such recent phenomena in the urban mobility landscape by which CR and CS are offered simultaneously with *one common* vehicle fleet. We term them *combined CR&CS systems*.

This development towards combined CR&CS systems appears economically reasonable, because both traditional CR and CS providers strive for higher utilization in their respective businesses that are characterized by high fixed costs (Guerriero



(a) Sixt's mobile application (Sixt, 2022) – Sixt traditionally offers CR with vehicle pick-up and drop-off at stations ("Rent", left). Since recently, also free-floating CS is offered, where pick-up and drop-off can happen at any location within the business area ("Share", right).

(b) Share Now's mobile application (Share Now, 2022) – Share Now traditionally offers free-floating CS, where pick-up and drop-off can happen at any location within the business area (left). Since recently, also CR-type products are offered, where customers can specify pick-up location and rental time (right).

Fig. 1 Mobile applications of established traditional car rental (CR) and car sharing providers (CS), demonstrating the blurring delimitation between pure CR and pure CS systems towards *combined CR&CS systems* and Olivito 2011; Golalikhani et al. 2021). However, a potential business success of a combined CR&CS system depends on its specific implementation. For example, consider a traditional CR provider that begins to offer CS in addition. Despite the overall increased demand, the fleet might be used less profitably, because one single short-term rental might prevent a more profitable long-term rental from realizing.

Thus, it is key to enable efficient usage of the shared resource and there are several influencing factors that need to be considered. First, CR and CS products have different revenues per time. Second, they differ strongly regarding their demand patterns. Third, traditional CR and CS providers make use of different revenue management instruments to control their respective sales processes to maximize profit. CR providers typically perform availability control, i.e., they decide which products —characterized, e.g., by a certain vehicle type, rental duration, and price— to make available for the users (e.g. Guerriero and Olivito 2011), *as well as* perform pricing. CS providers typically *solely* perform pricing for the spontaneously occurring demand (e.g. Jorge et al. 2015)), but do not perform availability control. The reason is that demand in modern free-floating CS systems is spontaneous, meaning that customers look for a vehicle when they need it and do not send requests in advance.

There is a vast literature on traditional CR systems as well as traditional CS systems, also in the context of revenue management as summarized, e.g., in the survey papers by Oliveira et al. (2017) and Golalikhani et al. (2021), respectively. However, combined CR&CS systems have not been addressed yet. Considering their growing existence in practice, there is a relevant research gap with the guiding overall research question:

"*What are benefits and drawbacks of combining car rental and car sharing?*"

To answer this general research question, various approaches seem appropriate. In this work, we consider the question as a strategic one. Our goal is to derive managerial insights which support high-level decision-making at traditional CR and CS providers. That is, we want to support decision making regarding the fundamental questions whether the respective other mobility concept should extend the product portfolio to serve an additional market. As a consequence, we model combined CR&CS systems on an aggregate level. That is, we consider the dependencies between the different aggregate demand patterns, the common resource of vehicles in the fleet, and the resulting rentals as well as profits throughout different periods of a typical week. However, we do not consider individual customers and vehicles.

Methodologically, we make use of mathematical optimization and we formulate several models that replicate different variants of combined CR&CS systems. These variants reflect the extent to which a traditional CR or CS system transitions towards a combined one. For example, one variant replicates a CR provider which additionally offers CS only at times when capacity is unused, thus, giving priority to the traditional CR products. The idea is that CR and CS providers presumably modify their business gradually instead of switching to a fully combined system immediately. The variants also consider the different revenue management instruments in place. Furthermore, we vary the demand level of the respective new mobility offer, reflecting that its demand presumably increases gradually when introduced.

This work contributes to the literature on CR, CS, and shared mobility in general in four fundamental ways:

- The recent practice of establishing combined CR&CS systems is identified and formally described as such for the first time in the scientific literature. We describe multiple system variants that cover the range between traditional systems and a fully combined one, also considering the different business practices of traditional CR and CS providers.
- We propose mathematical models that replicate these variants and that model the respective mobility system on an aggregate level.
- In a systematic approach, we perform extensive numerical studies for these mobility system variants based on real-life data.
- Based on these results, we derive several managerial insights that answer the question regarding the benefits and drawbacks of combined CR&CS systems. More specifically, they, e.g., allow CR and CS providers to make informed decisions regarding expected revenue increases and service level decreases when introducing the respective new mobility offer.

The remainder of the paper is organized as follows. In Sect. 2, we review the relevant related literature, followed by the description of this work's scope and the taken assumptions in Sect. 3. Section 4 describes our methodological approach. In Sect. 5, we formally state the considered problems and present their mathematical optimization models, followed by Sect. 6 which contains the numerical studies as well as the managerial insights. The paper finishes with a conclusion and outlook on future work in Sect. 7.

2 Related literature

As described in the introduction, combined CR&CS systems have not been addressed in the scientific literature yet. However, the two mobility concepts which they are based upon (CR and CS) have indeed been discussed broadly in two separate literature streams. We review these two streams in Sects. 2.1 and 2.2, respectively, focusing in particular on revenue management approaches, i.e., availability control and pricing. In Sect. 2.3, we summarize the state-of-the-art with regard to the transition towards combined CR&CS systems, i.e., works that consider changes in business operations of the traditional mobility concepts that start to indicate the recent trend of mutual integration, even though not explicitly considering combined systems.

2.1 Car rental

CR is a well-established mobility concept that allows customers to rent a vehicle for one or multiple days. From a business point of view, the provision of the vehicle fleet accounts for a high proportion of the total costs. The perishability of the inventory—i.e., if a vehicle is not rented on a given day, that rental day cannot be sold in the future—drives the need to manage supply and demand effectively. Therefore, CR is a prototypical application area for fleet management (Pachon et al. 2006) as well as for revenue management techniques (van Ryzin and Talluri 2005). The CR business has some interesting characteristics that distinguish it from other applications of fleet and revenue management—especially regarding flexibility in supply and demand. Regarding supply, in contrast to standard revenue management applications, capacity (i.e., the fleet) in CR is highly flexible. This is because it can be rapidly increased either by "short-term" leasing of vehicles, quickly acquiring new vehicles for the fleet through previous contracts with manufacturers, or by relocation. Regarding demand, CR is also very flexible because of the ability to dynamically change prices or to offer upgrades to manage fleet availability (i.e., offering a higher-valued vehicle than the one requested for the same value) (Oliveira et al. 2017). Additionally, CR providers allow for customers to book their rentals in advance (from some months to a few hours), besides last-minute walk-in reservations. All this flexibility allows for availability control techniques to be applied, i.e., to decide how many vehicles the provider should make available for the users or, alternatively, which rentals the provider would prefer to take (Guerriero and Olivito 2011). For a thorough review of the CR business's different characteristics and the problems tackled for fleet management and revenue management, we refer to Oliveira et al. (2017).

The key decisions a CR provider faces are framed and structured in Pachon et al. (2006) and Oliveira et al. (2017), from strategic challenges to tactical and operational problems. With regard to fleet management, the two most essential strategic problems are *pool segmentation* (clustering different stations that share the same fleet in "pools") as well as *fleet size and mix* (defining how many vehicles of which vehicle type of a heterogeneous fleet to use in each pool). It should be noted that, in this business, all rentals start and end at specific locations (or stations), even though not necessarily at the same one. Thus, at a tactical level, the pool fleet must be distributed over the interconnected stations (*fleet deployment* problem). The optimal deployment can change, e.g., daily, leading to *relocation*, which is one of the most studied operational problems in CR (i.e., deciding which vehicles to move and how they should be repositioned among the stations). Often in the literature and in practice, these levels of decision-making overlap due to the inherent flexibility of this business. For example, in You and Hsieh (2014), fleet sizing is integrated with fleet relocation. Methodologically, mathematical programming models have often been used to frame and tackle these problems at different levels, such as in Pachon et al. (2006).

Alongside fleet management, revenue management plays a relevant role in CR, with availability control and pricing as essential instruments to control the sales process. As a real-world example, the OptiCar System was implemented by Europcar as a decision-support system for advanced revenue management and optimization (Guillen et al. 2019). In fact, within a revenue management framework, CR operations can be seen as a network revenue management problem with flexible capacities (Haensel et al. 2012). The possibility of offering upgrades as a tool to manage capacity and demand has also been extensively studied (Fink and Reiners 2006; Steinhardt and Gönsch 2012; Klein et al. 2020). Additionally, integrating revenue management problems with fleet-related challenges has been prevalent in this body of research. For example, the integration of pricing and relocation decisions has been proposed in Madden and Russell (2012) and extended to include overall capacity decisions (fleet size, mix and deployment) as well as availability control and pricing (Oliveira et al. 2018), resorting to mathematical-programming-based approaches.

Overall, providers strive for increasing fleet utilization, since residual capacity (not rented in a given period) represents a high cost for CR operators (Guerriero and Olivito 2011). This is commonly achieved through fleet size optimization (e.g. Pachon et al. 2006) yet is also an important result of pricing or capacity optimization modules (Guillen et al. 2019).

2.2 Car sharing

In a traditional free-floating CS system, users can access short-term car rentals without needing to book in advance. This gives them similar flexibility to a privately owned vehicle, but without having to carry the vehicle ownership costs, such as maintenance costs or insurance (Shaheen et al. 1998).

CS systems may take different structures. We will focus on business-to-consumer CS, where a provider centrally manages a fleet and makes it available to the users. It can be further divided into different service types, most notably round-trip systems (i.e., a vehicle is picked up and dropped off at the same location) or one-way systems (i.e., pick-up and drop-off may occur at different locations). Moreover, they can be defined as station-based (i.e., pick-up and drop-off occur at predefined locations) or free-floating systems (i.e., pick-up and drop-off can occur anywhere within the business area) (Shaheen et al. 2019).

Besides the comfort and flexibility provided to the individual user, some environmental and societal benefits are attributed to CS. These include reduced congestion and parking shortages in cities, reduction of private vehicle ownership, increased attractiveness of public transport and reduced emissions (Ferrero et al. 2018). Many of the environmental benefits listed are related to CS electric vehicle fleets (Liao et al. 2017; Liao and Correia 2022). The valuable environmental effects of CS are also supported by several empirical studies (Becker et al. 2017; Rotaris et al. 2019; Jochem et al. 2020). Nevertheless, the availability of a CS system alone was found to have little effect on vehicle ownership decisions (Zhou et al. 2020).

As in the CR business, the main types of decisions in CS are also related to fleet and revenue management. As before, *fleet sizing* is a critical problem for CS as well as, especially when considering electric-vehicle fleet charging, defining the *location of the stations* (for station-based systems) (Boyaci et al. 2015). Also, *relocation* is studied as a mechanism to balance fleet and match supply and demand (Illgen and Höck 2019).

In CS, pricing is very relevant due to its potential to influence and manage demand, especially since there are no availability control mechanisms in typical free-floating CS systems, as discussed in Sect. 1. CS providers need to decide on pricing on a strategic level (i.e., the pricing plans offered to attract potential users) as well as on a more tactical/operational level (Golalikhani et al. 2021). Most research is focused on the latter, especially considering dynamic pricing.

A share of this body of research tackles pricing as dependent on a rentals' origin and destination (often called trip pricing) with results that point to higher profit and service level (Jorge et al. 2015; Weikl and Bogenberger 2013). Since the provider often does not know the destination of the trip beforehand, an alternative pricing mechanism proposed is to apply rewards or penalty payments depending on the drop-off location. Huang et al. (2020) tested such pricing for a one-way station-based electric vehicle car sharing, demonstrating profit and service increases. Yet another pricing variant, which could be more suitable for free-floating CS where providers typically do not know a rental's destination at the start of the trip, is called origin-based pricing (Soppert et al. 2022), where the (minute) price which is valid for a particular rental only depends on the rental's spatio-temporal origin, i.e., where and when the rental began. The authors also report increases in profit compared to undifferentiated prices on real-world data. Methodologically, mathematical optimization is often applied to address specific operational or tactical problems in CS (e.g., Boyaci et al. 2015; Jorge et al. 2015; Huang et al. 2020).

When reviewing current practices from CS operators, Golalikhani et al. (2021) highlight that combining CS services with different features (such as different requirements and flexibility for drop-off) is an emerging trend. Even though this challenge has not yet been tackled in the literature, it likely originates from a need to address users' different mobility needs and extend the operators' reach and fleet utilization.

2.3 Towards combined car rental and car sharing

To the best of our knowledge, no work in the literature has yet dealt with the combined operation of a CR and CS system. Nevertheless, the literature allows inferring that, even though CR and CS operations have particular differences in their day-to-day operations and the challenges tackled, they still have a common goal to provide mobility to their customers and use the same resources—a fleet of vehicles.

Some recent works are starting to look at specific changes in the traditional way of operating the business of CR and CS. For example, some studies examine the possibility of offering advance reservations in previously "pure" CS systems (instead of only spontaneous access). This is already a change in the mobility concept offered, closer towards CR, introducing the need to manage availability. In this context, Wu et al. (2022) propose a choice-based framework for modeling the supply/demand interaction in free-floating CS, in a dynamic pricing problem. They evaluate strategies for allowing (at an agreed price) customers to make guaranteed advance reservations. Similarly, Molnar and Correia, (2019) tackle a CS system offering reservations (short- and long-term), considering profit, user satisfaction and demand. In Soppert et al. (2022b), a CS provider's operational problem of controlling the availability of short-term rentals in order to guarantee the provision of vehicles for long-term rental reservations is considered.

Lin et al. (2021) study a different problem, yet it also helps demonstrate the transition to other businesses of CR providers. They study the current practice in CR of renting their vehicles to ride-sharing platforms so that drivers that do not own a vehicle can provide such services and increase the platform's capacity. They analyze the customer and driver surplus of this collaboration and the situations where it is a win-win-win situation (for the platform, customers and drivers).

In practice, as described in Sect. 1, combined CR&CS systems are already being implemented by CR and CS providers. Nevertheless, the literature is yet to explore what effects this has on the provider and users, as well as to provide adequate decision-support tools for the inherent challenges.

3 Scope and assumptions

In this section, we specify the scope of our work as well as the taken assumptions. That is, we explain our strategic-level view on the mobility systems in Sect. 3.1. We further describe the considered mobility concepts of traditional CR and CS providers, including their business models as well as our assumptions in Sect. 3.2.

3.1 Strategic-level scope

We consider the mobility systems on a strategic level, in contrast to an operational level. The approach we chose is to analyze overall supply–demand interaction and effects on metrics such as rentals, profit and utilization in an aggregate manner. Since the goal is to analyze the overall performance of the system, this approach allows considering aggregate data, without the need for considering individual customers, vehicles, and rentals. The required aggregate data is typically easier to obtain for companies compared to disaggregate data like individual user preferences, but it shall be noted that an accurately parameterized disaggregate model would allow to derive the desired strategic-level insights as well—plus more detailed operational insights. The high-level view that we take is reflected in the modeling of the systems (Sect. 5) in that we consider temporal variations across a typical week in 30-min periods, but we do not consider different locations within the system, as typically done in works on operational optimization (e.g. Soppert et al. 2022). This aggregate modeling proposed here allows to approximate the systems' overall behavior and it is suitable to consider the strategic-level scope on the research questions regarding benefits and drawbacks of combining CR and CS (Sect. 1).

3.2 Assumptions regarding traditional car rental and car sharing

The CR business practices we consider are in line with descriptions in You and Hsieh (2014) and Steinhardt and Gönsch (2012). That is, the provider possesses a fixed (homogeneous) fleet of vehicles which is rented to customers (private and business) on a daily basis. Customers can rent vehicles for 1 day or for several days. Internally, the provider defines different products (per vehicle category), which differ in their rental duration—e.g., the 1-day product and the 2–4 day products. The provider can perform a temporal price differentiation for each product and possesses a respective demand forecast. More specifically, for each product, there is a set of discrete price points from which the provider can choose and each price point corresponds to a respective demand forecast which varies throughout the week. Besides pricing, the provider can make certain products unavailable (availability/capacity control), which can be thought of as rejecting incoming requests for rentals. We assume that the costs for acquiring and maintaining the fleet are fixed. The provider's objective is to maximize profit through price and availability control. Building on standard objective functions in the literature, we mainly consider revenue maximization. In addition, we analyze the impact of product-dependent variable costs.

The CS business practice we consider consists of managing a free-floating car sharing system, as described, e.g., in Müller et al. (2023). The provider possesses a fixed fleet of homogeneous vehicles which customers can rent on a per-minute basis. From the provider's perspective, all rentals are spontaneous, meaning that there are no reservations of rentals in advance, which implies that there is no need for managing future vehicle availability. The pick-up and drop-off of vehicles can happen at any location within the system's business area. Rentals are short-term rentals that mostly last for up to half an hour and a rental's fee is determined by the rental duration multiplied with the minute price. The CS provider can vary the minute price, but has to choose from a discrete price set. We assume that the respective demand that realizes for a certain price at a certain time can be predicted. In contrast to the CR provider, the CS provider cannot perform availability control. That is, if vehicles are available to serve the demand which is induced at a chosen price, the rental realizes. This is because demand in free-floating is spontaneous and there are no rental requests. The CS strives for maximizing profit through pricing optimization.

4 Methodological approach

This section presents the methodological approach of this work, starting with an overview in Sect. 4.1. Sections. 4.2 and 4.3 focus on the two business practices that we consider for combined CR&CS systems within the approach, i.e., the CR and the CS business practices, respectively.

4.1 Overview

The developed methodological approach, depicted in Fig. 2, is a structured procedure composed of multiple steps which span from the *research question* (see Sect. 1) to the *managerial insights* and the *conclusion*. To derive the insights, we consider two *business practices* that can be applied for a combined CR&CS system—the business practices of a CR provider and of a CS provider. The rationale behind these two business practices is that traditional CR and CS providers have specific circumstances in which they operate and, thus, they have practices in place which differ fundamentally, especially concerning the revenue management instruments applied (see Sect. 1). Furthermore, for each business practice, there are multiple *degrees of combination* that span from a traditional CR or CS system to a combined CR&CS system. The idea of these degrees is that

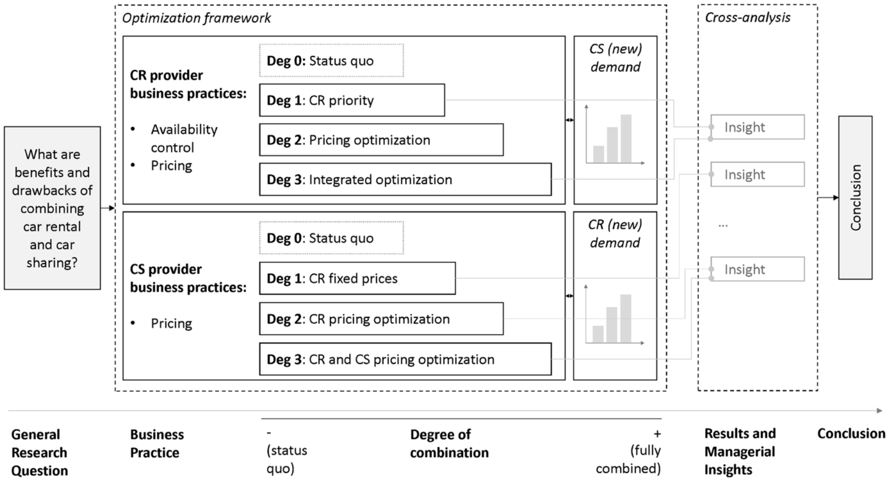


Fig. 2 Schematic representation of methodological approach. The general research question is addressed by considering the two business perspectives of a CR and a CS provider. Different degrees of combination replicate a gradual transition towards a combined CR and CS system. Depending on the perspective, availability control and/or pricing is applied. The managerial insights and conclusions are based on numerical studies that also consider variants of demand levels

traditional CR and CS providers presumably transition gradually towards a combined system, instead of changing all business practices immediately. Detailed descriptions of these degrees are given in Sects. 4.2 and 4.3. These business practices and degrees are embedded into an *optimization framework*, meaning that each pair of practice and degree is formulated as a (variant of a) mathematical optimization problem. We run comprehensive numerical studies and provide the full results, describing the optimal decisions and the resulting relevant metrics like revenue, rentals, utilization, and service level. Due to the large extent of numerical results, we structure the outcomes according to relevant questions, allowing us to cross-analyze results. From this, we derive corresponding *managerial insights*. Finally, all findings are jointly considered to state our *conclusion* to the research question.

Besides the degrees, we also vary the *demand level* for each of the two practices. The idea is that we can thereby represent the effect that a CR provider gradually acquires customers for the newly introduced CS offer and vice versa. Finally, note that depending on the practice, the terms *legacy* and *new*, e.g., in the context of demand or products, either refer to CR or CS.

4.2 Car rental

The different degrees of combination in the CR practice, from maintaining the status quo (Degree 0) to integrated optimization (Degree 3), are summarized in Table 1 and described in the following. Note that Table 1 also includes the reference of each degree to the optimization framework proposed in Sect. 5, which will be further detailed later in that section.

- **Degree 0—Status quo**: This baseline refers to a traditional CR's status quo setting, in which no CS mobility concept is offered and, thus, there is no relevant CS demand. Since the CR provider receives customer requests for future rentals, they perform availability control on top of the temporal price differentiation that allows to price a certain product differently throughout the week. For a more technical discussion as well as references to standard models from revenue management literature, we refer to Sect. 5.2.
- **Degree 1—CR priority**: The first extension of a traditional CR system towards a combined CR&CS system is one in which the fleet may also serve the CS demand, but only if all CR demand (resulting from the set prices) is satisfied. That is, priority is given to the realizing CR demand (after pricing) through availability control. Further, regarding pricing, CR prices are kept identical those resulting from the optimization in the status quo (Degree 0), and CS prices are set (without any optimization) to a baseline price that represents the median price of the discrete set of admissible prices (see Sect. 5). The idea is that by giving priority and fixing prices, the existing CR customers do not experience any drawbacks because of the newly introduced CS offer.
- **Degree 2—Pricing optimization**: CR still has priority in this further extension, but prices for CR and CS are now both optimized in an integrated manner. More specifically, CR prices may differ through the optimization compared to the status quo (and Degree 1). The CR demand realizing at these optimized prices has priority over the CS demand realizing at the optimized prices.
- **Degree 3—Integrated optimization**: In the fully combined CR&CS system of the CR business practice, no offer has priority, and there is full availability control and pricing optimization. This results in a comprehensive and integrated optimization of both offers. Here, it might happen, e.g., that CR customers perceive high service reduction because a large share of the fleet is assigned to CS customers.

4.3 Car sharing

The status quo and the different degrees of the CS practice are summarized in Table 2 and described in the following:

- **Degree 0—Status quo**: The baseline case denotes the status quo setting of a traditional CS provider in which no CR concept is offered and, thus, there is no CR demand. In contrast to the traditional CR provider, there is no availability control in place, so demand is managed solely through temporal price differentiation throughout the week.

Table 1 Degrees of combination (status quo and three combined systems) for CR business practice

Degrees in CR practice		Model assumptions and features: New demand	Priority	Prices legacy products	Prices new products	Mathematical model[1]
0	Status quo	Ø	–	Optimized	–	(1)–(4)
1	CR priority	Levels low-high	CR	Fixed to Degree 0 prices	Fixed to *base* prices	(1)–(6) fixed $\boldsymbol{x}$ ($i \in \mathcal{I}$)
2	Pricing optimization	Levels low-high	CR	Optimized	Optimized	(1)–(6)
3	Integrated optimization	Levels low-high	None	Optimized	Optimized	(1)–(4)

[1] Refers to the optimization framework presented in Sect. 5

Table 2 Degrees of combination (status quo and three combined systems) for CS business practice

Degrees in CS practice		Model assumptions and features				
		New demand	Priority	Prices legacy products	Prices new products	Mathematical model[1]
0	Status quo	Ø	–	Optimized	–	(7)–(15)
1	CR fixed prices	Levels low-high	None	Fixed to Degree 0 prices	Fixed to a baseline	(7)–(15) fixed $\boldsymbol{x}$ ($i \in \mathcal{I}$)
2	CR pricing optimization	Levels low-high	None	Fixed to *base* prices	Optimized	(7)–(15) fixed $\boldsymbol{x}$ ($i \in \mathcal{I}^L$)
3	CR and CS pricing optimization	Levels low-high	None	Optimized	Optimized	(7)–(15)

[1] Refers to the optimization framework presented in Sect. 5

- **Degree 1—CR fixed prices**: In the first extension towards a combined CR&CS system, there is CR demand, and all prices are fixed. That is, CS prices remain as optimized in the status quo (Degree 0), and CR prices are fixed to a baseline price. The idea is that existing CS customers do not experience price changes when CR starts being offered. Note, however, that priority (as in the CR business practice) cannot be given because this would require availability control on top of the pricing. Additionally, it is important to note that, as we discuss in detail in Sect. 5.3, the specifics of the problem in terms of pricing prevent that the availability control can be replaced by pricing.
- **Degree 2—CR pricing optimization**: In the next extension, CS prices remain fixed to the status quo optimization, but CR prices are optimized. Note again that, due to the missing availability control, this may reduce the service level for CS customers compared to Degree 1. Generally speaking, CR pricing optimization also influences CR demand (see Sect. 5.3).
- **Degree 3—CR and CS pricing optimization**: Finally, in the last degree of combination of the CR&CS system in the CS business practice, prices for both CR and CS are optimized. Again, CS customers might experience differences compared to the previous degrees of combination.

Note that in the CS practice, an "integrated optimization" as Degree 3 in the CR practice is not feasible, because in free-floating CS which we consider, the provider has no possibility to perform availability control (see Sect. 3).

5 Problem statements and mathematical modeling

This section comprises the statements of the considered problems as well as the formulation and description of the optimization framework. More specifically, we begin with an overview on the the notation (Sect. 5.1) and then present two general optimization models, i.e., one for the CR business practice (Sect. 5.2) and one for the CS business practice (Sect. 5.2). Each model can be customized to match the requirements of the corresponding degrees of combination (see Sect. 4). These customizations are either implemented by an appropriate choice of constraints, parameters, or both.

In the problems addressed, we differentiate between *mobility offers*, *products*, and different *rental durations*. More specifically, mobility offer refers to the two mobility concepts: CR and CS. Each mobility offer may encompass one or more products which can be priced independently. For example, a 1-day rental CR product usually has a higher price per day than a 2–4 days rental product. Note that the same product (e.g., the 2–4-day rental product) can have different durations (here, 2, 3 or 4 days). Demand patterns vary for different durations.

Table 3 Notation

Indices and sets	
$i \in \mathcal{I}^L = \{1, \ldots, I^L\}$	Legacy products
$i \in \mathcal{I}^N = \{1, \ldots, I^N\}$	New products
$i \in \mathcal{I} = \mathcal{I}^L \cup \mathcal{I}^N$	Products
$j \in \mathcal{J}_i = \{1, \ldots, J_i\}$	Rental durations for product i (in periods)
$p \in \mathcal{P}_i = \{1, \ldots, P_i\}$	Price levels of product i
$t \in \mathcal{T} = \{1, \ldots, T\}$	Periods
$t' \in \mathcal{T}_{ijt} = \{\max\{t - L_{ij}, 0\}, \ldots, t\}$	Previous relevant ("affected") and current periods for product i with duration j starting at period t
Decision variables	
$a_t \in \mathbb{R}_0^+$	Available vehicles at beginning of period t
$q_t \in \{0, 1\}$	Auxiliary variable determining if demand exceeds capacity at beginning of period t
$r_{ijt}^p \in \mathbb{R}_0^+$	Realized rentals for product i with duration j at price level p starting at beginning of period t
$u_{it} \in \{0, 1\}$	Auxiliary variable determining if all demand for legacy products $i \in \mathcal{I}^L$ that "affect" period t is fulfilled
$x_{it}^p \in \{0, 1\}$	Price level set for product i in period t
Parameters	
C	Fleet size
D_{ijt}^p	Demand for product i with duration j starting at beginning of period t for price level p
F_i	Friction parameter
L_{ij}	Periods affected by realized rentals of product i with duration j
M	Sufficiently large number
P_i^p	Period-specific price for product i at price level p

5.1 Notation

The notation comprises *indices and sets*, *decision variables*, and *parameters*, which are summarized in Table 3.

- **Indices and sets**: Regarding the products $i \in \mathcal{I}$, we propose a notation which applies to both business practices through using the terms *legacy* products $i \in \mathcal{I}^L$ and *new* products $i \in \mathcal{I}^N$. For example, in the CR practice, the CR products are legacy products, while CS products are the new ones, and vice versa. A particular product i may have different rental durations $j \in \mathcal{J}_i$ as well as different discrete price levels $p \in \mathcal{P}_i$ at which it can be offered. Limiting the pricing optimization to the prices within the discrete set of price points replicates the policies observed in practice. One reason for this procedure is that a price optimization over a continuous set of prices might be perceived as arbitrary by the customers.

The considered time frame (multiple weeks) is discretized into disjunct periods $t \in \mathcal{T}$. To keep track of the available vehicles a_t at the beginning of a certain period t (see below), we use $t' \in \mathcal{T}_{ijt}$ to denote the relevant periods, meaning previous periods in which rentals of product i with duration j started.

- **Decision variables**: The available vehicles at the beginning of period t are denoted as a_t and realizing rentals of product i, duration j, and price p, starting at the beginning of period t are denoted as r^p_{ijt}. Both are continuous decision variables that serve to model the expected (average) system, as typical in deterministic (certainty equivalent) formulations in revenue management (van Ryzin and Talluri 2005). As explained in more detail below, r^p_{ijt} being decision variables does not mean that the provider can freely choose their values—especially in the CS business practice where there is no availability control. For the CR practice, on the contrary, as availability control is performed, the realized rentals derive also from that instrument. As for the pricing decisions for price level p of product i in period t, they are modeled with the binary variable x^p_{it}. Note that the provider can solely differentiate prices across products i, but not across durations j within one product. Finally, there are two auxiliary binary variables: q_t for recording if (total) demand exceeds supply and u_{it} for recording if all demand of legacy product $i \in \mathcal{I}^L$ is fulfilled in period t. Additionally, we introduce the bold format for decision variables to represent them more compactly in the models (i.e., $\boldsymbol{x}$ corresponds to the set of all x^p_{it} $\forall i \in \mathcal{I}, t \in \mathcal{T}, p \in \mathcal{P}$).
- **Demand function and parameters**: The demand-price relation is assumed to be known and is modeled by an aggregate (deterministic) demand function (Talluri and van Ryzin 2004, Chapter 7.3). More specifically, we assume a function which returns a (product i-, duration j-, and period t-specific) demand level D^p_{ijt} for each of the admissible discrete price points $p \in \mathcal{P}_i$. With sufficiently many prices and corresponding demand levels, any nonlinear relation can be modeled arbitrarily precisely.
- **Remaining parameters**: We denote the fleet size as C and the specific rental duration of product i with duration index j as L_{ij}. F_i denotes a friction parameter which allows modeling that there never is a perfect match between supply and demand in CS, primarily because of the customers' limited willingness to walk (Niels and Bogenberger 2017). Finally, M is a sufficiently large number used to disable certain constraints.

5.2 Car rental

The optimization model for the CR business practice is formulated by (1)–(6). Not all constraints are required for every degree of combination, as presented in Table 1 and as discussed below in this section.

The objective (1) maximizes the revenue generated by the realizing rentals, considering the different prices and rental durations. This objective function can be straightforwardly changed if product-dependent variable costs are considered.

In Appendix E.1 (in the Supplementary Material), we present an alternative model that maximizes the contribution margin. This supports a discussion on the applicability of the current (revenue-maximizing) model, further detailed in Sect. 6.2.2. Constraints (2) ensure that exactly one price is set for every product and (starting) period. Constraints (3) serve two purposes. On the one hand, they ensure that rentals of a particular product at a specific price can only realize when the corresponding price is actually set. On the other hand, if a price is set, the corresponding rentals are limited by the demand, also considering friction. In constraints (4), the supply restriction through the limited fleet is considered for each period. Note that the left-hand side considers all relevant rentals, i.e., also rentals that started before the current period and are still ongoing. Finally, constraints (5) and (6) work in conjunction to model the priority for the legacy products. In (6), for a specific *legacy* product and period, the auxiliary variable that controls whether all legacy demand is fulfilled takes value one if any rentals of *new* product are realized. Through (5), this realization of rentals of the *new* product, however, is only permitted if demand for all *legacy* products is fulfilled.

$$\max_{\boldsymbol{a},\boldsymbol{q},\boldsymbol{r},\boldsymbol{u},\boldsymbol{x}} \quad \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}} r_{ijt}^p \cdot P_i^p \cdot L_{ij} \tag{1}$$

s.t.

$$\sum_{p\in\mathcal{P}} x_{it}^p = 1 \quad \forall i\in\mathcal{I}, t\in\mathcal{T} \tag{2}$$

$$r_{ijt}^p \le D_{ijt}^p \cdot F_i \cdot x_{it}^p \quad \forall i\in\mathcal{I}, j\in\mathcal{J}_i, t\in\mathcal{T}, p\in\mathcal{P} \tag{3}$$

$$\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{t_i'\in\mathcal{T}_{ijt}}\sum_{p\in\mathcal{P}} r_{ijt_i'}^p \le C \quad \forall t\in\mathcal{T} \tag{4}$$

$$\sum_{j\in\mathcal{J}_i}\sum_{t_i'\in\mathcal{T}_{ijt}}\sum_{p\in\mathcal{P}} r_{ijt_i'}^p \ge \sum_{j\in\mathcal{J}_i}\sum_{t_i'\in\mathcal{T}_{ijt}}\sum_{p\in\mathcal{P}} \left(D_{ijt_i'}^p \cdot F_i \cdot x_{it_i'}^p\right) - (1-u_{it})\cdot M \quad \forall i\in\mathcal{I}^L, t\in\mathcal{T} \tag{5}$$

$$\sum_{i'\in\mathcal{I}^N}\sum_{j\in\mathcal{J}_{i'}}\sum_{p\in\mathcal{P}} r_{i'jt}^p \le u_{it}\cdot M \quad \forall i\in\mathcal{I}^L, \forall t\in\mathcal{T} \tag{6}$$

We now specify the required constraints of (2)–(6) for each degree and refer to Table 1 for an overview.

- **Status quo:** For the status quo case (Degree 0), constraints (5)–(6) can be dropped, because there are no CS (new) products. In this case, prices and availability are optimized for the CR (legacy) products.
- **Degree 1:** Degree 1 makes use of all constraints (2)–(6) since priority is given to the CR products. Appropriate parameter settings ensure that the prices are fixed to those optimized in the status quo. More specifically, there is only one price

level for each product, and those of the CR products are set to the solution of Degree 0, whereas those of the CS products are set to some baseline price level (see Sect. 6).

- **Degree 2:** Degree 2 also uses all constraints, but now allows for price optimization of the CS products by having multiple price levels for these products.
- **Degree 3:** In Degree 3, constraints (5)–(6) are dropped since we do not enforce priority for the CR product. Thus, availability control can allocate the fleet across all products.

Technically speaking, (1)–(6) is a deterministic mixed-integer linear program. From a revenue management business practice, it is a *network* problem (Talluri and van Ryzin 2004, Chapter 3) in contrast to a *single-resource* problem (Talluri and van Ryzin 2004, Chapter 2). Note that, even for instances with only one product, this network-characteristic persists, because of the rentals' different potential start periods (and durations which span multiple periods). For the special case of only one price point (constraints (2) unnecessary), and without enforcing priority (constraints (5) and (6) unnecessary), the problem can be considered as the well-known *deterministic linear program* for availability control (Talluri and van Ryzin 2004, Chapter 3.3.1). A particularity of the model compared to standard models from the revenue management literature concerns the interaction of pricing and availability control. In the model at hand, the price of a specific product i affects the demand D^p_{ijt} of *multiple* rental durations j (see $\forall j \in \mathcal{J}_i$ in (3)). Availability control, in contrast, can be performed for each rental duration j individually (decision variable r^p_{ijt}). Thus, the availability control can be considered as the more flexible "lower level" control which complements the more rigid "upper level" pricing control. In this context, it is worth noticing that even with continuous and unbounded prices, the additional flexibility in control which the availability control in (1)–(6) provides, can in general not be replaced entirely by a pricing-only control. Only in the specific case where all products have exactly one duration ($|\mathcal{J}_i| = 1 \; \forall i \in \mathcal{I}$), there is no need for an additional availability control, because demand can be scaled arbitrarily by the unbounded prices.

5.3 Car sharing

The optimization model for the CS business practice is formulated by (7)–(15).

The objective (7), as above, maximizes the revenue generated by the realizing rentals, considering the different prices and rental durations. As for the CR model above, the model's adaptation to consider variable costs is straightforward. Constraints (8) ensure consistent pricing, and constraints (9) and (10) ensure the correct realization of rentals considering pricing, demand, friction, and the fleet size. Constraints (11)–(15) serve different purposes compared to the model of the CR business practice, and they work together. Constraints (11) determine the available vehicles for each period. One could drop these constraints by replacing a_t in constraints (12) and (13)—at the cost of clarity. Constraints (12) and (13) ensure that the auxiliary variable q_t takes the value of 1 if and only if demand exceeds supply in the corresponding period. Using this q_t, constraints (14) ensure that rentals for every product, duration, time, and price level realize if there is sufficient supply to fulfill the demand. Further, constraints (15) ensure that rentals for the different products and durations realize in proportion to the demand at the set prices. Note that both these latter two constraints ((14) and (15)) are required to model that the CS provider does not possess the ability to perform availability control—all rental realizations are solely a result of the pricing as well as the available supply. In other words, without these constraints, the model had several degrees of freedom to allocate the fleet most beneficially. For example, a particular product might be favored in case of insufficient supply, or rentals could be prevented to guarantee availability for later, more beneficial ones. In the literature, this idea was denoted as *pure pricing* (no other control means besides pricing) and *proportional demand fulfillment* (product-specific rentals realize in proportion to their demand distribution), within a price optimization problem in which the CS system was modeled on a more disaggregate level compared to this work (Soppert et al. 2022).

$$\max_{\boldsymbol{a},\boldsymbol{q},\boldsymbol{r},\boldsymbol{u},\boldsymbol{x}} \quad \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{t\in\mathcal{T}}\sum_{p\in\mathcal{P}} r_{ijt}^p \cdot P_i^p \cdot L_{ij} \tag{7}$$

s.t.

$$\sum_{p\in\mathcal{P}} x_{it}^p = 1 \quad \forall i\in\mathcal{I}, t\in\mathcal{T} \tag{8}$$

$$r_{ijt}^p \leq D_{ijt}^p \cdot F_i \cdot x_{it}^p \quad \forall i\in\mathcal{I}, j\in\mathcal{J}_i, t\in\mathcal{T}, p\in\mathcal{P} \tag{9}$$

$$\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{t_i'\in\mathcal{T}_{ijt}}\sum_{p\in\mathcal{P}} r_{ijt_i'}^p \leq C \quad \forall t\in\mathcal{T} \tag{10}$$

$$a_t = C - \sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{t_i'\in\mathcal{T}_{it}}\sum_{p\in\mathcal{P}} r_{ijt_i'}^p \quad \forall t\in\mathcal{T} \tag{11}$$

$$\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{p\in\mathcal{P}} D_{ijt}^p \cdot F_i \cdot x_{it}^p - a_t \leq M\cdot q_t \quad \forall t\in\mathcal{T} \tag{12}$$

$$-\sum_{i\in\mathcal{I}}\sum_{j\in\mathcal{J}_i}\sum_{p\in\mathcal{P}} D_{ijt}^p \cdot F_i \cdot x_{it}^p + a_t \leq M\cdot(1-q_t) \quad \forall t\in\mathcal{T} \tag{13}$$

$$r_{ijt}^p \geq D_{ijt}^p \cdot F_i \cdot x_{it}^p - M\cdot q_t \quad \forall i\in\mathcal{I}, j\in\mathcal{J}_i, t\in\mathcal{T}, p\in\mathcal{P} \tag{14}$$

$$r_{ijt}^p \geq \frac{D_{ijt}^p \cdot F_i \cdot x_{it}^p}{\sum_{i'\in\mathcal{I}}\sum_{j'\in\mathcal{J}_{i'}}\sum_{p'\in\mathcal{P}} D_{i'j't}^{p'} \cdot F_i \cdot x_{i't}^{p'}} \cdot a_t - M\cdot(1-q_t) \quad \forall i\in\mathcal{I}, j\in\mathcal{J}_i, t\in\mathcal{T}, p\in\mathcal{P} \tag{15}$$

Unlike the CR practice described before, all constraints (8)–(15) are required for every degree. The reason is that the concepts of pure pricing and proportional demand fulfillment apply to the status quo case and all degrees of combination. The adaptations for the different degrees, thus, solely rely on the parameter settings, as summarized in Table 2 and detailed below:

- **Status quo:** For Degree 0, there is no CR demand.
- **Degree 1:** For Degree 1, prices of the CS products are fixed to those resulting from the price optimization in the status quo, and those of the CR products are fixed to some baseline price (see Sect. 6.1).
- **Degree 2:** Degree 2 allows for price optimization of the CR product; thus, multiple price levels exist for these products.
- **Degree 3:** In Degree 3, likewise, the CS products have different prices.

Technically speaking, like the CR model (1)–(6), the CS model (7)–(15) is a deterministic mixed-integer linear program which addresses a network problem. In contrast to (1)–(6) and as described above, the CS model is a pure pricing problem, i.e., without the "lower level" availability control. Conceptually, it can be considered as a specific variant of a *deterministic multiproduct multiresource pricing problem without replenishment* (Talluri and van Ryzin 2004, Chapter 5.4.1). Regarding the special case with $|\mathcal{J}_i| = 1 \; \forall i \in \mathcal{I}$ and continuous unbounded prices discussed at the end of Sect. 5.2, note that in this case, the two models for CR (1)–(6) and CS (7)–(15) become equivalent in the sense that identical instances would result in identical solutions. In general, however, the CR model has additional flexibility in control, due to the availability control component.

6 Numerical studies and managerial insights

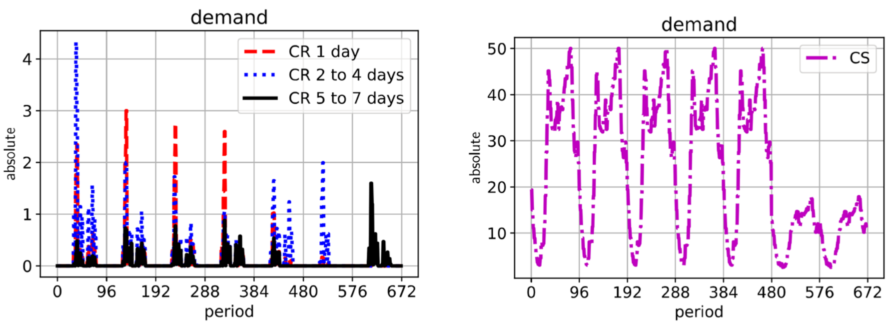
The presentation of the numerical studies and the derived managerial insights is structured as follows. In Sect. 6.1, we explain the used data as well as the experimental setup. Section 6.2 contains the description of results and the discussion of insights, starting with the status quo settings (Sect. 6.2.1), followed by analyzing combined systems for both business practices (Sects. 6.2.2 and 6.2.3). Finally, we summarize our findings (Sect. 6.2.4).

6.1 Data and experimental setup

Data sources: The most relevant data for this study, demand patterns and prices including sensitivities, is based on real-life data from two European cities: one from a Portuguese CR provider and other from a Europe-wide operating CS provider. More specifically, we used this data to define the *base* prices and their corresponding average weekly demand patterns. To accommodate differences in market sizes from the two sources of data, the patterns are scaled by adapting the maximum demand for a single period while retaining the relative differences in demand to this maximum for all other periods. The demand patterns for the two status quo settings are depicted for the CR products in Fig. 3a and for CS in Fig. 3b. Regarding the three demand levels, these patterns correspond to the "high" demand level, when considering the respective other business practice. The demand levels "low" and "medium" correspond to 1/3 and 2/3 of the "high" demand level, respectively.

Products and prices: Throughout the studies, we consider four products, three for CR and one for CS. We assume different products in CR to account for the typical practice of charging different daily prices for shorter or longer rentals. The three CR products were selected based on the typical step-wise pricing performed by CR companies, and they differ in their per-day prices, i.e., 1-day rental product (100€ per day), 2–4-day rental product (80€ per day), and 5–7-day rental product (65€ per day). As discussed before, for each product, different rental durations may exist (e.g., 2 days or 3 days, which would be priced per day within the same 2–4-day rental product). The CS product has a price of 0.3€ per minute and lasts 15 min. All prices are realistic values common in practice. Even though prices can change easily in this setting and are dependent on the type of vehicle or season, these values are approximated from the average values obtained from the CR and CS providers mentioned above.

For each product, there are two additional prices in our study, one *low* and one *high* price with corresponding demand values. The low (high) prices are 20% below (above) the base price, and the demand is scaled 20% higher (lower) for the low (high) price, keeping the real-world patterns. These percent values represent a common level of average willingness-to-pay, leading to typical changes in the market. Even though it is also possible that steeper increases and decreases are observed in very high seasons, especially in CR, these values seem to map the typical market behavior of the providers analyzed. Typical price variations in the CR market are analyzed in Costa (2019) and the chosen price changes (±20%) lie within the reported ranges (e.g., ±18% around the median price charged for standard vehicle groups in the middle season, averaged across competitors). Willingness-to-pay refers to the maximum price a customer will pay for a service. Thus, an increase



(a) Traditional CR

(b) Traditional CS

Fig. 3 Real-world average weekly demand patterns (15-min time periods) used in this work of price is expected to turn some customers away from the service (those whose willingness-to-pay is lower than the price charged), leading to lower demand levels. Conversely, decreasing the price attracts more customers, leading to higher demand levels. Finally, note that the base price generates the highest revenue when supply is not limited because the 20% increase in demand does not compensate the 20% decrease in prices (and vice versa), since $0.8 \cdot 1.2 < 1$.

Fleet size and alignment of data sources: The fleet size is set to $C = 100$ and serves as an anchor for the study. More specifically, the "high" demand level (see above) for Degree 0 (status quo) is calibrated such that there is realistic overall fleet utilization. That is, for the CR business practice, the utilization in Degree 0 is 86%, and for the CS business practice, the utilization in Degree 0 is 21%, to replicate realistic circumstances. Using the fleet size as an anchor and scaling the demand patterns through realistic utilization assumptions allows to align the two different data sources of the CR and the CS provider.

Friction: For CS, a friction parameter of $F_i = 0.9$ accounts for imperfect matching of supply and demand, as elaborated in Soppert et al. (2023). Since the causes for this mismatch do not apply to the CR products, the parameter is set to $F_i = 1$ for them. Figure 4 schematically represents this difference. The time periods are represented in the horizontal axis and the vehicles (used for both CR and CS rentals, depending on their availability) in the vertical axis. The availability of each vehicle in each period is represented, as well as idle periods. Considering the capacity consumption of rentals, one 1-day CR rental (of 1440 min) is equivalent to 96 CS rentals (of 15 min). However, due to the imperfect matching of supply and demand in CS, one entire day of available vehicles and CS demand will result in less than 96 CS rentals. To account for this effect, the friction parameter of $F_i = 0.9$ is introduced, resulting in 86 CS rentals.

Experimental setup: Each optimization is performed over 3 weeks, i.e., $3 \cdot 7 \cdot 96 = 2,016$ periods of 15 min, but we only evaluate the second week to reduce potential boundary effects (e.g., entire fleet available in first period). We use Python 3.7.16 with Gurobi 9.1.2 to solve the optimization problems. All computations were done on a local machine with Intel i7 1.8GHz processor and 32GB RAM. To speed up computation time (~20 min in the worst case), the optimality gap was set to 0.5%.

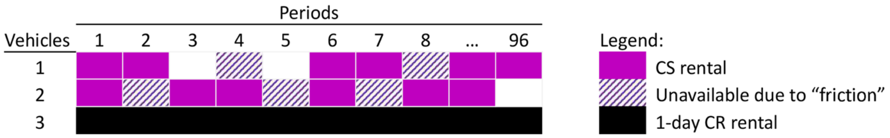


Fig. 4 Schematic visualization of vehicle occupation with CR and CS rentals

Table 4 Results for the average week of the status quo setting for CR and CS practices

	Revenue	Rentals	Utilization	Service
CR practice (total)	46,242€	205	86%	100%
1-day rentals	6438€	62	9%	100%
2–4-day rentals	24,342€	102	43%	100%
5–7-day rentals	15,462€	41	34%	100%
CS practice	62,872€	13,972	21%	90%

Metrics: Throughout this section, we will analyze different metrics, such as number of rentals served, overall revenue, utilization and service level. To clarify, we define utilization as the share of available fleet being used for a rental at a given period. The results shown (in percentage) relate to the full utilization throughout the week analyzed; i.e., the number of used time periods divided by the total number of available time periods across all vehicles. As for service level, it is also a relative metric, defined as the portion of demand requests for a rental (in response to the defined or optimized prices) that are actually served and, thus, translate into a rental. Similarly to utilization, the (percent) results shown refer to the total values throughout the week.

Limitations: It should be highlighted that, obviously, the results presented depend on the specific assumptions taken and the specific data used. As discussed above, we used representative real-world data, and the models proposed contribute to generalizing findings and insights. Nevertheless, the limitations of this work are acknowledged and clearly discussed throughout the remainder of the paper.

6.2 Results and managerial insights

The complete results of this study are available in Appendix A of the Supplementary Material. To facilitate their analysis and to derive managerial insights, we pose and answer multiple questions. This allows to shift the focus on relevant aspects, like the influence of a particular business practice or a particular revenue management instrument.

6.2.1 Status quo

We start by analyzing the status quo settings, which will serve as a baseline for the subsequent analyses of the different degrees of combination. Table 4 summarizes the optimization results as for weekly revenue, number of rentals, average utilization, and service level for both business practices, differentiating the three CR products. The revenue obtained in CR (approx. 46k€) and CS (approx. 68k€) is of the same order of magnitude, while the number of rentals is much higher for CS (approx. 14k) compared to CR (approx. 200). This is expected since the number of rentals possible to fulfill with the same fleet differs greatly in the two mobility offers, due to the friction caused by supply and demand mismatch in CS. In addition, it should be considered that the demand patterns for this CS status quo, with almost 20 CS rentals per day (approx. 14k rentals/7 days/100 vehicles), can be considered a best-case, meaning that especially in larger cities with more friction, vehicles are typically used less than 20 times per day. Thus, increases in revenue, rentals and utilization reported in the following sections are conservative results.

Interestingly, regarding revenue, approximately 23 CS rentals yield the same revenue as one 1-day CR rental. Thus, directly replacing one 1-day rental with CS rentals would be economically attractive. This helps explain the higher overall revenue obtained for CS, despite the lower fleet utilization. One should note, nonetheless, that the intermittency in CS demand (leading to high peaks and shallow valleys in the demand pattern) would only allow for this “complete replacement” of CR rentals for very few vehicles. For example, there is not enough CS demand to use 10 or more vehicles continuously throughout the entire week.

Regarding utilization, as mentioned before, the average utilization in the two status quo settings is quite different: 86% for CR and 21% for CS. In both cases, the utilization level varies considerably over time, following the demand patterns (which are also graphically represented in Fig. B1 in the Appendix). For CR, the period-specific total (all products) utilization during a week varies from 54 to 100%, and in CS, from 2 to 45%. In CR, even though demand peaks, as it does for CS, the number of vehicles in use is more stable due to the duration of the rentals. There is a clear opportunity to increase utilization for both businesses.

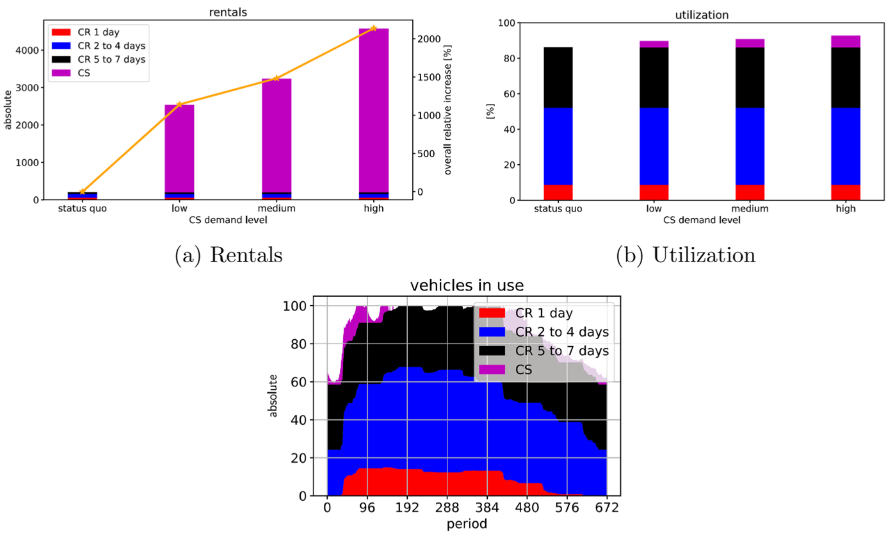
As for service level, it is 100% for CR and 90% for CS. Since demand is the limiting factor in both status quo settings (utilization < 100%) and given the choice of the friction parameter in CS, these results are not surprising.

6.2.2 CR business practice

On improving utilization: *Is a combined CR&CS system able to substantially increase utilization?*

Due to the short duration of CS rentals, it would be expected that additionally offering CS in the CR business practice can substantially increase utilization, because even short time intervals with idling vehicles between two CR rentals could be used efficiently. Nevertheless, the demand patterns may lead to counterintuitive results. We limit ourselves to presenting the analysis for Degree 1 since the utilization results have a similar interpretation for the remaining degrees.

Degree 1 of the CR business practice (CR priority) aims to keep the legacy business as close as possible to the business as usual by fixing prices and ensuring CR demand priority. As a result, CS rentals will only be used to fill idle slots. Figure 5 presents the key results for this degree, showing how rentals and revenue increase with increasing CS demand and how that translates to vehicle utilization throughout time (exemplified for the lowest CS demand level). The large increase in rentals (which relates solely to CS rentals) translates into a moderate increase in utilization. This phenomenon of highly different capacity consumption between a CR rental and a CS rental was discussed in the previous section and can be better understood by considering the resulting vehicles used during the week.



(a) Rentals (b) Utilization

(c) Vehicles in use (low CS demand level; fleet size: 100)

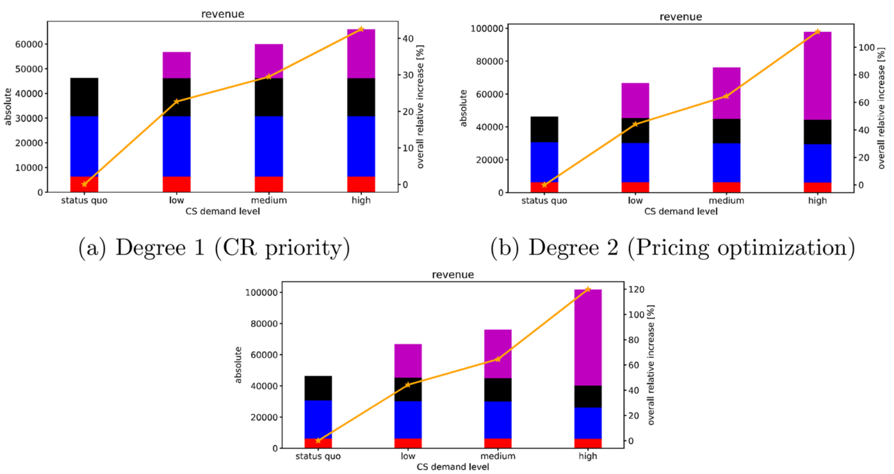
Fig. 5 Degree 1 (CR priority) for different CS demand levels. Overall relative increases with regard to the CR status quo depicted with yellow line

Overall, the increase in rentals and utilization is limited by the demand patterns. The periods with fewer CR vehicles in use and, thus, lower vehicle utilization due to lower demand match those with lower CS demand (e.g., at the start of the week, particularly during the early morning hours). Only if the CS demand pattern was complementary to the CR pattern or substantially higher in order of magnitude would the utilization be substantially higher. As mentioned before, this limited increase in utilization is also observable in higher degrees of combination and, thus, cannot be attributed to the priority given to the legacy business.

On protecting the legacy business: *What are the (positive and negative) impacts of protecting the legacy business?*

Protecting the legacy business—and thus opting for a smaller degree of combination—has clear advantages for a CR provider looking for a slower and lower-risk entry in the new CS market. Nevertheless, it is critical to assess the impact this may have on revenue regret (the loss of revenue for not opting for a higher degree of combination) and on the service level for the legacy business.

Figure 6 shows how revenue increases for the different levels of CS demand under increasing degrees of combination. There is an improvement of 23–53% in revenue in Degree 1, achieved without altering CR rentals and service level. The three degrees represent a gradual relaxation of the protection of the legacy business: Degree 2 (Pricing optimization) also prioritizes CR demand (as Degree 1) when allocating vehicles to demand. However, since the CR prices are optimized for the combined system, demand management through pricing can result in a lower



(a) Degree 1 (CR priority) (b) Degree 2 (Pricing optimization)

(c) Degree 3 (Integrated optimization)

Fig. 6 Revenue for Degrees 1, 2 and 3 in CR business practice and for different CS demand levels. Overall relative increases with regard to CR status quo depicted with yellow line

CR demand level to increase the available capacity for CS rentals. In Degree 3 (Integrated optimization), there is no protection for the legacy business. For both relaxations, revenue increases substantially with respect to Degree 1. With low and medium demand levels, the relative revenue increases for both degrees are 44% and 65%, respectively. The revenue increases for Degree 2 and 3 only differ for the high demand level (111% and 120%). Thus, these considerable improvements demonstrate that pricing optimization is an efficient lever for revenue maximization, even if priority is enforced for CR demand, and that there is additional value in additionally performing availability control, if demand levels are high.

Note that the difference in magnitude of rental increases compared to revenue increases could raise the question of the impact of variable costs on total profit when this large number of new rentals is added. Nevertheless, as long as the price of the CS rental is higher than the variable cost it represents (as we assume), the impact on profit will also be positive, even if smaller compared to the impact on revenue.

To further validate this impact, Appendix E presents a sensitivity analysis to varying product-dependent variable costs (maximizing contribution margins instead of revenue). Focusing on the highest degree of integration between CR and CS in both business practices, if we assume that variable costs are 20% of the base prices, the results show that the relative improvements in contribution margin when considering variable costs are in similar range to the revenue improvements when there are no variable costs. The differences mainly affect the prices (which increase, as expected), rentals (which favor more profitable products), and, thus the utilization and vehicles in use. Higher and product-dependent variable costs are also analyzed and are in line with the previous findings.

Further, it is important to understand whether this gain in revenue by relaxing the protection of the legacy business represents a relevant trade-off in terms of the

Table 5 Average prices for Degree 3 and different demand levels, with CR 1 representing the 1-day rental product, CR 2 the 2–4-day rental product and CR 3 the 5–7-day rental product

CS dmnd. lev.	Absolute (CR: [€/day], CS: [€/rental])				Relative to base price			
	CR 1	CR 2	CR 3	CS	CR 1	CR 2	CR 3	CS
Low	110.2	87.7	68.4	4.5	10.2%	9.6%	5.3%	1.0%
Medium	111.1	88.7	76.6	4.6	11.1%	10.9%	17.8%	1.5%
High	117.7	95.8	78.0	4.6	17.7%	19.8%	20.0%	3.2%

service level provided to customers. A previous analysis has shown that fully protecting CR legacy business (Degree 1) leads to a 100% service level for legacy customers, contrasting with less than 50% service level for new CS customers. Analyzing the service level values for Degrees 2 and 3, where the legacy business' priority is progressively reduced, they show it is possible to keep the 100% service level for the legacy customers while considerably increasing the service level for new customers already in Degree 2. Figure B2 in the Appendix graphically represents these results. This is the result of price optimization slightly reducing CR rentals in favor of several CS rentals, as discussed before, leading to slight gains in revenue and a substantial increase in CS service level. It should be noted that, due to the mismatch between supply and demand in CS, in this study, the theoretical upper bound for CS service level is 90%. Further, it should be noted that, as discussed before, demand management through pricing allows for keeping the highest service level in CR: as some prices increase, CR demand decreases, maintaining full service for the remaining demand. A slight decrease in service for the CR products only occurs for high CS demand (high demand level) in Degree 3, when it becomes economically beneficial to allocate resources from the multi-day CR products to the CS product.

On integrated optimization: *What is the impact of optimizing prices on the different metrics?*

In Degrees 2 and 3, the provider can perform availability control and pricing to manage demand, with differences in the priority given to legacy demand. As briefly stated above, there are no major changes in revenue, rentals, utilization or service level between Degrees 2 and 3, with the only exception for high CS demand. This means that CR priority does not need to be enforced, as it seems to be inherently optimal for the combined system. Nevertheless, in a fully integrated system (Degree 3), there is an increase in prices, especially for CR rentals, and prices increase with higher CS demand. This is visible in Table 5, which presents the resulting average prices for the different products under different demand levels. The differentiated impact for shorter or longer CR rentals is due to the flexibility offered by the availability control, which works together with pricing to maximize revenue.

To further understand the apparent inherent priority of CR rentals in Degree 3, we run a sensitivity analysis on the CS willingness-to-pay parameter used in this study to analyze if it could be made more attractive for the combined system. Figure 7 shows the results in terms of rentals for Degree 3 (Integrated optimization), and the

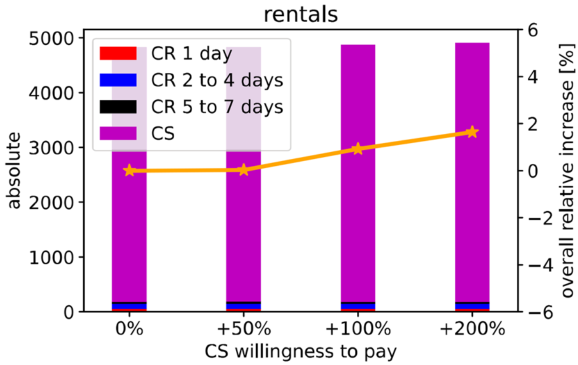


Fig. 7 Varying CS willingness-to-pay in Degree 3 (Integrated optimization). Overall relative increases with regard to Degree 3 with low CS demand level depicted with yellow line

full results can be found in Appendices C.1 and C.2 of the Supplementary Material. In fact, even increasing CS willingness-to-pay within realistic bounds would not lead to a substantial change in the number of rentals (while leading to a relative increase in revenue due to the higher prices charged for the same rentals). Therefore, considering the total number of CS rentals in Degree 3, it is possible to understand that CS demand is the limiting factor. The model favors CS rentals whenever possible, leading to some increase in revenue. Yet, it is limited by the highly variable patterns of CS demand, thus resulting in similar outcomes for Degrees 2 and 3 in the CR business practice.

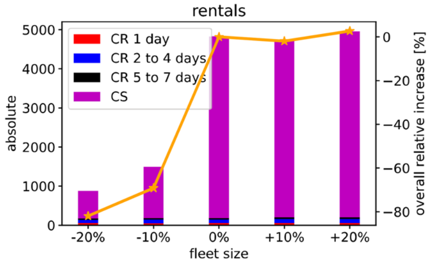
On integrated optimization: *What is the impact of increasing the fleet for a combined system?*

The previous conclusions lead to the question of whether it is beneficial for CR providers to increase their fleet for a combined CR&CS system. Figure 8 shows the results of a sensitivity analysis performed on the fleet size. The full results can be found in the Supplementary Material in Appendix C.3 (as well as a similar analysis for CS in Appendix D.3). Interestingly, increasing the fleet has no considerable effect on revenue. While it allows fulfilling more demand (almost all from CS rentals), the utilization also drops due to the high-peak/low-valley shape of the CS demand patterns. Therefore, based on the performed study, one would conclude that increasing the fleet does not seem reasonable for CR providers launching a combined CR&CS system.

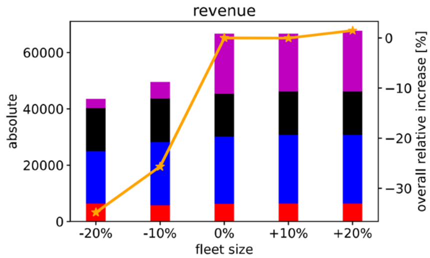
6.2.3 CS business practice

On utilization and service level: *What are the impacts on utilization and trade-offs regarding CS service level when offering CR?*

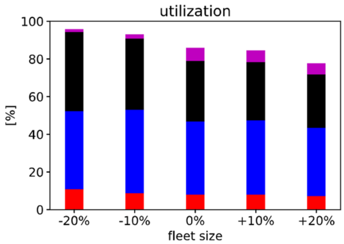
As discussed in Sect. 6.2.1, the average utilization on the CS business-as-usual system is low, and the advantage of combining mobility offers is that utilization is expected to increase. Nevertheless, it is important to understand the subsequent impact on the legacy CS service level since, with a pure-pricing CS approach, it



(a) Rentals

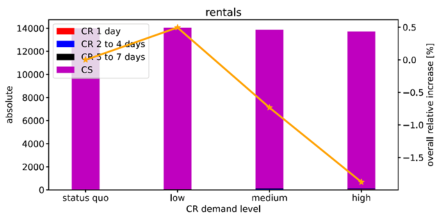


(b) Revenue

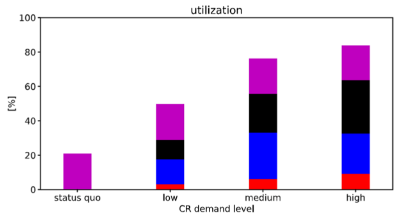


(c) Utilization

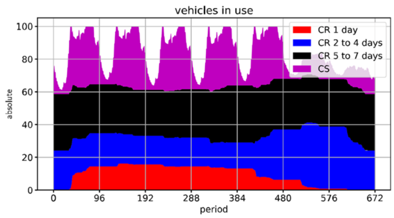
Fig. 8 Varying fleet size in Degree 3 (Integrated optimization). Overall relative increases with regard to Degree 3 with low CS demand level depicted with yellow line



(a) Rentals



(b) Utilization



(c) Vehicles in use (high CR demand level; fleet size: 100)

Fig. 9 Degree 1 (CR fixed prices) for different CR demand levels. Overall relative increases with regard to CS status quo depicted with yellow line

is impossible to protect the capacity for CS users by controlling availability as CR providers do.

Figure 9 presents the key results for Degree 1 from the CS business practice, i.e., the degree with the fewest changes w.r.t. the status quo setting, focusing on number of rentals, utilization, and vehicles in use throughout time. In this degree, prices for the new CR products are fixed to the ones optimized for the business-as-usual, and CR prices are fixed to the *base* prices. It is possible to see that the number of realized rentals changes only slightly. They increase for smaller CR demand levels and decrease as CR demand increases. Nevertheless, the utilization increases substantially. This is due to the large number of CS rentals fulfilled in the status quo setting and the already discussed effect that already a few CR rentals translate into high vehicle occupation. The impact of CR rentals in vehicle utilization throughout time is also visible, with the high peaks and low valleys of the CS business-as-usual being replaced by a more stable utilization of vehicles through CR rentals. The utilization increase of 50–84% (depending on the CR demand level) directly translates into a substantial increase in revenue (25–51%).

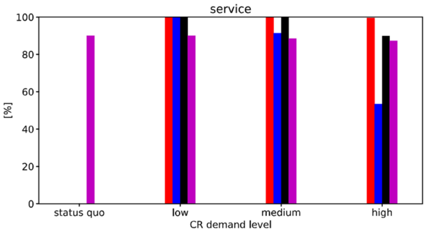
Interestingly, the CS service level is not highly impacted by introducing the new mobility offer (for more details, see Table A4 in the Appendix). If CR demand is low, the service level is the same as in the status quo setting (90%). For the higher levels of CR demand, it decreases only 3 p.p. In fact, as overall demand increases and gets increasingly limited by capacity, fixing the prices of both CR and CS impacts more specific CR products (as will be discussed further), not affecting CS legacy users considerably.

The trade-off between substantial utilization (and revenue) gains and a slight potential decrease in CS service level seems to support the interest in combining CR&CS concepts for CS providers. In this business practice, the results for Degrees 2 and 3 have a similar interpretation regarding this trade-off. W.r.t. business-as-usual, utilization increases from 50 to 81% in Degree 2 (this and the following ranges are dependent on the CR demand level) and 50–83% in Degree 3, whereas the service level is kept between 87 and 90% (Degree 2) and 89% and 90% (Degree 3).

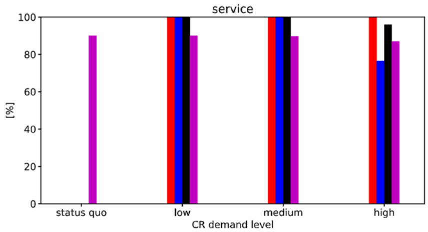
On offering new products: *What is the impact of different CR products in a combined CR&CS system from a CS provider business practice?*

Unlike in the CR business practice, a CS provider aiming to combine CR&CS systems is considering introducing multiple products, which may be priced differently and respond to the different needs of users. For example, a 1-day rental has a higher per-day cost for the user than a 5–7-day rental, and they are often requested for different needs, such as a private vehicle short-term substitution or a holiday. These differences translate into different demand patterns. For example, 1-day rentals are, on average, more requested at the start of workdays, and 5–7-day rentals are the only product with significant demand for Sunday mornings. Since, from a CS provider's business practice, capacity cannot be optimally allocated among different products (as capacity is proportionally divided amongst different demands), these demand patterns play a relevant role in the operational roll-out of the system, as well as the pricing optimization lever available for the providers to manage demand.

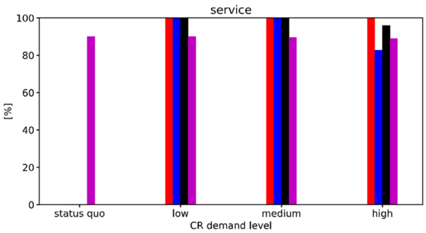
Figure 10 shows the service level results for Degrees 1, 2, and 3, for increasing levels of CR demand. As demand is proportionally distributed amongst the



(a) Degree 1 (CR fixed prices)



(b) Degree 2 (CR pricing optimization)

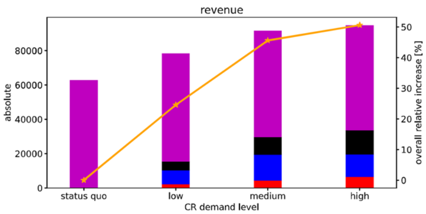


(c) Degree 3 (CR and CS pricing optimization)

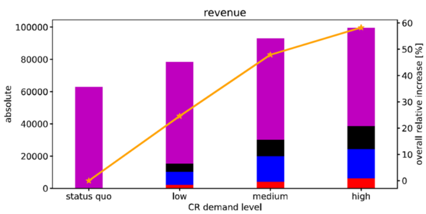
Fig. 10 Service level for Degrees 1, 2 and 3 in CS business practice and for different demand levels

available capacity, the service level metric allows understanding the impact of the combined system on the different products. For Degree 1, the service level is in fact quite different for the multiple CR products offered: for 1-day rentals, it stays at 100% even as CR demand increases, for 5–7-day rentals, it drops to 90% only for the highest demand level, whereas for 2–4-day rentals, it substantially drops to 53% in the same situation. In this degree, there is no price optimization, and therefore the results directly translate the demand patterns. This is easily understood by considering the vehicles-in-use. 1-day rentals, as they use vehicles for a shorter period, are easily served during their demand periods (weekdays). As CS and 1-day CR demand drops substantially at the weekend, 2–4-day and 5–7-day rentals that start at the weekend represent a higher share during these and the following periods they occupy. The lower average service level of 2–4-day rentals (versus 5–7-day rentals) is because the highest demand peak is on Mondays when 1-day CR and CS also compete for availability. In Degrees 2 and 3, CR prices are optimized. This way, demand for 2–4-day rentals is managed, and higher prices are charged to seize the willingness-to-pay of a smaller-sized demand that better fits the available capacity. Therefore, the service level significantly increases in these degrees for 2–4-day rentals. These conclusions are supported by the pattern of vehicles in use over time for all degrees, which can be seen in more detail in Fig. B3 in the Appendix.

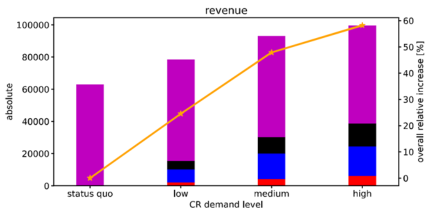
On pricing optimization: *What is the impact of (integrated) optimization of prices for both legacy and new products?*



(a) Degree 1 (CR fixed prices)



(b) Degree 2 (CR pricing optimization)



(c) Degree 3 (CR and CS pricing optimization)

Fig. 11 Revenue for Degrees 1, 2, and 3 in CS business practice and for different demand levels. Overall relative increases with regard to the CS status quo depicted with yellow line

The key difference between the degrees of combination in the CS business practice is the extent to which prices are optimized. In Degree 1, all prices are fixed to the business-as-usual (CS) or a baseline (CR). In Degree 2, the change is only w.r.t to the prices for the new products, which are optimized. Finally, in Degree 3, all prices are optimized.

The main factor that brings improvements w.r.t. to the business-as-usual is the addition of new demand. This allows considerable revenue improvements even for Degree 1 (21–54%, depending on the CR demand level. Figure 11 shows how revenue increases with the increase of CR demand, for all degrees. It is possible to see that the revenue increases of adding pricing are relevant but within a smaller order of magnitude (up to 58% in Degree 2 and 62% in Degree 3). Between the three degrees, the change in rentals is negligible (for more details, see Figure B4 in the Appendix). Degrees 2 and 3 show a small decrease in rentals for the highest CR demand level due to tighter capacity constraints and the substitution of CR rentals with CS rentals. Nevertheless, this impact is reduced. Consequently, the effect on average utilization of pricing optimization (CR-only or integrated) is also reduced.

As discussed before, introducing CR pricing optimization improves the service level for CR products due to demand management. Aside from that effect, the impacts on service level are also reduced. Nevertheless, this allows understanding the relevance of pricing from the CS business practice: it is indeed a critical tool to manage demand and influence it to match the available supply. This affects not only revenue but also the service level perceived by users, which is the maximum for the highest pricing flexibility (Degree 3).

Table 6 Average prices for Degree 3 and different demand levels

CR dmnd. lev.	Absolute (CR: [€/day], CS: [€/rental])				Relative to base price			
	CR 1	CR 2	CR 3	CS	CR 1	CR 2	CR 3	CS
Low	100.0	80.0	65.0	4.5	0%	0%	0%	0%
Medium	108.3	85.9	68.9	4.5	8.3%	5.9%	3.9%	1.0%
High	117.7	95.8	78.0	4.7	17.7%	15.8%	13.0%	3.0%

These results suggest that optimizing a combined CR&CS system from a CS provider's business practice leads to overall higher CS prices. Table 6 shows the average prices resulting from the optimization in different CR demand levels, as well as their relative increase compared to the base prices. It is possible to see that this increase is more substantial for the new (CR) products. From the legacy (CS) user business practice, an increase of up to 3% may be an acceptable difference, given that the service level remains comparable.

To validate that these conclusions were supported for a different ratio between the prices of CR and CS products (i.e., to ensure the parameterization is not favoring either type of mobility offer through the available prices), we run a sensitivity analysis on the CR willingness-to-pay. The full results of this analysis can be found in Appendices D.1 and D.2 in the Supplementary Material. This analysis shows that CR willingness-to-pay has virtually no impact on the number of rentals fulfilled, which leads to nearly no changes in utilization and service level. Revenue will evidently increase as willingness-to-pay increases, yet this results directly from the higher prices charged for the same rentals. This supports the conclusions of this study for other contexts regarding the relative willingness-to-pay for the two mobility offers.

6.2.4 Summary

In summary, the following insights can be drawn from our numerical study on combining CR and CS.

CR practice: For the considered traditional CR provider, the revenue increase by offering an additional CS product ranges from 23 to 120%, depending on the degree of combination and the CS demand level. Thus, offering CS in addition is an attractive business decision. The revenue increase resulting from relaxing CR priority is substantial, especially for high CS demand levels. While the number of rentals increases substantially when offering CS due to the many CS rentals realized, the overall utilization increase is slight because of the few periods in which capacity is used compared to CR rentals. Regarding the benefit of control flexibility in the different degrees, any optimization—availability control or pricing—allocates resources from CR to CS. With regard to service level, CS customers benefit strongly when CR priority is dropped, but this effect comes with slightly higher prices for CR. Overall, the transition towards a combined CR&CS system is an attractive option for CR providers that comes with the potential for moderate revenue increases.

Drawbacks are related to limited utilization improvements, a required trade-off in service level, and higher prices for legacy customers. As discussed, the expected increase in rentals and utilization is limited by the demand patterns. It turns out that offering CS products does not perfectly complement offering CR in terms of demand patterns because, at peak times of CS demand, most vehicles are used for CR products. To substantially increase utilization, the CS demand pattern would have to be more complementary to the CR pattern, or there would need to be substantially more CS requests. At the same time, even though demand management through pricing allows for good service levels (even if the legacy business is not protected), for higher CS demand levels, a slight decrease in CR service level is expected. Finally, advancing to a combined CR&CS system leads to higher prices for CR products, especially in the face of high CS demand, which may be detrimental to legacy users. As a side effect, the benefits previously stated come from fulfilling substantially more rentals of CS customers, which may affect operations.

CS practice: For the considered traditional CS provider, the revenue increase by additionally offering CR is substantial as well, but not as high as for the CR provider. Depending on the degree of combination and the CR demand level, it varies between 21 and 62%. Even though there are very few CR rentals and overall rentals actually tend to decrease, the comparably high absolute revenue of CR rentals causes overall revenue to increase. Due to the high occupation of CR rentals, offering CR comes with a large increase in utilization (between 50 and 83% for Degree 3). The service level for CS is not affected by the introduction of CR, mainly because the low utilization in the status quo setting allows to use the fleet alternatively without causing scarcity, but also because of increased prices which reduce CS demand. For the CR products, in contrast, service levels are impacted considerably when integrating CS and CR fully. The effects vary strongly per product, but it has to be kept in mind that, in this business practice, CR demand is new and thus this does not represent a decrease versus the status quo. Overall, the transition towards a combined CR&CS system is an attractive option for CS providers that comes with the potential for high revenue increases.

At this level of analysis and under the assumptions of this study, there are limited drawbacks because the service level for legacy customers is retained while prices only increase marginally. However, it should be noted that there is an additional challenge in managing many different products (vs. one product in traditional CS practice), as different demand patterns play a relevant role in the operational roll-out of the system. Moreover, the gains of increasing the level of pricing optimization are somewhat limited, and the change in rentals and utilization is negligible between increasingly optimized degrees of combination. Additionally, optimizing a combined CR&CS system for a CS provider leads to overall higher CS prices, yet only up to 3%, which may be acceptable for legacy users.

7 Conclusion

In accordance with latest developments in practice, the two traditional mobility offers of car rental (CR) and car sharing (CS) can no longer be considered separately, but instead intertwine increasingly. To account for this development, we analyze *combined CR&CR systems*, where providers use a common fleet of vehicles to serve both the demand for CR and CS. So far, combined CR&CS systems have not yet been addressed in the literature, and, with this work, we lay the foundation for a new branch which is at the intersection of the vast literature on (pure) CR and CS. This study examines the benefits and drawbacks of combined CR&CS systems at an aggregate level that can support strategic decision-making of CR and CS providers. We propose a mathematical optimization approach to model different degrees of integration and assess key performance metrics such as revenue, rentals, utilization, and service level using real-life data, alongside sensitivity analyses.

The main insights regarding the economic benefit of combining CR and CS can be summarized as follows. For a **CR provider**, in our study, additionally offering CS increases revenue between 23 and 120%. The more CS demand and the higher the degree, the more revenue can be generated. Higher flexibility for availability control and pricing when transitioning towards a fully combined system allocates resources from CR to CS, causing a substantial increase of CS rentals while CR rentals decrease only slightly. Further rentals and revenue increases are limited, because the demand patterns of the CS products do not perfectly complement the CR demand patterns. For a **CS provider**, in contrast, additionally offering CR increases revenue between 21 and 62% in our study. The more CR demand and the higher the degree, the more revenue can be generated. These high revenue gains come from additional CR rentals that utilize unused capacity and fewer CS rentals at peak times that free capacity for the longer CR rentals with higher absolute revenue. Another reason for these large revenue increases for CS providers compared to CR providers is the substantially smaller fleet utilization in the status quo setting which allows more potential for improvement when increasing demand.

In summary, traditional CR and well as traditional CS providers can benefit substantially from additionally offering the respective other service in addition. When retaining current business practice in terms of revenue management instruments, this transition towards a combined CR&CS system is more attractive for a CR provider, due to the additional demand management flexibility related to availability control. Conversely, CS providers should consider deviating from current business practice when transitioning towards a combined system, because of the substantial revenue increase when performing availability control in addition to pricing.

Regarding limitations of our work, we see three main points. The first concerns the assumption that the pricing optimization is restricted to a discrete set of price points with corresponding demand values. Even though this approach mirrors the policies typically observed in practice, it confines the model to this specific price-demand relationship as well as the specific parameters. Thus, employing continuous prices, testing different price-demand relationships as well as incorporating uncertainty would yield more global and more robust results. Second, although we consider a strategic view on these systems, as discussed in Sect. 3.2, a more granular analysis using user-level data and individual vehicle movements in a disaggregate model might offer valuable more detailed insights and, thus, strengthening the robustness of the findings. Third, this work does not consider potential technological and operational constraints of implementing a combined CR&CS system, nor does it account for regulatory or policy changes that could impact its operation.

Regarding future work on combined CR&CS systems, three key research streams should be considered, namely extending the models to: (i) represent a more disaggregated view of the system, (ii) enhance market demand representation, and (iii) consider additional real-world features. On the one hand, extending these models to consider the system on a more disaggregated level, including individual demand patterns, individual customer choices, and individual vehicle movements, may bring more relevant insights. The main question would be if the general findings of this work regarding benefits for CR and CS providers when transitioning towards a combined system can be explained in greater detail. On the other hand, extending the market demand models may shed more light on the impact of how customers use different shared mobility modes. More specifically, the models can be extended to tackle the heterogeneity in customer preferences and choice behavior, and to consider additional features that influence choice other than price, such as brand effects or availability and reliability perceptions. When considering realistic constraints and settings, the consideration of a heterogeneous fleet would be insightful. Since different use cases when renting a vehicle come with different requirements regarding vehicle specifics, the fleet's mix and optimal assignment are relevant questions. Finally, analyzing different pricing approaches for combined CR&CS systems can further support the observed development in practice. For example, once a system is fully combined, a flat-rate pricing model in which customers buy a mobility budget that they can spend flexibly for the CR or the CS offer can be implemented.

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Data availability statement The data that support the findings of this study were used under license of the companies that own it for the current study and so are not publicly available. The data are, however, available from the authors upon reasonable request and with the permission of the shared mobility companies involved.

Declaration

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Becker H, Ciari F, Axhausen KW (2017) Modeling free-floating car-sharing use in Switzerland: a spatial regression and conditional logit approach. Transp Res Part C 81:286–299. https://doi.org/10.1016/j.trc.2017.06.008

Boyaci B, Zografos KG, Geroliminis N (2015) An optimization framework for the development of efficient one-way car sharing systems. Eur J Oper Res 240:718–733. https://doi.org/10.1016/j.ejor.2014.07.020

Costa SIS (2019) Understanding Demand and Pricing Behaviour in the Car Rental Business. Master's thesis. https://hdl.handle.net/10216/121292. university of Porto

Euromonitor International, 2023. Car rental: top six industry trends. Accessed on 2023-05-26 at: https://www.euromonitor.com/car-rental-top-six-industry-trends/report

Ferrero F, Perboli G, Rosano M, Vesco A (2018) Car-sharing services: an annotated review. Sustain Cities Soc 37:501–518. https://doi.org/10.1016/j.scs.2017.09.020

Fink A, Reiners T (2006) Modeling and solving the short-term car rental logistics problem. Transp Res Part E 42:272–292. https://doi.org/10.1016/j.tre.2004.10.003

Golalikhani M, Oliveira BB, Carravilla MA, Oliveira JF, Pisinger D (2021) Understanding carsharing: a review of managerial practices towards relevant research insights. Res Transp Bus Manag 41:100653. https://doi.org/10.1016/j.rtbm.2021.100653

Guerriero F, Olivito F (2011) Modelling and solving a car rental revenue optimisation problem. Int J Math Oper Res 3:198–218. https://doi.org/10.1504/IJMOR.2011.038911

Guillen J, Ruiz P, Dellepiane U, Maccarrone L, Maccioni R, Pinzuti A, Procacci E (2019) Europcar integrates forecasting, simulation, and optimization techniques in a capacity and revenue management system. INFORMS J Appl Anal 49:40–51. https://doi.org/10.1287/inte.2018.0970

Haensel A, Mederer M, Schmidt H (2012) Revenue management in the car rental industry: a stochastic programming approach. J Revenue Pricing Manage 11:99–108. https://doi.org/10.1057/rpm.2011.2

Huang K, An K, Rich J, Ma W (2020) Vehicle relocation in one-way station-based electric carsharing systems: a comparative study of operator-based and user-based methods. Transp Res Part E 142:102081. https://doi.org/10.1016/j.tre.2020.102081

Illgen S, Höck M (2019) Literature review of the vehicle relocation problem in one-way car sharing networks. Transp Res Part B 120:193–204. https://doi.org/10.1016/j.trb.2018.12.006

Jochem P, Frankenhauser D, Ewald L, Ensslen A, Fromm H (2020) Does free-floating carsharing reduce private vehicle ownership? The case of SHARE NOW in European cities. Transp Res Part A 141:373–395. https://doi.org/10.1016/j.tra.2020.09.016

Jorge D, Molnar G, de Almeida Correia GH (2015) Trip pricing of one-way station-based carsharing networks with zone and time of day price variations. Transp Res Part B 81:461–482. https://doi.org/10.1016/j.trb.2015.06.003

Klein R, Koch S, Steinhardt C, Strauss AK (2020) A review of revenue management: recent generalizations and advances in industry applications. Eur J Oper Res 284:397–412. https://doi.org/10.1016/j.ejor.2019.06.034

Liao F, Correia G (2022) Electric carsharing and micromobility: a literature review on their usage pattern, demand, and potential impacts. Int J Sustain Transp 16:269–286. https://doi.org/10.1080/15568318.2020.1861394

Liao F, Molin E, van Wee B (2017) Consumer preferences for electric vehicles: a literature review. Transp Rev 37:252–275. https://doi.org/10.1080/01441647.2016.1230794

Lin X, Sun C, Cao B, Zhou YW, Chen C (2021) Should ride-sharing platforms cooperate with car-rental companies? Implications for consumer surplus and driver surplus. Omega. https://doi.org/10.1016/j.omega.2020.102309

Madden T, Russell RA (2012) Modelling the rental car pricing and relocation problem. Int J Revenue Manage 6:246–257. https://doi.org/10.1504/IJRM.2012.050400

Molnar G, Correia GHA (2019) Long-term vehicle reservations in one-way free-floating carsharing systems: a variable quality of service model. Transp Res Part C 98:298–322. https://doi.org/10.1016/j.trc.2018.11.017

Müller C, Gönsch J, Soppert M, Steinhardt C (2023) Customer-centric dynamic pricing for free-floating vehicle sharing systems. Transp Sci 57:1406–1432

Niels T, Bogenberger K (2017) Booking behavior of free-floating carsharing users: empirical analysis of mobile phone app and booking data focusing on battery electric vehicles. Transp Res Rec 2650:123–132. https://doi.org/10.3141/2650-15

Oliveira BB, Carravilla MA, Oliveira JF (2017) Fleet and revenue management in car rental companies: a literature review and an integrated conceptual framework. Omega 71:11–26. https://doi.org/10.1016/j.omega.2016.08.011

Oliveira BB, Carravilla MA, Oliveira JF (2018) Integrating pricing and capacity decisions in car rental: a matheuristic approach. Oper Res Perspect 5:334–356. https://doi.org/10.1016/j.orp.2018.10.002

Oliver Wyman Forum, 2022. How urban mobility will change by 2030 - value pool report. Technical Report. Accessed on 2023-05-25 at: https://www.oliverwymanforum.com/content/dam/oliver-wyman/ow-forum/mobility/2022/Value%20Pool%20Report_7_2022.pdf

Pachon J, Iakovou E, Ip C (2006) Vehicle fleet planning in the car rental industry. J Revenue Pricing Manage 5:221–236. https://doi.org/10.1057/palgrave.rpm.5160041

Rotaris L, Danielis R, Maltese I (2019) Carsharing use by college students: the case of Milan and Rome. Transp Res Part A 120:239–251. https://doi.org/10.1016/j.tra.2018.12.017

Shaheen SA, Sperling D, Wagner C (1998) Carsharing in Europe and North America: past, present and future. Transp Q 52:35–52. https://doi.org/10.1068/a201285

Shaheen S, Cohen A, Farrar E (2019) Carsharing's impact and future, vol. 4. https://doi.org/10.1016/bs.atpp.2019.09.002

Share Now (2022) SHARE NOW (Version 4.53.1) [Mobile application]. Accessed on 2022-01-31 at: https://apps.apple.com/us/app/share-now-car2go-drivenow/id514921710

Sixt (2022) Sixt rent, share, ride & plus (Version 9.98.0) [Mobile application]. Accessed on 2022-01-31 at: https://apps.apple.com/de/app/sixt-rent-share-ride-plus/id295079411

Soppert M, Steinhardt C, Müller C, Gönsch J (2022) Differentiated pricing of shared mobility systems considering network effects. Transp Sci 56:1279–1303. https://doi.org/10.1287/trsc.2022.1131

Soppert M, Steinhardt C, Müller C, Gönsch J, Bhogale PM (2023) Matching functions for free-floating shared mobility system optimization to capture maximum walking distances. Eur J Oper Res 305:1194–1214. https://doi.org/10.1016/j.ejor.2022.06.058

Soppert M, Wagemann A, Steinhardt C (2022b) Block now or relocate later? Availability control of short-term rentals in shared mobility systems considering long-term rental reservations. SSRN https://doi.org/10.2139/ssrn.4228996

Statista (2023) Car-sharing - Europe. Accessed on 2023-05-30 at: https://www.statista.com/outlook/mmo/shared-mobility/shared-rides/car-sharing/europe

Steinhardt C, Gönsch J (2012) Integrated revenue management approaches for capacity control with planned upgrades. Eur J Oper Res 223:380–391. https://doi.org/10.1016/j.ejor.2012.05.047

Talluri KT, van Ryzin G (2004) The theory and practice of revenue management, vol 1. Springer

van Ryzin GJ, Talluri KT (2005) An introduction to revenue management. Emerg Theory Methods Appl. https://doi.org/10.1287/educ.1053.0019

Weikl S, Bogenberger K (2013) Relocation strategies and algorithms for free-floating car sharing systems. IEEE Intell Transp Syst Magazine 5:100–111. arXiv:1204.3968. https://doi.org/10.1109/MITS.2013.2267810

Wu C, Le Vine S, Sivakumar A, Polak J (2022) Dynamic pricing of free-floating carsharing networks with sensitivity to travellers' attitudes towards risk. Transportation 49:679–702. https://doi.org/10.1007/s11116-021-10190-8

You PS, Hsieh YC (2014) A study on the vehicle size and transfer policy for car rental problems. Transp Res Part E 64:110–121. https://doi.org/10.1016/j.tre.2014.01.007

Zhou F, Zheng Z, Whitehead J, Perrons RK, Washington S, Page L (2020) Examining the impact of car-sharing on private vehicle ownership. Transp Res Part A 138:322–341. https://doi.org/10.1016/j.tra.2020.06.003